STP-PT-006

# DESIGN GUIDELINES FOR HYDROGEN PIPING AND PIPELINES

ASME STANDARDS TECHNOLOGY, LLC

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# DESIGN GUIDELINES FOR HYDROGEN PIPING AND PIPELINES

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# FOREWORD

Commercialization of hydrogen fuel cells, in particular fuel cell vehicles, will require development of an extensive hydrogen infrastructure comparable to that which exists today for petroleum. This infrastructure must include the means to safely and efficiently generate, transport, distribute, store, and use hydrogen as a fuel. Standardization of pressure retaining components, such as tanks, piping and pipelines, will enable hydrogen infrastructure development by establishing confidence in the technical integrity of products.

Since 1884, the American Society of Mechanical Engineers (ASME) has been developing codes and standards (C&S) that protect public health and safety. The traditional approach to standards development involved writing prescriptive standards only after technology has been established and commercialized. With the push toward a hydrogen economy, government and industry have realized that they cannot afford a hydrogen-related safety incident that may undermine consumer confidence. As a result, ASME has adopted a more anticipatory approach to standardization for hydrogen infrastructure which involves writing standards with more performance-based requirements in parallel with technology development and before commercialization has begun.

The ASME B31 Standards Committee has established a new Section Committee, B31.12, to develop new Code rules for piping and pipelines in hydrogen infrastructure applications. Research activities are being coordinated to develop data and technical reports concurrent with standards development and have been prioritized per B31.12 Section Committee needs.

The Technical Reports to be developed will establish data and other information to be used to support and facilitate separate initiatives to develop ASME standards for the hydrogen infrastructure. An initial report, developed under the sponsorship of the National Renewable Energy Laboratory (NREL), Hydrogen Standardization Interim Report for Tanks, Piping and Pipelines was, issued on May 3, 2005. This interim report addressed priority topical areas within each of the four pressure technology applications for hydrogen infrastructure development: storage (stationary) tanks, transport tanks, piping and pipelines and vehicle fuel tanks.

The present report builds on the work of the interim report to develop specific recommendations for design guidelines for hydrogen piping and pipelines.

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## ABSTRACT

This report provides recommendations and guidance to the ASME B31.12 Hydrogen Piping and Pipelines Section Committee for design factors for metallic and nonmetallic pipe materials when used in a dry hydrogen gas environment; design life considerations; nondestructive examination (NDE) recommendations; in-service inspection (integrity management) recommendations; research needs and recommendations. The scope of this report includes all common metallic piping and pipeline materials used in the construction of piping and pipeline systems, of seamless and welded construction; composite reinforced welded or seamless metallic-lined piping and pipelines that are currently commercially manufactured and for which technical design data is available; composite reinforced plastic-lined piping and pipelines that are currently commercially manufactured and for which technical design data are available. Design factors are developed considering the operating conditions, internal hydrogen environment within the piping and pipeline systems and the effect of dry hydrogen gas on the material of construction. Composite piping and pipeline line pipe are considered as hoop-wrapped construction with liners capable of withstanding longitudinal loads. Other examination and inspection recommendations are made using similar considerations. Research recommendations are made based on lack or vagueness of existing data or where the research results were not readily adaptable to engineering use.

# 1 INTRODUCTION

Depletion of fossil fuels and the search for other sources of energy has been a current endeavor of mankind. Gaseous hydrogen is believed to play an important role in this endeavor and a “hydrogen economy” is a strong possibility within the next 50 years. In such a scenario, large scale production, storage, and transportation of hydrogen gas will become necessary. The objective of this work is to provide design guidelines for piping and pipelines transporting hydrogen gas under pressure. It is well documented that the hydrogen has no beneficial effects on steels but only detrimental effects. The term “hydrogen damage” represents a number of processes by which the load-carrying properties of metals, often in combination with applied and residual stresses, are reduced due to the presence of hydrogen. Hydrogen damage occurs most frequently in carbon and low-alloy steels while many metals and alloys are susceptible to it. Hydrogen damage can severely restrict the use of certain materials.

The containment and pressurization of hydrogen gas within metallic pipes is not a new concept or process. Hydrogen has been used in chemical processes for many years and industrial gas companies have produced, stored and transported hydrogen in its gaseous and liquid forms in the United States, Europe, and in other parts of the world. It is believed that piping and pipeline systems will need to be operated at pressures with possible cyclic pressure loading in excess of our current operating regimes. It is expected that hydrogen piping systems will have to be operated up to 15,000 psig (100 MPa) and that transport pipelines will operate up to 3000 psig (20 MPa) and both piping and pipeline systems will be operating at or below 300˚F (150˚C). In doing so, the metallic pipe materials in use today could be placed in an operating environment for which we have little or no data on their mechanical properties and behavior in a dry hydrogen environment. This report deals primarily with the bulk properties of the material, however localized properties have been considered. Components' mechanical strength may be reduced for materials susceptible to hydrogen embrittlement in the presence of stress concentrations, such as weld reinforcements, threads, etc. [29].

This report provides recommendations to the ASME B31.12 Hydrogen Piping and Pipelines Section Committee for design factors for commonly used metallic piping materials. The use of nonmetallic materials has also been considered and where design information is available, guidance has been provided. These factors are to be applied to the design process information contained within ASME B31.12 Hydrogen Piping and Pipeline Code. In developing design factors industry standards, technical references, research reports and technical presentations were reviewed.

A discussion is presented to establish the major concerns with hydrogen gas embrittlement of currently used pipe materials and how the material properties of these alloys are affected. With these effects in mind the rationale for the design factors and the method used to derive them is provided.

## 2 DEFINITIONS

| | |
|---|---|
| $A$ | Cross-sectional area |
| $A_o$ | Initial cross-sectional area |
| $C$ | Hydrogen concentration |
| $E$ | Modulus of elasticity |
| $da/dn$ | Fatigue crack propagation speed |
| $e$ | Engineering strain, $(l - l_o) / l_o$ , equal to $\varepsilon$ for small strains less than 2% |
| $f$ | Design factor |
| FRP | Fiber-reinforced plastic |
| $l$ | Length of test bar |
| $P$ | Axial force, pressure |
| $r$ | Radius |
| $R$ | Universal gas constant |
| $S$ | Nominal engineering stress, $P/A_o$ |
| SMYS | Specified minimum yield strength |
| $S_Y$ | Yield strength |
| $S_U$ | Ultimate strength, $P_{max}/A_o$ |
| $T$ | Temperature (absolute) |
| $t$ | Thickness |
| $\sigma$ | True stress, $P/A$, $S(1 + e)$ , equal to $S$ for small strains less than 2% |
| $\sigma_d$ | Design stress |
| $\sigma_f$ | True fracture stress, $P_f/A_f$ |
| $\sigma_{kk}$ | Hydrostatic (average stress) |
| $\sigma_h$ | Hoop stress |
| $\sigma_{rr}$ | Radial stress |
| $\sigma_T$ | An alternative symbol for ultimate tensile strength |
| $\sigma_Y$ | An alternative symbol for the yield stress |
| $\sigma_{zz}$ | Axial stress |
| $\varepsilon$ | True or natural strain, $d\varepsilon = dl/l$, $\varepsilon = \ln (l/l_o) = \ln (A/A_o)$ |
| $\varepsilon_f$ | True fracture strain or ductility $= \ln (A_o/A_f) = \ln [100/(100 - \% RA)]$ |
| %EL | Percent elongation, $100 (l_f - l_o)/l_o$ |
| %RA | Percent reduction in area, $100 (A_o - A_f)/A_o$ |
| $V_H$ | Partial molar volume |

**Subscripts**

| | |
|---|---|
| d | design |
| f | fracture |
| g | gage |
| k | kilo |
| o | initial |
| T | ultimate tensile |
| x, y, z | coordinates |
| Y | yield |

**Unit Conversions**

1 psi = 6.894757 kPa

1 ksi = 1000 psi

# 3 REVIEW OF HYDROGEN EFFECTS ON PIPING AND PIPELINE MATERIALS

## 3.1 Overview of Metallic Pipe Materials

### 3.1.1 Hydrogen Damage and the Influence of Pressure

**Hydrogen Damage:** A major concern in designing piping and pipeline systems for use in hydrogen service is the hydrogen damage. There are many ways in which hydrogen can be retained in steels to cause damage and pure hydrogen gas is one of them. Hydrogen gas (atomic) enters the metals by surface absorption and diffuses through the metal and eventually causes damage. Damages (also called attacks) are categorized and cover many industries. This report is focused on the effects of processes grouped under "hydrogen embrittlement." These are (1) hydrogen environment embrittlement, (2) hydrogen stress cracking, and (3) the loss in tensile ductility. These phenomena occur at temperatures approximately below 200˚C. Hydrogen-induced embrittlement depends on factors such as material strength, composition and heat treatment/microstructure, gas pressure and concentration, temperature, and the type of mechanical loading (e.g., strain rate).

