Material Selection and Design Considerations for Hydrogen Pipelines

Introduction

Most H2 pipelines consist of carbon steel materials that have previously been used as gas pipelines, however austenitic stainless steels meeting the temperature limits of ASME B31. 12 are preferred for liquid and gaseous hydrogen products, the most stable grade is Type 316/316L.

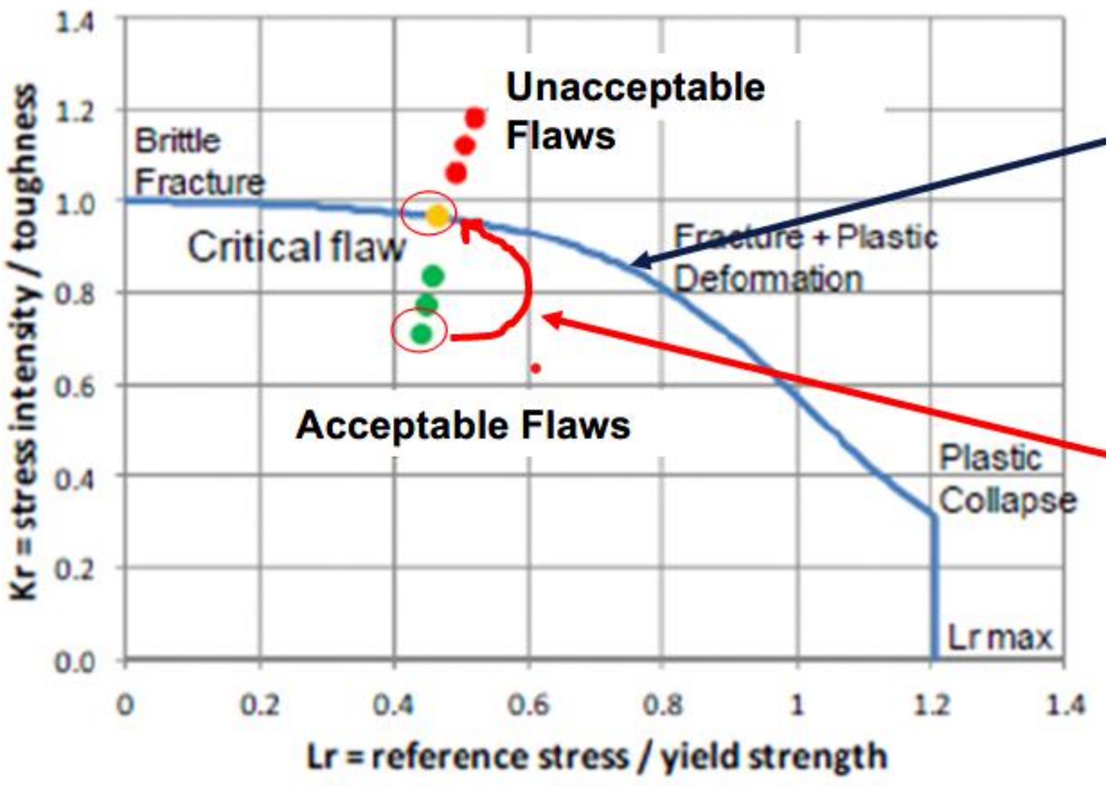
Gaseous hydrogen can be transported through pipelines much the way natural gas is today. There are approximately 2,800 miles of H2 pipelines globally, with around 1,600 miles in the United States.

