Final Report

on

Review of Integrity Threat Characterization Resulting from Hydrogen Gas Pipeline Service

DOT/PHMSA Project 693JK32210013POTA

to

Department of Transportation
Pipeline and Hazardous Materials Safety Administration

by

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EXECUTIVE SUMMARY

DOT/PHMSA Project #693JK32210013POTA addresses the threat changes associated with the transport of hydrogen in existing pipelines. It is well established that hydrogen has a detrimental effect on various properties of steel. However, there are still many uncertainties about the magnitude of these impacts and whether they will have a significant effect on mechanical integrity. Moreover, questions regarding the relationship between hydrogen concentration and the degree of degradation in mechanical properties still exist. There are currently many active research programs in the U.S. and around the world developing data relevant to hydrogen effects on pipeline steels. To date, most efforts have focused on steel for new construction and less on existing infrastructure, i.e., pre-1970 (vintage) US pipelines. There is also a lack of well-defined procedures for the analysis of various forms of damage that take account of the presence of hydrogen. This latter issue is being addressed in DOT/PHMSA project #693JK324RA001, "Repurposing Existing Pipelines for Hydrogen Service." In this study, relevant past and very recent data and input from subject-matter experts have been collected to provide an assessment of changes in threat level once hydrogen has been introduced into existing pipeline networks in the U.S. There are currently a limited number of pipelines transporting hydrogen in the U.S. or elsewhere, so the field experience is not extensive, especially for the higher operating stresses of current natural gas Class 1 pipelines. In the U.S., PHMSA regulates approximately 1,500 miles[*]. Nevertheless, based on the current information that has been collected as part of this study, operational experience transporting hydrogen has been without incident. Through a comprehensive literature survey (Task 1), it has been possible to provide an indication of changes to threat levels and a ranking of their relative importance. Current codes, standards, and regulations have been reviewed to identify gaps, and recommendations have been developed to help address areas that are not covered. Potential mitigation strategies are reviewed to provide guidance on likely changes in Integrity Management Plans for Operators. Finally, a five-year plan has been developed as a roadmap for developing the necessary lab data and field (full-scale) experience as well as associated analyses to more clearly understand the ramifications of converting existing pipelines transporting natural gas to containing hydrogen.

Primary recommendations from this study

While there currently is no broadly accepted threshold hydrogen concentration below which no changes would be required to an operator's integrity management plan, it has been shown that even modest amounts of hydrogen can cause a measurable effect on properties, although, for fracture toughness values, some of the test procedures might unintentionally being biased to that conclusion. Operators should utilize current criteria in B31.12, ASME VIII-3 KD-1040, future B31.8 updates, and relevant literature to assess the integrity threats posed by the addition of hydrogen. The permissible limits will be a function of many factors and, therefore, are specific to each pipeline.

Crack-like flaws and hard spots/hard seams are likely to be the greatest integrity threat to existing pipelines in hydrogen service from the integrity challenges reviewed to date. Aspects like mechanical damage (dent and gouge) defects or the life of wrinkle bends have yet to be assessed and might be equally important.

- Crack management plans should reflect reduced fracture toughness and higher fatigue crack growth rates when repurposing existing pipelines to contain hydrogen. Before doing that, fracture

[*] PHMSA presentation, "PHMSA Hydrogen Pipeline Safety Regulations", Mary McDaniel – Acting Director US DOT - PHMSA – Office of Pipeline Safety, Engineering and Research Division June 7, 2023

constraint interactions with hydrogen must be established to make corrections to the published data that frequently may not involve consistent testing techniques or specimen designs.