Hydrogen environment embrittlement (HEE) occurs during the plastic deformation of alloys in contact with hydrogen gas. It is dependent on strain rate. The degradation of the mechanical properties is greatest when the strain rate is low and the hydrogen gas pressure is high [5], [19]. Hydrogen stress cracking, also known as hydrogen-induced cracking or static fatigue, occurs when a steel containing hydrogen fails at a stress that is below its yield strength (or much below its tensile strength [32]). This phenomenon is characterized by a delayed brittle fracture of a normally ductile alloy under sustained load in the presence of hydrogen. Hydrogen stress cracking is related to the absorption of hydrogen and a delayed time to failure during which hydrogen diffuses into the regions of high triaxial stress. The third mode of hydrogen damage in this category is the "loss in tensile ductility," in which large decreases in elongation and ductility is observed often in lower strength alloys that are exposed to hydrogen. The loss in tensile ductility is sensitive to strain rate and increases as the strain rate decreases.

High-strength steels were found to be susceptible to both brittle and delayed fracture at very low hydrogen concentrations. Also, delayed failures have been observed at applied stresses less than one-tenth of the yield strength in notched specimens of high strength steels [31]. It was found that substantially greater hydrogen concentrations were necessary to induce brittleness in lower- strength quenched and tempered steels. HEE will be further discussed section 3.1.2 below.

High-temperature hydrogen attack is another form of hydrogen damage that occurs in steels exposed to high-temperature and high-pressure hydrogen. At temperatures approximately above 200˚C (400˚F), a form of decarburization occurs in the metal. It is due to the formation of methane bubbles in the grain boundaries by chemical reaction between carbon and hydrogen. The discussion in this report will be restricted to temperatures below 200˚C. API 941 should be consulted for hydrogen service temperatures above this threshold [5].

**The Influence of Pressure:** Pressure of hydrogen clearly is one of the important independent variable in pipeline design and operation. First, it contributes to the state of stress in the pipe. Second, absorption of hydrogen gas on the metal surface is a function of pressure and amount of gas absorbed increases as the pressure increases. Third, pressure controls the diffusion process of hydrogen into the metal since the diffusion coefficient is a function of pressure.

The influence of elevated hydrogen pressure on the strength of steels has been experimentally investigated [24], [33], [34]. Walter and Chandler [24] tested AISI 310 stainless steel and ASTM

A-302 at hydrogen test pressures ranging between 1 atm and 10,000 psi (69 MPa). They found that the degree of hydrogen environment embrittlement to be more severe at higher hydrogen pressures but could be considerable at lower pressures extending down to 1 atm pressure. The reduction of tensile properties in hydrogen was found to be a linear function of the square root of hydrogen pressure. The influence of hydrogen pressure, from 1 atm to 2200 psi (15 MPa), on the embrittlement of unnotched 0.22% carbon steel specimens was determined [32]. The results showed that ductility, as measured by percent elongation, decreased by increasing hydrogen pressure, but even at 10 atm there was a significant decrease in ductility. A pipeline steel similar to X-42 was tested [33] under high pressure hydrogen from 1 atm to 2000 psi (14 MPa) and high susceptibility to hydrogen was found. Approximately above 1000 psi (7 MPa) 40% change in reduction of area was observed.

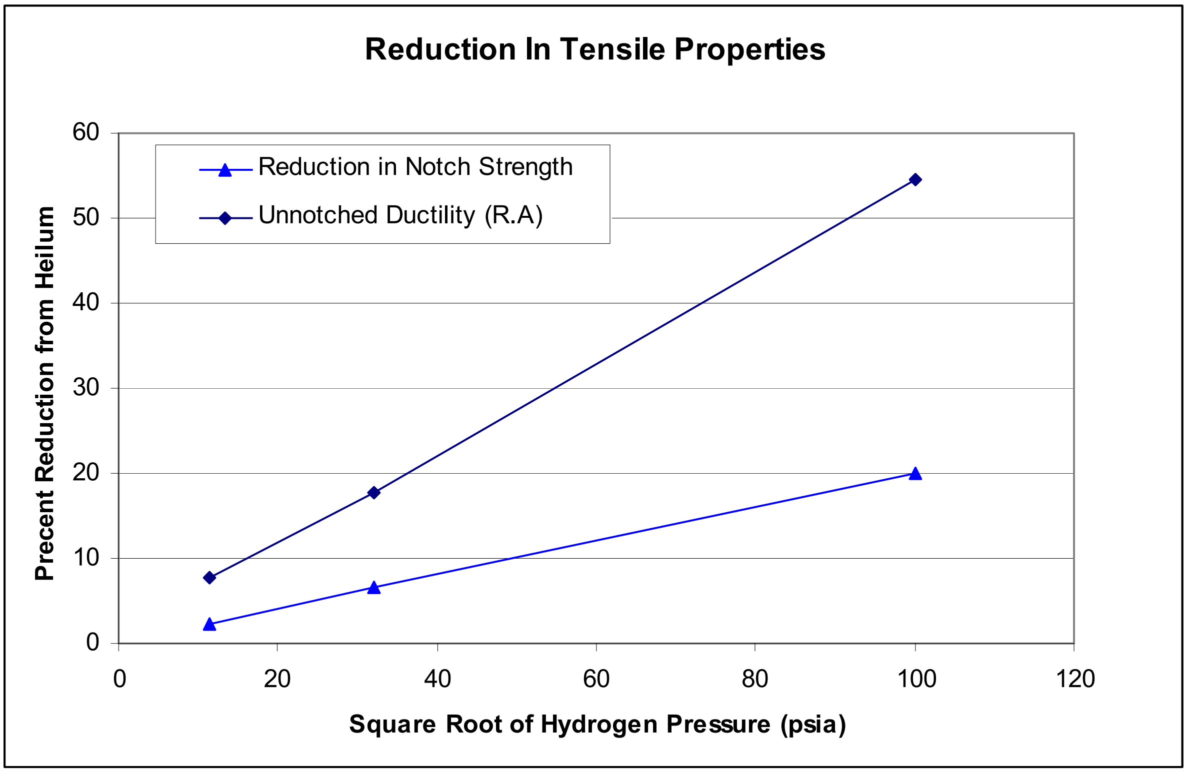


**Figure 1 Reduction of Tensile Properties in Hydrogen from those in Helium as a Function of Hydrogen Pressure for ASTM A-302**
Adapted from [24]

The reduction of tensile properties in hydrogen was found to be a linear function of the square root of hydrogen pressure as shown in Figure 1. The notch strength and unnotched specimen ductility reductions extrapolate to zero effects at zero hydrogen pressure [24]. The reduction in notched specimen ductility, as in area reduction, also shows linear relationship with the square root of hydrogen pressure on Figure 1 between zero and 30 √psia. It may also be noted that the crack growth rate of 4130 steel in hydrogen was a linear function of the square root of hydrogen pressure [35].

Hydrogen embrittlement (HE) as introduced above includes all of the effects that piping and pipeline alloys might experience in dry hydrogen gas at ambient temperature. These effects vary from very slight to very severe. Proper design and selection of materials can minimize the effects of HE. In general, the effects of HE which amount to the degradation of mechanical properties are the greatest when the strain rate is low and the hydrogen pressure and purity is high [5], [19]. These are the exact operating conditions expected for piping and pipeline systems in the new hydrogen infrastructure.

**Loss of Ductility due to Embrittlement:** The effects of hydrogen on yield and tensile properties of metals and alloys have been investigated for many years. Tests have been performed using notched and unnotched specimens with high and low rates of strain. The results of investigations indicate that while there are changes in tensile properties, the most sensitive indicators of these tests are the reduction in area (%RA) and reduced elongation (%EL) at the fracture. Furthermore, percent reduction in area at fracture is preferred by investigators in reporting their data.

It is well known that the decrease in tensile ductility is sensitive to strain rate and becomes more pronounced as strain rate decreases [5]. Many materials showed significant change in RA when tested in hydrogen gas while others were not affected and showed no loss. Those alloys most affected were high nickel- or nickel-based alloys, high strength steels, high-strength stainless steels and titanium alloys. Those least affected were aluminum alloys, stable austenitic stainless steels and Oxygen-Free High Conductivity (OFHC) copper. Carbon steels as used in many piping and pipeline systems have shown a loss of RA as high as 40% when tested in hydrogen compared to tests in air. In comparison, 316 stainless steel and 6061-T6 aluminum show no change or a modest gain in RA when tested in hydrogen [18].