The majority of H2 pipelines are existing retired gas pipelines that are converted to carry Hydrogen; however the preferred method is for a greenfield approach ,which is specifically designed for H2 transportation

Pipelines provide is a low-cost option for transporting large volumes of hydrogen. The high initial capital costs of new pipeline construction vs reuse of retired NG pipelines constitute a major barrier to expanding hydrogen pipeline delivery infrastructure. Research today therefore focuses on overcoming technical concerns related to pipeline transmission, including:

- The potential for hydrogen embrittlement of the steel
- The reduction in material mechanical properties
- The need to control hydrogen permeation and leaks
- The need for lower cost, more reliable, and more durable hydrogen compression technology, whilst finding safer ways to design and construct new H2 pipelines

Materials & Assessment ECA Failure Assessment Diagram



Material property input such as Fracture Toughness (FT) and Yield Strength (YS) define the boundary limits in a H2 environment

Time required for a defect to become critical is governed by the applied stresses and forces and measured / governed by the Fatigue Crack Growth Rate (FCGR)

<u>Fracture Mechanics</u> has been used to measure FCGR and FT properties in H2 atmosphere

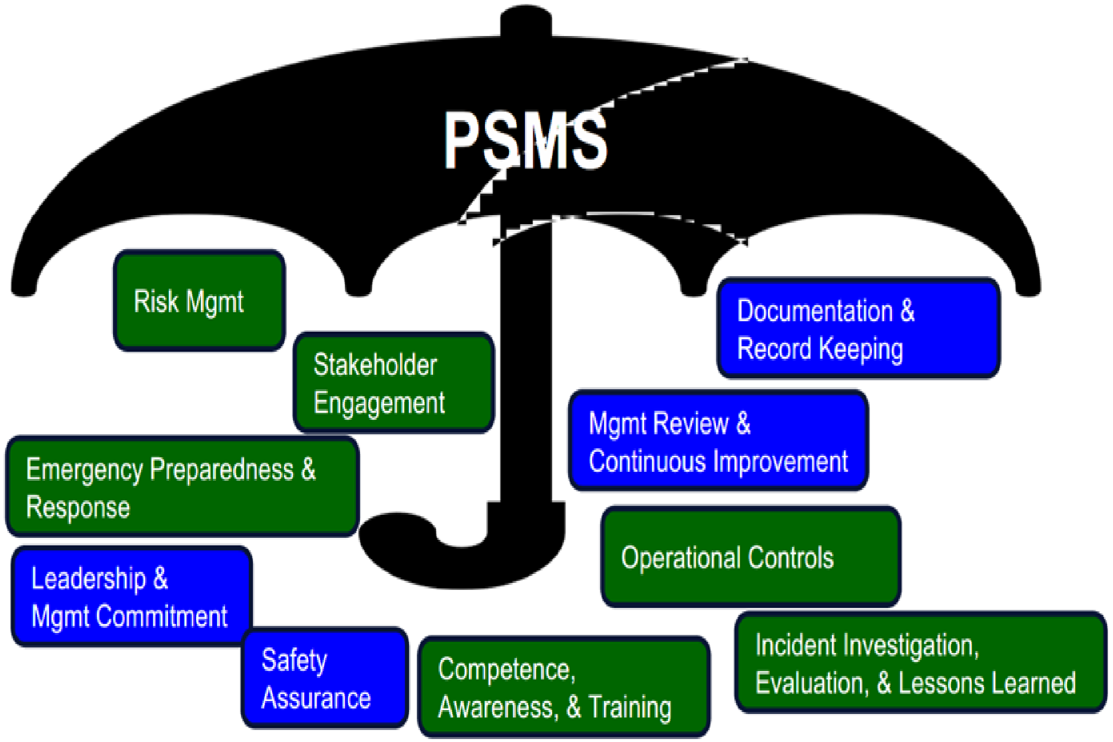
Engineering Critical Assessment (ECA) – Failure Assessment Diagram

Materials & Assessment PSMS

Hydrogen can have an adverse effect on the fracture and fatigue properties of steel. The magnitude of the effect can vary depending on steel grade and microstructure, concentration of Hydrogen, and other factors. Therefore, integrity assessments need to be based on the material properties that we investigate . An effective means of achieving this is through development and use of a Pipeline Safety Management System (PSMS)

The key challenges in Hydrogen pipelines design can be categorized as follows:

- Low volumetric energy density.
- Maximum pressure limits.
- Materials degradation.
- Hydrogen embrittlement
- Compressor Design.
- Safety.