- Screening for hard spots through inspection and manufacturing records is needed to assess this threat. Additional testing in this area will be important in mitigation strategies. The magnitude of the hydrogen concentration in a hard spot from hydrogen gas transportation to initiation of hydrogen cracking is unknown, but we suspect it may be lower than the hydrogen generated by coating loss/wet soil/CP [1], [2]. So, there may be different hardness and hard-spot size limits for hydrogen transportation.
- Where ILI tools are relied upon as a primary means to mitigate a threat, operators must consider their detection and sizing capability for each damage mechanism due to more restrictive damage acceptance criteria in hydrogen service. Inspection intervals may need to be adjusted to address increased crack growth rate and detection limits. Improvements and upgrades to ILI tools may be necessary to detect smaller anomalies and provide more accurate sizing capability.
- A consensus standard is needed to define testing protocols in gaseous hydrogen for fracture toughness, fatigue crack growth, and tensile testing, including notched bars. Burst-pressure flaw evaluation procedures may also require some slight modifications in the case of hard seam welds, which may be a higher concern.
- Future research should focus on strain limits for various conditions (e.g., dents, gouges, wrinkle bends, buckles, etc.). At present, insufficient data is available to provide strain limits for hydrogen service. Until guidance is available, operators must be aware of the increased threat of damage associated with plastic deformation.
- The use of full-scale testing to measure burst pressure or failure stress, while expensive and time-consuming, is an important means of validating ECA methods and, in some cases, showing aspects not considered in the analyses. Moreover, where ECA approaches are subjective due to uncertainty in analysis methods, they provide realistic data to guide the development of acceptance criteria used in codes, standards, and regulations.

A summary of the general trends in threats is provided in Table 1.

Table 1 Overview of hydrogen effects on threats

Threat	Some Potential Impacts of +H on Damage Mechanisms
General Corrosion	There may be an increased tendency for blistering or hydrogen-induced cracking (HIC) due to the inclusion size and density in older steels. The tolerable flaw size will be affected if these types of defects are judged to be crack-like due to a reduction in fracture toughness.
Local Corrosion	The tolerable size of local thin areas is generally governed by the flow stress of the material. This is not likely to be affected significantly by gaseous hydrogen, but this needs further study. However, research has shown a relationship between electrolytic charging with hydrogen and the rate of anodic dissolution in near-neutral pH environments [3]. A loss in fracture strain could affect local corroded regions if their geometry creates a region of high stress-strain concentration.
Stress Corrosion Cracking	Stress corrosion cracking associated with the pipe body (e.g., near neutral pH SCC) is generally associated with HE at a mechanistic level. The effect of an additional source of gaseous hydrogen is unknown. However, the tolerable size of the SCC field will be affected by a loss in fracture toughness. Linkage/coalescence of small cracks is potentially more likely due to reduced fracture strain.
Manufacturing Flaws	The presence of cracks in ERW seams of vintage pipelines is common. Due to loss in fracture toughness the tolerable crack size will be lower. Fatigue crack growth rate will increase. These factors will influence inspection intervals. ILI detection minimum sizes may require improvement due to smaller tolerable flaw lengths and depths. An additional issue is subcritical crack growth. This occurs under constant load and causes stable crack propagation. This is the source of the 55 MPa-√m limit in ASME B31.12. Implications here are also increased potential for hydrotest failures. Another form of manufacturing defect is a hard spot. It is assumed that hard spots are susceptible to hydrogen cracking from CP, and it is likely cracking potential would be increased with an additional source of hydrogen.
Fabrication/Repairs	Field fabrication that induces high levels of strain (e.g., cold bends) could increase the hydrogen content locally. Pipe strain due to soil or vibrations in flowing water would also likely be more susceptible to cracking. Due to the decrease in fracture strain these could be sources of crack formation. Weld repairs like Type B sleeves also introduce the potential for cracking or crack extension.
Third-Party Damage	Damage associated with dents and gouges could be affected in various ways by hydrogen. The current tolerable size of these types of defects would likely be smaller based on lower fracture strain. Due to a reduction in fatigue life (S-N), crack initiation would be expected in fewer cycles. Once cracking occurs, a lower fracture toughness would promote further stable crack propagation and fracture.

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Ms. Stephanie Flamberg of RSI was part of our team for the development of the SME Elicitation questionnaire. Her efforts were extraordinary. Mr. Michael Rosenfeld of RSI was on the SME panel. Others volunteering their time to the SME Elicitation panel are listed below. As evident in this report, we took their opinions very seriously. There may have been several hundred follow-up emails with additional information, clarifications, and consensus building along the way from these members.

Professor Xiaosheng Gao of the University of Akron performed hydrogen migration numerical analyses in our companion DOT/PHMSA project, which are cited in numerous places in this report. He was wonderful to work with and supplied much-needed technical expertise.