### 3.1.2 Hydrogen Stress Cracking

In the presence of hydrogen gas the resistance to cracking of some materials is reduced. The failure manifests itself as cracking at sustained stress levels below materials' yield strength. This phenomenon was referred to as hydrogen stress cracking (HSC) above. It usually occurs at room temperature for susceptible materials (e.g., carbon steel). HSC effects do not occur at cryogenic temperatures or above 150˚C (302˚F) [5]. The susceptibility of steels to HSC increases with increasing yield and tensile strength. This mode of failure has been observed in the HAZ of welds and other areas of high residual stress. The term "sustained load cracking" has been used to describe hydrogen-assisted slow crack growth in pipeline steels [17].

## 3.2 Overview of Nonmetallic Pipe Materials

Currently very little information is available on nonmetallic materials in hydrogen service. In fact most if not all plastic pipe manufacturers do not recommend their pipe in combustible gas service. The exception to this is obviously the large amount of natural gas distribution piping currently in service. The available data are sparse and general in nature. Some general information on chemical resistance, chemical attack and maximum service temperatures for thermoplastics in nonpressure service are given by [30]. CGA G-5.6-2005 [19] also provides limited guidance on the use of plastic pipe in pipeline service.

Another potential application for hydrogen gas service is composite pipe materials. These vary from thermoplastic pipe with an aluminum intermediate layer to fiber reinforced metallic or plastic lined piping. These types of pipes are currently used in services ranging from domestic water and natural gas supply to high-pressure natural gas transmission lines. The most promising advantages of these types of pipes is lower permeability, higher pressure ratings and the possibility of minimizing or eliminating hydrogen embrittlement effects on the piping material.

### 3.2.1 Thermoplastic Pipe Considerations

In general, chemicals affect plastics in two distinct processes. One process is chemical solubility or permeation. The other one is direct chemical attack. In the case of solubility (or permeation), physical properties may be affected, but the molecular structure of the polymer itself is not chemically changed. In solubility mode, gas, vapor or liquid molecules pass through the polymer, typically without damaging it. If the solvating chemical can be removed completely, the plastic is generally restored to its original condition. However, it is not always possible to remove a solvating chemical from plastic, and in such cases, effects relating to chemical salvation may be permanent. Permeation may do little if any harm to the material, but it may have application-related effects. In general, thermoplastic pipes should not be used where a permeating chemical could compromise the purity of fluid or where slight loss of a transmitted gas or vapor is unacceptable. Lastly, a permeating chemical may be entrained in the material and be released when heat fusion or solvent cement joining is performed. Heat fusion or solvent cement joining may be unreliable if performed on permeated pipes.

Direct chemical attack occurs when exposure to a chemical causes a chemical alteration of the polymer molecules by chain scission, crosslinking, oxidation or substitution reactions. Direct chemical attack may cause profound, irreversible changes that cannot be restored by removal of the chemical. Direct chemical attack frequently causes a severe reduction of mechanical physical properties such as tensile strength, ductility and impact resistance along with susceptibility to cracking form applied stress (stress cracking). Chemical resistance of a plastic pipe is basically a function of the chemical resistance of the thermoplastic material, and processing of the plastic in such a way that its full chemical resistance is developed. In general, the less compounding ingredients used the better the chemical resistance. Most plastic pipe compounds covered by current ASTM specifications and product standards use a minimum of compounding ingredients, except for Type II polyvinyl chlorides (PVCs) and cellulose acetate (CAB) plastics. Thermoplastic pipes with significant filler percentages may be susceptible to chemical attack where an unfilled material may be affected to a lesser degree or not at all.

Some newer plastic piping products utilize multilayered (composite) construction. Both thermoplastic and metallic materials are used for the layers. Examples are PE/AL/PE or PEX/AL/PEX pipes where there is a midwall aluminum layer. A typical standard for this type of composite pipe is ASTM F1281-05 Standard Specification for Crosslinked Polyethylene/Aluminum/Crosslinked Polyethylene (PEX/AL/PEX) Pressure Pipe. This type of construction could prove very useful in hydrogen.

### 3.2.2 Fiber-Reinforced Lined Pipe

One of the main considerations for carbon steel pipe material in hydrogen gas service is embrittlement. The use of fiber-reinforced plastic pipe (FRP) with a liner made of embrittlement resistant material could be a substitute to metals embrittled by hydrogen. Two primary options are currently available, (1) fiber-reinforced plastic pipe with a metallic liner made of hydrogen embrittlement- resistant austenitic stainless steel or aluminum, or (2) fiber-reinforced plastic pipe lined with one of several thermoplastic materials that are unaffected by hydrogen. A discussion of each option follows:

#### 3.2.2.1 Metallic-Lined Pipe

Metallic-lined fiber-reinforced pipe offers a real potential solution to the problem of hydrogen environment embrittlement (HEE). Pipe of this type is currently being tested by TransCanada Pipelines in natural gas service [28]. The product TransCanada has installed is called Composite Reinforced Line Pipe (CRLP), this is a patented technology developed by NCF Industries which has been licensed to TransCanada on a worldwide basis. CRLP is composed of a composite material reinforcing with a proven high-strength and carbon steel pipe (X42 to X80). This hybrid construction provides an alternative to an all-steel pipe. The first field trials of this type of pipe were started in the late 1980s. The first installations were short runs of CRLP installed into existing pipeline systems where the carbon steel liner matched the existing linepipe thickness. The composite pipe material concept was tested in these installations and did not take advantage of the composite overwrap for strength. These installations have proven that this type of pipe will survive in an underground environment in natural gas service.

TransCanada has installed a short, 50-m section of CRLP, which included two 10˚ bends. This test piece had an outside diameter (OD) of 24 in. (~ 61 cm), a steel liner thickness of 6.4-mm grade X42 steel, and a laminate overwrap of 5 mm thickness. This pipe was designed to operate at 1440 psi with a safety factor of 2.0 on burst strength. Without the laminate the pipe would be limited to an operating pressure of 705 psi. This pipeline segment was installed in 2001 and is still in service with continuous monitoring from embedded strain gauges [28].

With this type of pipe construction, the fiber overwrap is applied circumferentially with only a very small deviation form being perpendicular to the cylindrical axis of the pipe, providing virtually all of its strength in the hoop stress direction. The metallic liner must carry all of the longitudinal loads as the fiber overwrap has little strength in the cross-fiber direction. Consideration of longitudinal strain is required to account for installation, thermal differences, and ground movement for underground systems. The primary concern with this type of pipe at this time is the hoop strength of the composite pipe and resistance to hydrogen embrittlement. With the CRLP manufacturing process, impregnated glass fiber is wound under tension over the metallic liner as the composite wrap is applied. During construction, the hydrostatic pressure test results in the composite pipe being prestressed. The metallic liner is in residual compression and the composite wrap is in tension. This state ensures that the composite overwrap and metallic liner stay in contact during future load cycles, ensuring hoop strain compatibility. Unlike a steel pipe, a metallic lined composite pipe reaches its ultimate strength without exhibiting any substantial yielding. The strain response is essentially linear up to failure. To the point where the metallic liner begins to yield, the composite elastic modulus may be 5 to 6 times lower that of the metallic liner. The composite then quickly becomes the stiffer material. It should be noted that rupture strain of the composite material is an order of magnitude less than that of most metallic liner materials compatible with a hydrogen gas environment. This fact dictates that composite pipe failure will be governed by the composite rupture where strain compatibility is enforced. It should also be noted that typically the ultimate tensile strength of the composite is greater than that of hydrogen compatible metallic liners, and that at the point of composite rupture the stress in the metallic liner will be somewhere between yield and ultimate.

#### 3.2.2.2 Thermoplastic-Lined Pipe

Thermoplastic-lined pipe could provide immunity from hydrogen embrittlement not normally associated with metallic or metallic-lined pipe construction. Currently a number of manufacturers make thermoplastic-lined composite pipe for chemical process and high-purity services. The cross section of piping manufacturers whose products were investigated had targeted the highly corrosive services where most metallic piping would not survive or would require alloys that were prohibitively expensive. In most instances these services can be covered by pipes that will operate under temperature ranges of –20 to 250˚F and pressures from full vacuum to 150 psi. Many manufacturing companies state that their fiber-reinforced, plastic-lined pipes meet the requirements of B31.3 Chapter 7, Part 9. With high-temperature, low-permeability thermoplastic liners, these composite pipes offer an alternative to metallic construction.

Composite plastic-lined pipe currently available should be designed and installed in accordance with the manufacturers' instructions. Issues on hydrogen permeability should be discussed with the pipe manufacturer prior to pipe order.