Pipeline Management Safety System overview

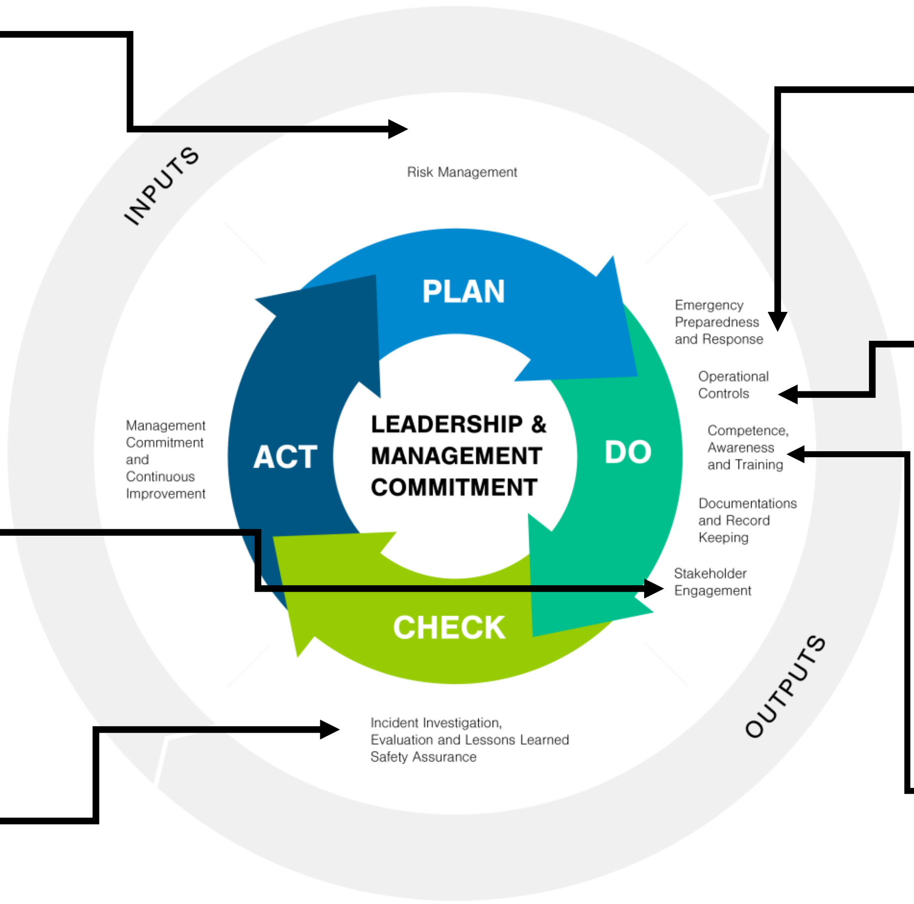
Materials & Assessment PSMS

Risk Management
Updated risks from H2 service, e.g.
- Cracking
- Axial Loading
- Increased demand / MAOP/ Cycling

Updated Consequence modelling
- Increased MAOP (new HCA's)
- Revised class Locations

Stakeholder Engagement
- End users now play a much more significant role and ensuring compatibility of assets/ appliances/ equipment using H2 or H2 – NG blends

Evaluation & LL
- Expand network of collaborative partners to share information and learn from industry experience / lessons learned
- Elevate near misses related to H2 service



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Emergency Preparedness & Response
- Revised plan for H2 assets
- More frequent discussion and updates with emergency responders
- Education in the differences between H2 and H2 –NG blended behavior

Operational Controls.
- More frequent leak detection surveys
- Updates to hydraulic and flow modelling
- Revised start-up / shutdown procedures
- Heightened procedures for responding to potential release scenarios

Competence, Awareness & Training
- Rigorous training program for all stakeholders on impacts of H2 on operations, integrity & consequence potential
- Create H2 SME / coordinator to ensure accuracy of information