There were other Emc^2 staff members who helped too. Dr. Cedric Sallaberry assisted in the data reduction and evaluations of the SME Elicitation responses. Drs. Bud Brust, Fabian Orth, Robert Kurth, and Yunior Hioe offered expert opinions on different topics. Mr. Matt Walburn, Mr. Justin Hunter, and Mr. Russell Hattery assisted in the hard-spot residual stress measurements – a first-of-kind effort that is essential in understanding hard-spot hydrogen-stress cracking. Administrative assistance from Ms. Ann Roty, Mrs. Rita Wilkowski, and Ms. Roxie Stafford was essential to getting the project done. We offer our deep appreciation to our village of support.

Those asked to be on the SME Elicitation Panel were:

Code and Standards

- Mike Rosenfeld – Vice Chairman of B31.8
- Mahendra Rana – Chairman of B31.12
- Josh Wickham – Australian standards committee
- Bostjan Bezensek / Otto Jan Huising - European hydrogen pipeline standards committee

Pipeline Operations

- Fan Zhang, Phillips 66
- Steve Potts, Williams Pipeline
- Ken Doering, Chevron
- Taylor Shie, Shell Midstream US
- Danielle Mark, Pacific Gas & Electric (PG&E)
- Munendra Tomar, TCE
- Steve Rapp, Enbridge
- Rick Noecker - ExxonMobil

Material Science – Testing, Hydrogen expertise, SCC expertise

- Neeraj Thirumalai / Greg Pioszak, ExxonMobil Research & Engineering
- Ramgopal Thodla, DNV-Ohio
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- Kevin Garrity, Mears
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- Lance Hill, Emc^2
- Pete Riccardella, SIA

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- Simon Slater, Rosen

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ACRONYMS

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BM	Base Metal
C(T)	Compact (Tension)
CE	Carbon Equivalent
CP	Cathodic Protection
DCPD	Direct-Current Potential Difference
DOT	Department of Transportation
DSAW	Double Submerged Arc Weld
DVWG	Deutscher Verein des Gas und Wasserfaches
ECA	Engineering Critical Assessment
EDM	Electrical Discharge Machined
EFW	Electric Flash Weld
EIGA	European Industrial Gases Association
EMAT	Electromagnetic Acoustic Transducer
EPRG	European Pipeline Research Group
ERW	Electrical Resistance Welding
FCGR	Fatigue Crack Growth Rates
FEA	Finite Element Analysis
HAZ	Heat Affected Zone
HDPE	High-Density Polyethylene
HF-ERW	High-Frequency Electric Resistance Weld
HIC	Hydrogen-Induced Cracking
HSC	Hydrogen-Stress Cracking
ILI	In-Line Inspection
IMP	Integrity Management Plan
IMU	Inertial Measurement Unit
ITD	In-The-Ditch
LF-ERW	Low-Frequency Electric Resistance Weld
MAOP	Maximum Allowable Operating Pressure
MDPE	Medium Density Polyethylene
MFL	Magnetic Flux Leakage
NDE	Non-Destructive Examination
NG	Natural Gas
PHMSA	Pipeline and Hazardous Materials Safety Administration
POD	Probability of Detection
PRCI	Pipeline Research Council International
SCC	Stress Corrosion Cracking
SEN(T)	Single Edge Notched Tension
SMAW	Submerged Arc Weld

SME	Subject Matter Expert
SOHIC	Stress Oriented Hydrogen-Induced Cracking
UT	Ultrasonic Testing
UTCD	Ultrasonic Crack Detection
UTS	Ultimate Tensile Strengths
WCL	Weld Centerline
WRS	Weld Residual Stress

1 Introduction

1.1 Report Structure

This report is structured into the various tasks and based on the project deliverables in DOT/PHMSA #693JK32210013POTA.