# 4 DISCUSSION OF DESIGN FACTOR RATIONALE

The design factors contained in this report have been derived from extensive review of standards, technical research papers, technical reports, engineering reports, technical presentations, books, manufacturers' literature, operating case histories and personal conversations with academic and engineering experts. Much of the data available are scientific in nature and deals with the mechanisms of failure due to exposure to dry hydrogen gas. Much of the testing of material exposed to dry hydrogen gas has been focused on a single property or effect and does not give a complete comprehensive result. It is difficult to take this data and establish engineering guidelines that are exact. Almost all test data reported to date has been for parent metal (the bulk material of a piping or pipeline system) and not welds or heat affected zones (HAZ). What can and has been done is a review of the data to determine trends among the various reports/papers along with cause and effect relationships that lead to decisions based on engineering judgment.

Current ASME Piping Codes list acceptable materials in tables and specify design stress allowables based on a percentage yield or tensile strength. These design stress allowables are then reduced as service temperature increases. In ASME Pipeline Codes, pipelines are designed using a percentage of specified minimum yield strength (SMYS) of acceptable materials. The percentage of SMYS is determined by the location class of the pipeline being designed and temperature correction factors. In reviewing the literature, pressure of the hydrogen environment appears to have the most impact on reduction of mechanical properties (e.g., % RA) of metallic pipe materials [5] operating at or below 300˚F. Oriani [6] cites the work of Walter and Chandler [24] and states that "the reduction of RA was found to be proportional to the half-power of the hydrogen gas pressure." Walter and Chandler [24] have stated, "The reduction of tensile properties in hydrogen was found to be a linear function of the square root of hydrogen pressure. The notch strength and unnotched specimen ductility reductions extrapolate to zero effects at zero hydrogen pressure." This report will present design factors for the various pipe materials as a function of yield or tensile strength with variation due to pressure levels using the $\sqrt{\Delta P}$.

## 4.1 Metallic Pipe Materials

The discussion for metallic pipe materials must be broken into major classifications based on material type. The literature currently available shows significant performance differences between commonly used pipe materials in dry hydrogen gas service. The following subsections will address groups of pipe materials that tend to behave similarly in a dry hydrogen gas environment.

### 4.1.1 Carbon Steels

Carbon steel piping materials are affected by dry hydrogen gas service [16–24]. They show significant reduction in ductility, fatigue strength, burst strength and could be subject to sustained load cracking. There are many carbon steel piping and pipeline systems operating in hydrogen service with no history of failure that can be attributed to any of these properties or failure modes. One fact that has been well documented is that in hydrogen service the strain to failure is lowered with increasing tensile strength of the material [19]. Carbon steel materials with successful long-term use in hydrogen service are generally low strength alloys with specified minimum yield strengths (SMYS) ≤ 52,000 psi and specified minimum tensile strengths (SMTS) ≤ 80,000 psi (550 MPa). Typical materials are SA-106 Gr. B, API 5LX42 and API 5LX52. In reviewing system design data and discussions with engineers from industrial gas companies, the industry trend is to operate carbon steel hydrogen piping/pipeline systems at low stress levels, sometimes at 30–50% specified minimum yield strength (SMYS). This trend probably accounts for operation without any major reported failures. Research has shown (Figure 1) that increasing stress levels in a gaseous hydrogen environment does decrease the resistance of carbon steel to hydrogen embrittlement failures [2]. With the lack of comprehensive material test data for carbon steel in a high-pressure hydrogen environment, additional design conservatism must be utilized to account for these diminished mechanical properties until such time as comprehensive test data are available and has been reviewed by piping engineers. Design factors for carbon steels used in piping systems are expressed as a function of specified minimum specified tensile strength and the square root of hydrogen pressure are shown in Table 1 in Section 9. Table 1 provides design factors for pressures from 0 to 6000 psi (41 MPa) as a function of √ P and the specified minimum tensile strength (SMTS) from 70 ksi (482 MPa) to 90 ksi (620 MPa). The design factor for 1000 psi (6.9 MPa) is 33% of SMTS as used in B31.3 based on long successful service experience. The design factor at 6000 psi is 27.7% of SMTS or 84% of the design factor at 1000 psi (6.9 MPa). The reduction of 16% is based on test data from flawed pipe burst tests preformed by Sandia National Laboratories [17]. Design factors between 1000 psi (6.9 MPa) and 6000 psi (41 MPa) are established using the √ P for the desired pressures.

Design factors for carbon steels used in pipeline systems expressed as a function of specified minimum yield strength, class location and the square root of pressure are shown in Table 3 and Table 4 in Section 9. These tables provide design factors for pressures from zero to 3000 psi (20.7 MPa) and SMYS from 52 ksi (358 MPa) to 80 ksi (551 MPa). Table 3 is for location class 3 and Table 4 is for location class 4 areas. The design factor for SMYS ≤ 52 ksi (358 MPa) pipe in location class 3 is 50% of SMYS from zero to 2000 psi (13.8 MPa). The design factor for the same SMYS in the location class 4 is 40% of SMYS from zero to 2000 psi (13.8 MPa).

### 4.1.2 Low-Alloy Carbon Steels

Low-alloy carbon steel pipe materials are normally used to resist the effects of high temperature and corrosion in piping systems. Following on the carbon steel discussion in section 4.1.1, the effects of hydrogen embrittlement are more pronounced as the tensile and yield strength of the material increases. In general, alloying elements such as carbon, manganese, sulfur, phosphorus and chromium impart greater susceptibility to hydrogen embrittlement in low-alloy steels [5]. This class of materials is more difficult to weld and welds may have a high hardness which can lead to subcritical crack growth [17]. The material test data for this group of pipe materials are lacking and designers are cautioned in selection of these materials for dry hydrogen gas service in the pressure and temperature range covered in this report. Design factors for low-alloy carbon steels are shown in Table 2 of Section 9. Table 2 provides design factors for pressures from zero to 6000 psi as a function of √ P and SMTS from 60 ksi to 90 ksi. The design factor for zero psi is 33% of SMTS as used in B31.3 based on long successful service experience. The design factor at 6000 psi (41 MPa) is 26.4% of SMTS or 80% of the design factor at zero psi. The reduction of 20% is based on research data [5] and flawed pipe burst tests preformed by Sandia National Laboratories [17]. Design factors between zero psi and 6000 psi (41 MPa) are established using the √ P for the desired pressures.

### 4.1.3 Austenitic Stainless Steels

Stable austenitic stainless steels show little to no loss of mechanical properties when exposed to dry hydrogen gas. These materials appear to be the best choice for hydrogen piping systems with regard to resisting hydrogen embrittlement. One cautionary statement must be made: metastable austenitic stainless steels such as SA321, 304, 304L and 302 should be used with some caution. When subjected to strain (cold bending, machining, etc.), these materials can experience a change in microstructure from austenitic to martensitic. This shift in structure renders these materials much more susceptible to hydrogen embrittlement [1]. The effect of hydrogen embrittlement will be more pronounced as hydrogen pressure increases. From a review of the current literature it appears that SA316L is the best choice for high-pressure dry hydrogen gas service. Design factors for austenitic stainless steels are not required and design stress allowables should be used as listed in Table A-1 in ASME B31.3.

### 4.1.4 Martensitic, Ferritic and Duplex Stainless Steels

Martensitic, ferritic and duplex stainless steels may be significantly affected by hydrogen embrittlement and therefore should be avoided or only used at very low stress levels for service in dry hydrogen gas. The toughness of these materials is generally lower that the austenitic varieties. Ferritic and duplex stainless steels, if used, should be used in the fully annealed condition. Martensitic and precipitate-hardening grades, if used, should be heat treated to develop strengths in the lower end of the specification range [18]. Design factors for these materials are not shown in a table. If they must be utilized in dry hydrogen gas service, they should be used at or below 15% of SMTS.

### 4.1.5 Aluminum Alloys

Aluminum alloys listed in ASME B31.3 Process Piping Code appear to be essentially immune to the effects of dry hydrogen gas within the temperature and pressure ranges considered in this report. A review of the available literature shows no to very minor changes in mechanical properties of commonly used aluminum piping materials. Design factors for aluminum alloys are not required and design stress allowables should be used as listed in Table A-1 in B31.3.

### 4.1.6 Copper and Copper Alloys

Copper and copper alloys have received little attention from researchers and data are sparse. The data that do exist show that oxygen free copper is very resistive to hydrogen embrittlement [18]. It should follow that alloys of copper that do not contain metals known to be embrittled in hydrogen service should perform equally as pure copper. Designers should exercise caution when selecting Cu–Ni alloys as no data have been found to support the foregoing assumption and nickel alloys can be susceptible to hydrogen embrittlement. Design factors for copper and copper alloys are not required and design stress allowables should be used as listed in Table A-1 in B31.3.