Materials & Assessment - Acceptable Materials for ASME B31.12

Material	Gaseous Hydrogen Compatible	Notes
Carbon steel	Acceptable	
Aluminum & aluminum alloys	Acceptable	
Austenitic stainless steels with more than 7% nickel (e.g., 304, 304L, 308, 316, 321, 347)	Acceptable	Awareness of martensitic conversions at low temperatures if material is stressed above the yield point
Copper & copper alloys (e.g., brass, bronze, & copper-nickel)	Acceptable	Although low in likelihood, possibility of Intergranular cracking at oxide inclusions, however
Grey, ductile or cast iron	Not Acceptable	Not permitted for Hydrogen service
Low alloy steels	Acceptable	
Nickel & nickel alloys (e.g., Inconel, and Monel)	Not Acceptable	Susceptable to Hydrogen Embrittlement
Nickel s(e.g., 2.25%, 3.5%, 5% and 9% nickel)	Not Acceptable	Ductility Loss
Titanium & titanium alloys	Acceptable	

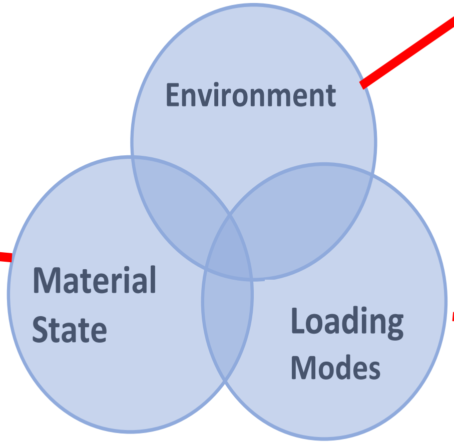
Comments

- Acceptable does not always mean that it does not show loss or reduction in mechanical properties
- Proper considerations must be made for material strength levels, applied load levels, etc.
- Lower strength Carbon steels (X42, X52, etc., although more resistant to degradation, they are not immune