- Task 1 was a literature survey of existing data and the state of current knowledge relevant to assessing the mechanical integrity of pipelines in hydrogen service. This work has been used along with additional data gained in other tasks to assist in the assessment of threat level changes addressed. There is a separate report on this task; see Reference [4].
- Task 2 included developing a team of subject-matter experts (SMEs) to assist in this assessment. This was accomplished early in the program to guide the work and provide valuable input. The opinions of the SME Team participants on 64 questions are provided in APPENDIX I.
- Task 3 focused on the threat changes associated with transporting hydrogen. This was approached through the collection of existing experience, relevant data from industry and government laboratories, and efforts outside the U.S. The SME team assembled in Task 2 was then queried extensively to develop a consensus on the overall impact of hydrogen on mechanical integrity and likely mitigation strategies.
- In Task 4, data collected from Task 1 was briefly summarized to provide an evaluation of the effects of hydrogen/natural gas mixtures on the integrity of existing pipelines. As the existing natural gas (NG) infrastructure in the U.S. comprises a large fraction of so-called "vintage" pipelines (pre-1970), the impact of hydrogen on these steels is of primary importance. Root causes identified in B31.8S that are expected to be affected by hydrogen are discussed, and mitigation tasks are summarized.
- Task 5 identifies a qualitative threat algorithm for ranking current or future threats. This work addresses questions about proper in-line inspection tools, repair criteria, and acceptance limits. As mentioned earlier, the companion study on repurposing existing pipelines, RA 697JK322RA001, describes the assessment approaches and specifics on fitness-for-service assessment of threats in more detail. This report will cover them in a general sense by providing the relative ranking of threats, identifying the criteria for acceptance, and comparing this with existing approaches. This includes a summary of existing methods for evaluating damage to pipelines, reviewing current regulatory requirements, and summarizing changes or gaps in existing procedures.
- Finally, Task 6 provides a five-year plan that includes a roadmap for developing the information needed to further evaluate threats due to the transport of hydrogen in a more quantitative manner. This includes laboratory testing to develop the necessary material property data, development of analytical approaches for the engineering critical assessment (ECA) of damage, full-scale tests to validate ECA analyses, and operating experience needed to improve integrity management plans. Task 1 is published separately, but some important information from that study is included here to support the discussion.

1.2 Current Hydrogen Pipelines in the U.S.

As of 2019, there were 47 hydrogen pipelines in the U.S., with a total length of about 1,500 miles, according to data provided by 34 different operators in their 2019 annual reports for gas transmission pipelines to the U.S. DOT [5]. The three largest companies operate 16 of the 47 hydrogen pipelines, accounting for 86% (1,315 miles) of the total, and the 31 other companies operate 14% (206 miles) together. The existing hydrogen pipelines range from 4 inches or less to 30 inches in diameter, with 81%

having a diameter of 14 inches or less. Ten percent of hydrogen pipelines were installed pre-1980 and 4% pre-1940. The hydrogen pipeline mileage is predominantly located in Texas (63%) and Louisiana (31%), while 10 other states represent 6% of the mileage. The majority (60%, 905 miles) of hydrogen pipeline mileage is in Class 1 locations, and a small portion (0.5%, 7 miles) is in densely populated Class 4 Locations, as shown in Figure 1 and Figure 2.