### 4.1.7 Titanium Alloys

Titanium alloys are severely embrittled in dry hydrogen gas service and should not be considered for piping/pipeline applications. No design factors will be provided.

### 4.1.8 Cast Irons

Gray cast iron, malleable cast iron and ductile cast iron are not acceptable materials for use in dry hydrogen gas service. No design factors will be provided.

# 5 DESIGN LIFE

Piping and pipeline systems in hydrogen service should be designed with a design life period in mind. This period should take into account as many factors as possible that will positively or negatively affect the life of the piping system. The following is a discussion of factors that should be considered in establishing the expected design life of the system.

## 5.1 Piping Systems

Piping systems for industrial, commercial and residential hydrogen service should have a design life established as a part of their design process. Thirty years should be considered as a minimum acceptable design life. The following system parameters should be considered in establishing the predicted design life of the system:

**Service conditions:** pressure and temperature

**Hydrogen:** gas or liquid, purity and dew point

**Pipe material;** type of alloy, tensile/yield strength, type of pipe, heat treat condition and resistance to hydrogen embrittlement

**Welding:** process, consumables, procedure, shop/field fabrication and postweld heat treatment

**Nondestructive examination:** visual weld inspection, spot x-ray of welds, 100% x-ray of welds, hardness check of welds and pressure testing of system

**Pressure testing:** hydrostatic proof and leak testing

**System location:** above ground, indoors/outdoors, underground and local weather conditions

**Operating conditions:** constant pressure, cyclic pressure, system vibration, overpressure, constant temperature and cyclic temperature

**Corrosion protection:** coating, anodes, impressed voltage

**Historical data:** what has been the service history of other similar piping systems in the same or similar service in the proposed location

**In-service inspection plan (integrity management plan):** establish an in-service inspection (integrity management plan) and remediation plan at the time of design

Although ASME B31.8S is designated as a gas pipeline document, it should be considered for the establishment of a system integrity management plan for piping systems. Some modifications will be required to develop a plan for piping in industrial, commercial or residential settings but the intent of the document is valid for these systems.

## 5.2 Pipeline Systems

Pipeline and distribution systems should have a design life established as a part of their design. An integrity management process should be developed. ASME B31.8S should be used to plan and implement the pipeline integrity management process and in doing so the pipeline operator should establish a predicted system design life. A minimum design life for pipeline systems of 30 years or more is recommended.

# 6 NONDESTRUCTIVE EXAMINATION (NDE)

One of the most important aspects of constructing new hydrogen piping and pipeline systems is the nondestructive examination of the system. This examination process must be set forth in the design drawings, specifications and installation procedures of the project. There are current ASME Codes that contain most of the information needed to provide the examination criterion for hydrogen systems. Some minor modifications need to be made to take into account the effects of hydrogen on the materials from which the system is constructed.

## 6.1 Piping Systems

The NDE requirements for piping systems in industrial, commercial and residential service should be modeled after the requirements of ASME B31.3 Process Piping Code. Suggested modifications to B31.3 examination requirements for piping systems by service category are listed as follows.

### 6.1.1 Industrial Piping Systems

Piping shall be considered to be in the normal fluid service category per paragraph 341.4.1. This paragraph should be modified as follows:

341.4.1 (a) (1): all materials and components shall be visually examined.

341.4.1 (a) (2): all girth welds shall be visually examined.

New requirement: all welds in carbon steel systems shall be hardness tested to assure a maximum hardness of HRC22. Testing shall be per B31.3, paragraph 331.1.7 except Table 331.1.1 does not apply.

New requirement: carbon steel piping systems with a design pressure ≥ 3000 psi shall have all welds examined by 100% radiograph or ultrasonic methods per B31.3 paragraphs 344.5 and 344.6.

### 6.1.2 Commercial and Residential Piping Systems

Piping shall be considered to be in normal fluid service category per paragraph 341.4.1.

This paragraph should be modified as follows:

341.4.1 (a) (1): all materials and components shall be visually examined.

341.4.1 (a) (2): all girth welds shall be visually examined

341.4.1 (a) (4): all nonwelded joints shall be visually examined regardless of type of pressure test.

New requirement: all welds in carbon steel systems shall be hardness tested to ensure a maximum hardness of HRC22. Testing shall be per B31.3, paragraph 331.1.7 except Table 331.1.1 does not apply.

New requirement: carbon steel piping systems with a design pressure ≥ 1000 psi shall have all welds examined by 100% radiograph or ultrasonic methods per B31.3 paragraphs 344.5 and 344.6.

## 6.2 Pipeline Systems

The NDE requirements for pipeline systems shall be modeled after the requirements of ASME B31.8 Gas Transmission and Distribution Piping Systems Code. Suggested modifications to B31.8 examination requirements for pipeline systems are listed as below.

### 6.2.1 Pipelines Whose Design Pressure is ≤ 2200 psi and Pipe Material has a SMYS ≤ 52 ksi

Welds shall be inspected per paragraph 826. This paragraph should be modified as follows:

**Field weld inspection:** all welds shall be volumetrically inspected per paragraph 826.2 (b) to location class 3 requirements except when the pipeline is located in a location class 4. All welds shall be visually inspected. Paragraph 826.2 (e) shall not be utilized.

**Longitudinal weld inspection:** all long seams in pipe shall be inspected 100% at the producing mill by x-ray or ultrasonic means.

**New requirement:** all welds shall be hardness tested to ensure a maximum hardness of HRC22. Testing shall be per B31.3, paragraph 331.1.7 except Table 331.1.1 does not apply.

### 6.2.2 Pipelines Whose Design Pressure is Larger than 2200 psi (15 MPa) or Pipe Material Has a SMYS Larger than 52 ksi (358 MPa)

Welds shall be inspected per paragraph B826. This paragraph should be modified as follows:

**Field weld inspection:** all welds shall be volumetrically inspected to location class 4 requirements. Nondestructive examination shall be performed after stress relief if required. All welds shall be visually inspected. Paragraph 826.2 (e) shall not be utilized.

**Longitudinal weld inspection:** all long seams in pipe shall be inspected 100% at the producing mill by x-ray or ultrasonic means.

**New requirement:** all welds shall be hardness tested to ensure a maximum hardness of HRC22. Testing shall be per B31.3, paragraph 331.1.7 except Table 331.1.1 does not apply.

**New requirement:** all pipe materials and components shall be visually examined to check for defects prior to fabrication.

# 7 IN-SERVICE INSPECTION RECOMMENDATIONS FOR PIPING AND PIPELINE SYSTEMS

In-service or postconstruction inspection of piping and pipeline systems is one of the most critical aspects of safe operation of a hydrogen piping or pipeline system. ASME B31.8S was created to provide guidance to system operators in the creation and implementation of an integrity management process, which includes guidance on data gathering and in-service inspection. It was written with gas pipelines in mind but it may be adapted to any piping system. With this thought in mind, the following sections will reference B31.8S and suggest how it may be applied to piping and pipeline systems in hydrogen service.

## 7.1 In-service Inspection/Integrity Management of Industrial, Commercial and Residential Piping Systems

Historically ASME piping codes have concerned themselves with new construction and have not covered post construction issues. Hydrogen service can be severe especially for carbon steel piping systems. With the advent of the hydrogen infrastructure hydrogen piping systems will be designed, installed and operated in facilities and locations that have no previous experience with this type of system. New ASME hydrogen piping codes must address the long-term safe operation of these systems. The following sections will present a plan for using B31.8S for piping systems by service category.

### 7.1.1 Industrial Piping Systems

Most if not all industrial owners/operators have some type of preventative maintenance process in place. These processes are normally aimed at maximizing system availability, productivity and safety. In doing this they also provide for in-service inspection. These processes may not actually be a complete integrity management process but serve as a platform to build a complete program. B31.8S provides the elements needed to establish this process. The following discussion is a brief review of B31.8S with suggestions on how to apply this standard to industrial piping.