Design Considerations Hydrogen Embrittlement

Hydrogen Embrittlement Considerations

Transported H2

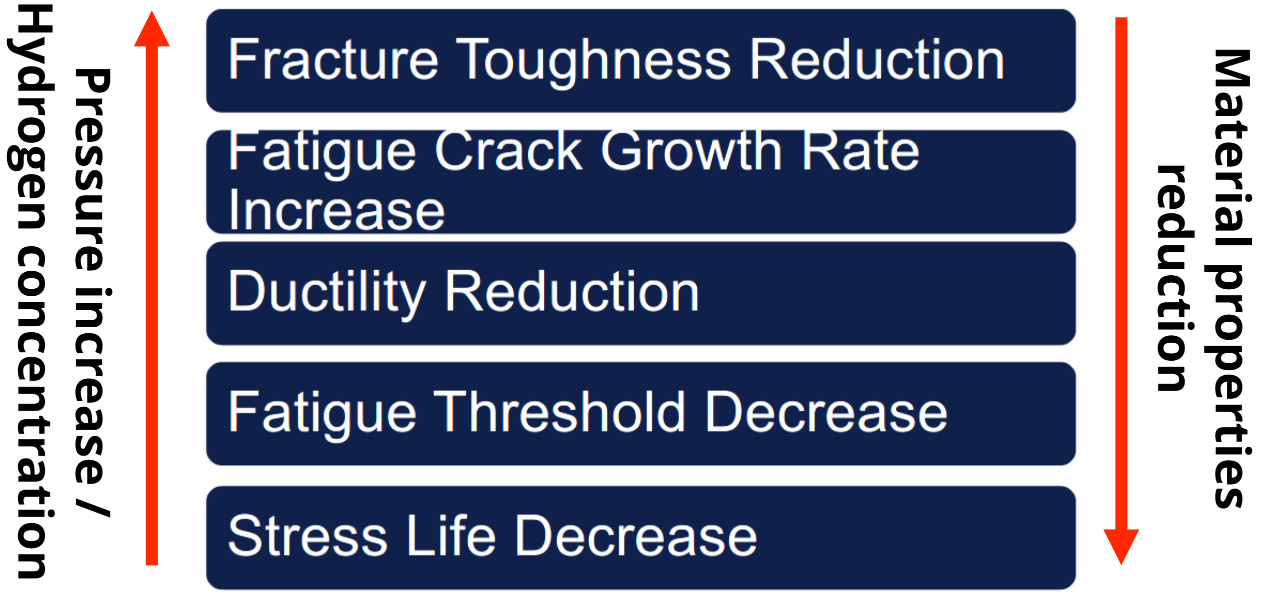


- Alloy Chemistry
- Processing
- Welding
- Internal coatings
- Residual Stress
- Plastic Deformations due to dents / installation/ seismic events/ movement

- Load/ stress due to transported gas pressure
- Operational Fatigue due to pressure fluctuations
- Static load form steady state operations
- Earth movements

Design Considerations -
Impact of Hydrogen on Mechanical Properties

- Mechanical properties deteriate in the presence of Hydrogen due to Hydrogen embrittlement
- With no internal coating barrier, higher yield strengths, and higher concentration of hydrogen, or increased pressure, results in greater deterioration in material properties
- It is of vital importance to make sure that testing parameters, such as strain rate be carefully selected to ensure accurate results for hydrogen effects on Fracture Toughness property degradations



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Design Considerations - Material Condition/ Microstructure Control

- Steel microstructure is influenced by heat treatment and alloy processing designs
- Quenched and tempered or Normalized and tempered are the preferred material conditions
- Quench and Tempered microstructure produces the best toughness; however, they are rare for older existing line pipe steels (sometimes used in fittings where high strength is required, and mechanical properties cannot be enhanced by TMCP rolling practices)
- Normalized material conditions are common Control practices which provide a homogeneous microstructure or fine-grained microstructure

Quenched and tempered

Normalized and tempered

Normalized

Untempered bainite

Untempered martensite

Increased hydrogen embrittlement susceptibility

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Coatings

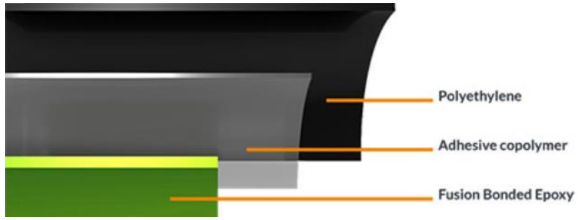
Internal Coatings

- Application of internal coatings using Polyurethanes and Epoxy resins can provide a good barrier against Hydrogen Embrittlement (HE) on Carbon steel (P1) materials, specially in higher strength materials

- Other metallic compounds such as Zinc and other metallic compounds, provide can efficient hydrogen barriers, but are not practical due to their brittle nature

External Coatings

- Polyurethane or 3LPE is the preferred system for external coatings on Hydrogen pipelines



- Coating thickness of up to 2.5mm for Polyurethane, and between 1.8mm - 4.0 for 3LPE coating systems

Material Selection and Design Considerations for Hydrogen Pipelines

Designing pipeline transportation systems as a greenfield project is preferable and less problematic that retrofitting a brownfield pipeline that was originally designed for transportation of NG

The importance of internal coatings cannot be underestimated.

The development and use of a PSMS provides multiple benefits

Pipelines remain the most practical, safest and economic means of transporting Hydrogen

The use of an internal coating system based on Polyurethane or Epoxy has significant benefits and reduces the possibility of Hydrogen embrittlement

An ECA is essential for assessing the suitability of existing NG pipelines when considering change to H2 service

For converting exiting Carbon steel NG pipelines, it is preferred to use lower strength materials (X42, X52, etc. with a constant pressure

Capital costs for a green field system are much higher than reuse of existing pipelines

The preferred material for H2 pipelines is 300 series Austenitic stainless steels with Nickel content over 7%

Questions ?

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