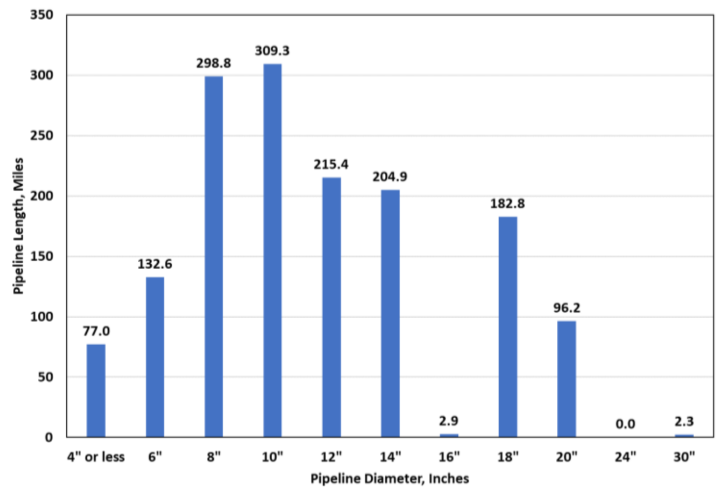


Figure 1 Hydrogen pipelines in the US by size

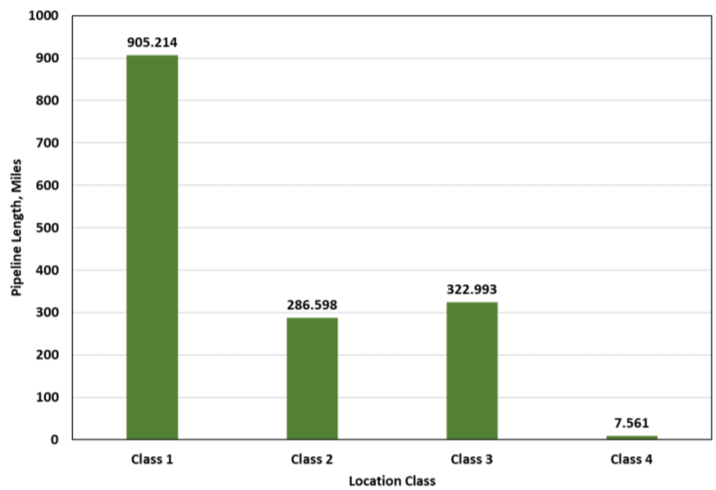


Figure 2 Location class of hydrogen pipelines in the US (2019)

To date, there have been several utilities in the U.S., and several experimental trials have successfully demonstrated the blending of hydrogen into natural gas for either gas transmission or distribution. Hawaii Gas is the most widely referenced example, transporting a 12% blend of hydrogen since the 1970s, and prior to that, "town gas" consisted of about 50% hydrogen. New Jersey Natural Gas and SoCalGas have also successfully demonstrated safe transmission of NG blends with hydrogen. To date, lines transporting hydrogen in the U.S. have operated safely. However, it is recognized that the mileage is extremely small and at lower operating pressures compared to Class 1 NG transmission lines; hence, only limited information can be obtained from this experience.

2 Task 3 – Compare Threat Level Changes to ASME B31.8S Resulting from Transport of Hydrogen

2.1 Threats Identified in B31.8S

ASME B31.8S provides a framework for the identification of threats to pipeline integrity and the process for managing risks. An integral part of this process is the development of an integrity management program (IMP) that includes five key elements:

1. Integrity Management Plan (IMP),
2. Performance plan,
3. Communication plan,
4. Management of change plan, and
5. Quality control plan.

Based on work performed by the Pipeline Research Council International (PRCI), 22 root causes have been classified into 3 categories so that appropriate timing and mitigation tasks can be planned. These threats are then evaluated to determine their overall integrity risk by assessing the probability of occurrence and associated consequences. Mitigation plans are then developed to address these threats based on a risk assessment designed to maintain the target goals established by each operator. The primary effects of introducing hydrogen into existing pipelines are due to a change in material properties, as given in Table 2.

Table 2 Primary impacts of hydrogen in steels

Hydrogen effects on steel
Increased fatigue crack growth
Decreased endurance limit
Decrease in low-cycle fatigue
Decrease in fracture toughness
Decrease in fracture ductility
Minor effect on YS and UTS

These changes affect defect tolerance of both time-based as well as time-independent (resident) threats, and, therefore, must be incorporated into an operator's IMP. A high-level summary of the expected impacts of hydrogen on the various threats outlined in B31.8S is summarized in Table 3.

Table 3 Effects of hydrogen on B31.8S threat categories

(a) Time Dependent	1. External Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse limit of local thin area. **(M)**
	2. Internal Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse limit of local thin area. **(M)**
	3. SCC	May be an effect on SCC, but decrease in fracture toughness reduces critical flaw size **(M)**
(b) Resident	4. Seam Crack	Decrease in fracture toughness results in smaller tolerable flaw size. Higher fatigue crack growth rate, potential for subcritical crack growth under constant load, particularly during hydrotesting. **(H)**
	5. Defective Pipe: *Hardspot*	Decrease in fracture stain and toughness but overall high impact **(H)**
	6. Girth Weld, Fillet Weld, etc.	Decrease in toughness and concentration of hydrogen in HAZ reduces tolerable flaw size **(H)**
	7. Fabrication Weld	Decease on toughness results in smaller tolerable flaw size **(M)**
	8. Wrinkle Bend/Buckle	Decreased in fracture stain and concentration of hydrogen could result in cracking and failure **(M)**
	9. Stripped Threads, etc.	No impact **(L)**
	10. Gasket O'ring Failure	No **(L)**
	11. Control/Relief Equipment Malfunction	No impact **(L)**
	12. Seal/Pump Packing Failure	Moderate impact **(M)**
	13. Miscellaneous	No impact **(L)**
(c) Random/Time Independent	14. Third Party Damage	Decrease in toughness and fracture strain results in potential for fast fracture. This is likely to manifest some time later, and not on impact due to high loading rate. **(H)**
	15. Previous Damage: dents/gouges	Decreased in fracture stain and concentration of hydrogen could result in cracking and failure **(H)**
	16. Vandalism	Low impact **(L)**
	17. Operating Temperature	Low impact **(L)**
	18. High Wind	Decrease in fracture stain, but overall low impact **(L)**
	19. Water-related	Decrease in fracture stain, but overall low impact **(M)**
	20. Geotechnical	Decrease in fracture stain, but overall low impact **(M)**
	21. Lightning	Low impact **(L)**