One of the first things that must be done is to list the threats to the piping system. Threats have been grouped into nine categories of related failures in B31.8S. These have been divided into three (3) time-related defect types; time dependent, stable and time independent. The following is a suggested listing of failure mode grouping according to time factors for industrial piping:

A. Time-dependent
   - (1) External corrosion
   - (2) Internal corrosion
   - (3) Hydrogen embrittlement cracking

B. Stable
   - (1) Manufacturing defects
     - (a) Defective pipe seam
     - (b) Defective pipe
   - (2) Welding/fabrication/erection related
     - (a) Defective pipe girth weld
     - (b) Defective attachment weld

(c) Defective pipe threads/flange facing

(d) Improperly hung or supported pipe

(3) Equipment

(a) Gasket, O-ring, packing failure

(b) Block valve, control valve, relief valve failure

(c) Pressure regulator failure

(d) Compressor or pump failure

C. Time-independent

(1) Mechanical damage

(a) Damage inflicted by first, second or third party with immediate failure

(b) Damage with delayed failure

(c) Vandalism

(2) Operation

(a) Incorrect or inadequate operational procedure

(b) Operator error

(3) Weather-related or outside force

(a) Cold or hot weather

(b) Heavy rain or flood

(c) Lightning

(d) Wind storm

(e) Earth movement

The above listing does not include fatigue failure as a threat. Hydrogen systems should be designed to avoid fatigue loading if possible. Additionally this listing is for illustrative purposes and may not be a complete listing of piping system threats. Once the threats have been established a risk assessment of the piping system must be performed. The risk assessment process identifies the location-specific events and/or conditions that could lead to piping system failure and provides an understanding of the likelihood and consequences of an event. Risk is the mathematical product of the likelihood (probability) and the consequence of the events that result from a failure. Risk may be decreased by reducing either the likelihood or the consequences of a failure or both [26]. The B31.12 code should manage piping integrity by adjusting design, safety factors, inspection and maintenance frequencies as the potential consequences of a failure increase. Section 3.0 of B31.8S, Consequences, is referenced for guidance in this effort. The next step in integrity assessment is data gathering, review and integration. This is a systematic method for piping system owners/operators to gather and effectively utilize data necessary for risk assessment and B31.8S, paragraph 4.0 should be consulted for guidance. Risk assessment must be done next and depending on the type of integrity management process selected (prescriptive or performance based) will vary in scope. For prescriptive processes, risk assessments are used to prioritize integrity process activities. In performance-based processes, risk assessments serve two purposes. First, to organize data and information to help owner/operators prioritize and plan activities and second, to determine which inspection, prevention and/or mitigation activities will be performed and when.

The next phase of integrity management is integrity assessment or in-service inspection. B31.8S discusses in-line inspection, crack detection and metal loss inspection methods for pipelines and as such some of these may not be possible or practical for piping systems. However most piping systems are above ground and accessible to more direct inspection methods common to piping systems. Industry has used x-ray and ultrasonic inspection to volumetrically check piping for metal loss, cracks and other defects effectively for many years. Additionally, most piping systems are more easily inspected by direct assessment methods for external corrosion, dents and gouges as well as leaking joints and improper pipe movement. It is not implied that all sections of the system have to be checked ultrasonically or by radiographic (x-ray) methods unless indicated by the system integrity management procedures. If the integrity management process is properly laid out, the sections of a system that are identified as potential trouble spots will be inspected with higher priority and frequency than the other sections.

This allows the focus to be placed in the areas that will benefit most and minimize wasted effort and expense. The next step of successful integrity management of piping systems is responses to integrity assessments and mitigation (repair and prevention). These points are explained in B31.8S Section 7.0. With proper mitigation of system threats the inspection response times may be extended as more system data are gained, analyzed, and integrated into the integrity management process. There are five more steps to a total integrity management process that must be a part of any plan. Available information in B31.8S requires only minor changes to work well with piping systems.

Piping systems should be approached as location class 4 pipeline systems for initial establishment of inspection frequencies. It is also suggested that a prescriptive integrity management process be established unless the owner/operator has extensive information, repair records and extensive operational knowledge of the hydrogen system in question. As the operational data are accumulated, it will be possible for the operator to switch to a performance-based integrity management process if desired.

### 7.1.2 Commercial and Residential Piping Systems

Commercial and residential hydrogen piping systems present a different type of situation to consider when reviewing the requirements for in-service inspections. When looking over systems such as commercial and residential natural gas piping it is difficult to find any requirement for in-service inspection for these systems. It appears that these systems are designed, installed and tested to a set of nationally recognized codes and local regulations that are conservative in nature with a long history of safe operation. The same may be said for equipment and appliances attached to these systems.

It is difficult to impose in-service inspection requirements on these systems. Consequently, they must be designed and constructed in such a manner as to generally preclude the need for such inspections. Design requirements must be prescriptive and conservative and testing of systems must be stringent enough to find system defects prior to system turnover or shipment. ASME should consider the application of an approval stamp or some other form of certification of systems and hydrogen equipment and appliances (similar to UL approval).

## 7.2 Pipeline Systems

Pipelines used for hydrogen transport must comply with ASME B31.8S. There is some adaptation of this standard from natural gas to hydrogen but the changes are minor and easily accomplished.

In establishing an integrity management process for a hydrogen pipeline system the following location class designations should be observed.

Pipelines with design pressures $\leq$ 2200 psi (15 MPa) whose material of construction has a SMYS $\leq$ 52 ksi (41 MPa) should be considered as location class 3 pipelines unless they are operating in a location class 4 areas. Pipelines with design pressures > 2200 psi (15 MPa) and ≤ 3000 psi (20.6 MPa) whose material of construction has a SMYS ≤ 52 ksi (41 MPa) should be considered as a location class 4 pipeline. Pipelines whose SMYS > 52 ksi (41 MPa) shall be considered as a location class 4 pipeline.

Integrity management processes should take into account the embrittlement affects of dry hydrogen gas on carbon steel pipeline materials and welds used to join pipe sections. It is strongly suggested that API type pipe be purchased to the PLS 2 requirement. This requires impact testing and also places an upper limit on tensile/yield strength. It is also highly recommended that microalloyed steels be requested in the purchase specification for line pipe.

# 8 RECOMMENDATIONS FOR RESEARCH ON MATERIALS IN DRY HYDROGEN GAS SERVICE

There is a great need for materials research to support piping and pipeline design and safety code documents. This report may not have been necessary if comprehensive engineering data had been available at the onset of hydrogen task group activities and the work of the group would have progressed at a more rapid pace. The extensive review of hydrogen embrittlement research documents has shown that although germane to the mechanics and science of hydrogen embrittlement failures, the data and results are narrow in focus as to be difficult to utilize by engineers to substantiate design processes or decisions. Oriani stated "the variety and complexity of the actions of hydrogen are responsible for causing the history of the investigation of the hydrogen embrittlement of steels to resemble the fable of the blind men and the elephant. Investigators have tended to perceive only single aspects of the problem and to design experiments in which important variables were either not appreciated, not controlled or not measured" [6]. What is needed to cure this myopic approach is a marriage of science and engineering to plan and execute comprehensive research programs where the results are aimed at supporting the new hydrogen infrastructure on an engineering level. This will require control of research funding and professional engineering input and project management skills by a single entity to be successful. Specific areas of needed research or listed as follows:

## 8.1 Carbon Steels

The more common steels in use for natural gas and other compressed gas systems must be tested to determine their resistance to hydrogen embrittlement as defined in Section 3.1. This must be correlated to service pressure, temperature and tensile strength of the various materials. Engineering designers have been successful in using these materials by incorporating them into their designs at relatively low percentages of their SMYS. In the future designers will be asked to increase system design pressures and minimize material costs. This data will either support using current carbon steels or point in another direction. There may be an upper pressure limit at which carbon steels are not safe to use due to increased embrittlement at higher pressures. We may be operating piping systems at 15,000 psi (103 MPa) and pipelines at 3,000 psi (20.6 MPa) and embrittlement data correlated to pressure will be invaluable.

The resistance of "microalloyed" steels to hydrogen embrittlement needs to be documented, correlated to pressure and compared to values of non-microalloyed steels. If in fact these steels offer enhanced resistance their use must be specified and their chemistry and strengths must be controlled to assure uniformity.

Currently most research points to avoiding fatigue situations in hydrogen piping design. The rate at which fatigue cracking propagates is said to be 10 to 50 times as fast as in air. Fatigue cracking in hydrogen appears to be worst at low frequencies and small (da/dn) values. This may seem strange until the cracking process is thought of in terms of hydrogen migration to the crack tip. The whole issue of fracture due to dry hydrogen gas needs to be fully investigated. There are sparse data on the behavior of welds made in carbon steels to assemble systems. Research has either assumed that the weld metal will behave the same as the base metal or simply stated "keep your welds below RCH22 and all will be OK." With the certainty of increased system pressures ahead of us this approach is inadequate. There is a need for weld specific research and development of welding procedures and consumables that provide the most embrittlement resistant welds possible. At present the welds in a carbon steel or stainless steel system in hydrogen service are the most susceptible part of the system to the affects of hydrogen embrittlement. This is due to the metallurgical differences in the weld and base metal, the heat affected zone and the high potential for defects that may exist at or grow to critical size over time and cause failures. All of these characteristics must be investigated and data provided for engineers to use in decision making during system design.

## 8.2 Stainless Steels

Currently stainless steels are thought of as “the answer” to hydrogen embrittlement issues in piping systems. This statement should be narrowed to reflect that only “stable” grades of stainless steel are really highly resistant to embrittlement. But is this really true at some of the higher pressures that we are forecasting? One fact that must be reviewed is the practice of “alloy shaving” that became possible with the advent of argon-oxygen-decarburization (AOD) in the late 1980’s. The AOD refining process produces very low carbon and sulfur content steel. This allows closer control of alloying elements and extensive use of scrap metal. It does not mean that steel mills are making steels that do not meet minimum specification requirements. Quite to the contrary, the mills can now control alloy content much better than before and produce to the lower end of the specification range. The primary affect of alloy shaving is a rise in delta ferrite content which reduces ductility. Higher delta ferrite means more austenite to martensite transformation during cold working of austenitic stainless steels, reducing their resistance to hydrogen embrittlement [27]. On this basis the affect of alloy content (austenite formers) on the resistance of alloys like 304, 304L, 316 and 316L should be investigated to determine if the current chemistry ranges are adequate for hydrogen service at high hydrogen pressures (15,000 psi or 103 MPa). In addition, it is necessary to verify the affects of strain (cold work) on the same alloys. The martensite transformation needs to be evaluated to determine what strain levels expressed as a %, have a detrimental effect on austenitic stainless steel resistance to hydrogen embrittlement at high hydrogen pressures. Welding of stainless should also be investigated and delta ferrite content correlated against weld performance at high hydrogen pressures. As with carbon steels, fracture and fatigue performance of stainless steels to be used in hydrogen service must be determined.

## 8.3 Other Metals

Materials such as aluminum and copper alloys are assumed to be immune to hydrogen embrittlement at current system operating conditions. These materials need to be investigated at higher pressures. Due to lower strengths they may not be suitable for system pipes but they may be used as liner materials for FRP composite pipe or as small-diameter tubing. Copper-nickel alloys need to be investigated for embrittlement. The high nickel content may make them more susceptible to hydrogen than other copper alloys.

## 8.4 Plastics

Data for commonly used plastic pipe materials used in natural gas distribution lines do not seem to exist for hydrogen service. These materials are listed in Appendix D of B31.8 [27]. Although manufacturers’ data are available for permeability and maximum service temperature, the data on the effects of hydrogen on the mechanical properties of materials are lacking [19]. These pipe materials will most probably not be used at future high service pressures but there is a need to know if they will perform adequately in hydrogen service. This would be true for distribution lines that have been used in natural gas service and that are converted to hydrogen use, and new distribution systems.

There may be usage of plastic pipe for higher service pressures. These pipes could be fiber-reinforced plastic with plastic or metallic liners as discussed in Section 3.2. This type of pipe may be viable in a transmission pipeline to avoid the problem of hydrogen embrittlement of carbon steel. The FRP pipe could be lined with a thin metallic liner that is basically immune to HGE such as 316L stainless steel or 6061T6 aluminum or a plastic liner if longitudinal stress is not anticipated or is minimized. Pipelines of similar construction that are intended for natural gas service have been built and are being tested by TransCanada Pipelines in Canada [28]. This pipe has a carbon steel liner of a thickness to sustain longitudinal stresses. The liner and hoop wrapped fiber overwrap then act in unison to resist the hoop stress due to pressure. This type of pipe must be investigated thoroughly to determine if it is a viable pipe type to replace metallic pipe in hydrogen service. The investigation must include not only the pipe development but design method development, installation processes and integrity management parameters.

# 9 TABLES OF DESIGN FACTORS FOR METALLIC PIPE MATERIALS

Material presented in previous sections of this report has stated the case for additional conservatism when designing piping and pipeline systems that will operate within the hydrogen embrittlement range of under 150˚C (300˚F). The following tables of design factors have been developed by using available data from pipe material research and testing in hydrogen environments. Primary attention has been focused on carbon steel, low-alloy carbon steel and carbon steel used in pipeline service. Some materials groups have been reviewed and found to be essentially immune or only marginally effected by hydrogen embrittlement in environments up to 10,000 psi (68.9 MPa). These material groups have been discussed in Section 4 of this report and no design factor table will be provided for them in this section.

**Table 1 Design Factors for Piping, Carbon Steel**

| | | PRESSURE, PSI | | | | | |
|---|---|---|---|---|---|---|---|
| TENSILE (SMTS) KSI | YIELD (SMYS) KSI | ≤ 1000 | 2000 | 3000 | 4000 | 5000 | 6000 |
| | | SQUARE ROOT OF PRESSURE | | | | | |
| | | ≤ 31.62 | 44.72 | 54.77 | 62.25 | 70.71 | 77.45 |
| ≤ 70 | ≤ 52 | 0.33 | 0.313 | 0.301 | 0.292 | 0.284 | 0.277 |
| ≤ 75 | ≤ 56 | 0.307 | 0.291 | 0.280 | 0.272 | 0.264 | 0.257 |
| ≤ 80 | ≤ 65 | 0.277 | 0.263 | 0.253 | 0.246 | 0.239 | 0.233 |
| ≤ 90 | ≤ 80 | 0.236 | 0.224 | 0.216 | 0.209 | 0.204 | 0.198 |

**Table 2 Design Factors for Piping, Low-and Intermediate-Alloy Steels**

| | | PRESSURE, PSI | | | | | | |
|---|---|---|---|---|---|---|---|---|
| TENSILE (SMTS) KSI | YIELD (SMYS) KSI | 0 | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 |
| | | SQUARE ROOT OF PRESSURE | | | | | | |
| | | 0 | 31.62 | 44.72 | 54.77 | 62.25 | 70.71 | 77.45 |
| ≤ 60 | ≤ 55 | 0.33 | 0.303 | 0.291 | 0.283 | 0.276 | 0.269 | 0.264 |
| ≤ 75 | ≤ 45 | 0.316 | 0.290 | 0.279 | 0.271 | 0.265 | 0.258 | 0.253 |
| ≤ 85 | ≤ 60 | 0.261 | 0.240 | 0.231 | 0.224 | 0.219 | 0.213 | 0.209 |
| ≤ 90 | ≤ 65 | 0.244 | 0.224 | 0.216 | 0.210 | 0.205 | 0.200 | 0.195 |

**Table 3 Design Factors for Pipeline, Carbon Steel Location Class 3**

| TENSILE (SMTS) KSI | YIELD (SMYS) KSI | PRESSURE, PSI | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ≤ 1000 | 2000 | 2200 | 2400 | 2600 | 2800 | 3000 |
| | | SQUARE ROOT OF PRESSURE | | | | | | |
| | | ≤ 31.62 | 44.72 | 46.90 | 48.99 | 50.99 | 52.92 | 54.77 |
| ≤ 66 | ≤ 52 | 0.5 | 0.5 | 0.477 | 0.455 | 0.44 | 0.42 | 0.39 |
| ≤ 75 | ≤ 60 | 0.437 | 0.437 | 0.417 | 0.398 | 0.385 | 0.367 | 0.341 |
| ≤ 82 | ≤ 70 | 0.388 | 0.388 | 0.371 | 0.353 | 0.342 | 0.326 | 0.303 |
| ≤ 90 | ≤ 80 | 0.347 | 0.347 | 0.331 | 0.316 | 0.305 | 0.292 | 0.271 |

**Table 4 Design Factors for Pipeline, Carbon Steel Location Class 4**

| TENSILE (SMTS) KSI | YIELD (SMYS) KSI | PRESSURE, PSI | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ≤ 1000 | 2000 | 2200 | 2400 | 2600 | 2800 | 3000 |
| | | SQUARE ROOT OF PRESSURE | | | | | | |
| | | ≤ 31.62 | 44.72 | 46.90 | 48.99 | 50.99 | 52.92 | 54.77 |
| ≤ 66 | ≤ 52 | 0.4 | 0.4 | 0.38 | 0.357 | 0.342 | 0.325 | 0.30 |
| ≤ 75 | ≤ 60 | 0.350 | 0.350 | 0.332 | 0.312 | 0.299 | 0.284 | 0.262 |
| ≤ 82 | ≤ 70 | 0.311 | 0.311 | 0.295 | 0.278 | 0.266 | 0.252 | 0.232 |
| ≤ 90 | ≤ 80 | 0.278 | 0.278 | 0.264 | 0.248 | 0.238 | 0.226 | 0.208 |

Notes for Table 1 through Table 4:

1. Tables 1 through 4 are for use in designing piping systems that will operate or have a design temperature within the embrittlement range of recommended lowest service temperature up to 150˚C (300˚F). If the system temperature is out of this range, use the design stress allowables from Table A -1 of B31.3, for piping or for pipelines table D1 from appendix D, B31.8.

2. Table 1 and Table 2 were developed for piping systems and as such the design factors are based on the SMTS of the material strength ranges shown.

Example: For a carbon steel piping material having a SMTS of 70 ksi (482 MPa) and a SMYS of 50 ksi (344 MPa) used in a system whose design pressure is 2000 psi (13.8 MPa), the allowable design stress would be;

$$\sigma_a = 0.313 \times 70 \text{ ksi} = 21.9 \text{ ksi (151 MPa)}$$

3. Table 3 and Table 4 were developed for pipeline systems and as such the design factors are based on the SMYS of the material strength ranges shown.

Example: For a carbon steel pipeline material used in a location class 3 system, having a SMYS of 60 ksi whose design pressure is 2200 psi (15 MPa), the % of SMYS used for the system design would be would be 41.7% or 25.02 ksi (172.5 Mpa).

4. Design factors may be calculated by interpolation between pressures shown in the tables in this guideline.

## 9.1 Design Factor Table Population Methodology

In designing hydrogen piping and pipeline systems, engineers must consider the effects of hydrogen gas on the materials of construction. Classical ASME designs have used percentages of SMTS or SMYS adjusted for the design maximum and minimum temperatures with correction factors applied to adjust for product form quality. This approach may not be conservative when these systems are designed for higher pressures when system service temperatures are expected within the hydrogen embrittlement range (–100˚C to 150˚C/300˚F). To provide conservatism to piping and pipeline system designs, "design factors" have been developed taking into account two major facts appearing in much of the research data reviewed for this project. First, hydrogen embrittlement increases as a linear function of the square root of pressure and the second, hydrogen embrittlement increases as the tensile and yield strength of the material increases. The design factors created with these two major facts should be used to determine the design stress allowables used in wall thickness calculations. Table 1 and Table 2 are based on B31.3 (all factors are derived from the base of 33% of SMTS) and should be used for piping designs for the range of materials covered. Table 3 and Table 4 are based on B31.8 (all factors are derived from the base of 50% or 40% of SMYS) and should be used for pipeline designs for the materials covered. The rows and columns of Table 1 through Table 4 were populated as described in paragraphs 9.1.1 and 9.1.2 below.

### 9.1.1 First or Base Row Population

The first or base row decisions are the most important in the population of the design factor tables. In each table the material range selected for the base row was the lowest range of alloys represented in ASME B31.3 or B31.8. These materials will be the least effected by hydrogen embrittlement in their respective category. Since embrittlement has not been measured over a range of pressures and the rows of these tables deal with increasing pressure, a decision had to be made as to the total reduction of ASME code percentage of SMTS and SMYS. For Table 1 this reduction was established as 16% (0.277 at 6000 psi (41 MPa)) and for Table 2, 20% (0.264 at 6000 psi (41 MPa)) was selected [17]. Table 3 and Table 4 this reduction was established as 11% (0.390 at 3000 psi) and 10% (0.30 at 3000 psi). For each table the initial comfort zone for pressure was established based on industry experience. Form this point to the maximum reduction of design factor point the values for the intermediate design factors were calculated and plotted as a function of the square root of pressure.

### 9.1.2 Population of Columns

Once the base row as described in paragraph 9.1.1 was populated with design factors, the columns for each pressure are populated using the process described below [36]. This process takes the effect of embrittlement increase with increasing tensile and yield strength. The steady state concentration of hydrogen $C_L$ in normal interstitial lattice sites (NILS) in a stressed lattice is given by

$$C_L = C_{L0} \exp[\frac{\sigma_{kk} V_H}{3RT}]$$

**Equation 1 Steady State Lattice Hydrogen Concentration**

where $C_{L0}$ is the hydrogen concentration in the absence of stress and is proportional to square root of the hydrogen gas pressure $P$, $\sigma_{kk}/3$ is the average stress (hydrostatic stress), $R$ is the universal gas constant, $T$ is the temperature and $V_H$ is the partial molar volume of hydrogen in solution. Therefore, the hydrogen concentration in a lattice at a given temperature is a function of pressure and hydrostatic stress

$$C_L = C_L(P, \sigma_{kk})$$

**Equation 2 Lattice Hydrogen Concentration—Functions**

If the lattice hydrogen concentration $C_L$ is smaller than an experimentally measured safe concentration $(C_L)_s$, then the system will be safe under a given load provided that

$$C_L(P, \sigma_{kk}) \leq (C_L)_s$$

**Equation 3 Lattice Hydrogen Concentration—Experimentally Measured Safe**

Considering a closed cylindrical vessel under internal pressure *P* with wall thickness *t* and radius *r*, one has

$$\sigma_{rr} = 0, \quad \sigma_h = \frac{P\,r}{t}, \quad \sigma_{zz} = \frac{P\,r}{2t}$$

**Equation 4 Stresses in Cylindrical Vessel under Internal Pressure**

where $\sigma_{rr}$ is the radial stress, $\sigma_h$ is the hoop stress and $\sigma_{zz}$ is the axial stress in the vessel. Then, the hydrostatic stress is

$$\frac{\sigma_{kk}}{3} = \frac{\sigma_{rr} + \sigma_h + \sigma_{zz}}{3} = \frac{P\,r}{2t} = \frac{2}{3}\sigma_h$$

**Equation 5 Hydrostatic Stress**

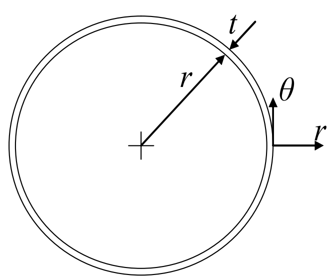


**Figure 2 Schematic of a Cross Section of a Pipeline**

Let us assume that the design factors as given by the first row of the tables are correct and ensure safe operation. Using Table 1 as an example, the first row is for a material with specified minimum tensile stress $\sigma_T$ = 70 ksi (482 MPa) and specified minimum yield stress of $\sigma_Y$ = 52 ksi (358 MPa). Hence, the safe design factor under pressure ≤ 1000 psi (6.9 MPa) is $f_s = 0.33$.

Now, one may fill the rest of the columns in Table 1 by using the given safety factor values of the first row for each design pressure and Equation 4. From Equation 4 and Equation 5, one may deduce that the safety condition is expressed in terms of the hoop stress $\sigma_h$ as

$$\sigma_h \leq (\sigma_h)_s \,.$$

**Equation 6 Safety Condition—Hoop Stress**

Since the hoop stress is the maximum stress in the pipe, one can substitute it by the safety factor times the design stress, i.e.,

$$f\,\sigma_d \leq f_s\,(\sigma_d)_s$$

**Equation 7 Safety Condition—Design Stress**

or

$$f \leq \frac{f_s\,(\sigma_d)_s}{\sigma_d}$$

**Equation 8 Tensile and Yield Stress**

If the design stress is assumed to be the average value of tensile stress and yield stress, the design factor can then be calculated as shown below.

For instance,

1. If pressure is 1.0 ksi (6.9 MPa), then $f_s$ = 0.33 and $(\sigma_d)_s$ = (70 + 52) / 2 = 61 ksi (420 MPa). The design factor for the material with specified minimum tensile stress $\sigma_T$ = 75 ksi (517 MPa) and specified minimum yield stress of $\sigma_Y$ = 56 ksi (386 MPa) ($\sigma_d$ = (75 + 56) / 2 = 65.5 ksi (451.6 MPa)) can be calculated as $f \leq 0.33 \times 61 / 65.5 = 0.307$;

2. For pressure of 3.0 ksi (20.7 MPa), we find $f_s$ = 0.301 and $(\sigma_d)_s$ = (70 + 52) / 2 = 61 ksi (420.6 MPa). Then, the design factor for the material with specified minimum tensile stress $\sigma_T = 80$ ksi (551.6 MPa) and specified minimum yield stress of $\sigma_Y = 65$ ksi (448 MPa) ($\sigma_d$ = (80 + 65) / 2 = 72.5 ksi (500 MPa)) is $f \leq$ 0.3 x 61 / 72.5 = 0.253.

Looking at the calculated safety factor values, the underlying thesis is that the safety factor for the first row is correct. Certainly, this is the case for a material with specified minimum tensile stress $\sigma_T$ = 70 ksi (482.6 MPa) and specified minimum yield stress $\sigma_Y$ = 52 ksi (358.5 MPa) under a pressure of 1 ksi (6.9 MPa).

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