The various root causes are colored-coded based on the level of impact as follows:

Table 4 Threat categorization

Impact	Color	Code
High	Red	H
Medium	Yellow	M
Low	Green	L

The threat level change will be discussed in more detail in Section 4.1.

2.1.1 Time-Dependent Threats

2.1.1.1 Corrosion

The time-dependent threats identified in ASME B31.8S include corrosion from internal and external sources, as illustrated in Figure 3.

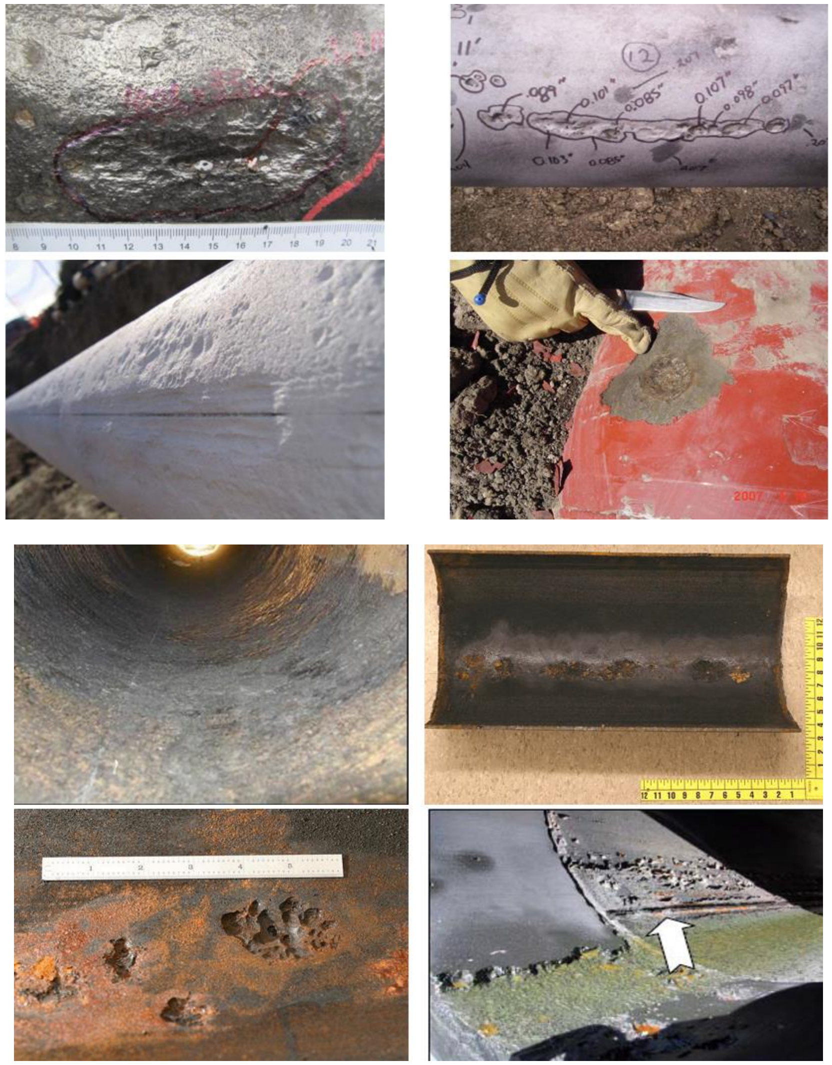


Figure 3 Illustration of corrosion features

The presence of hydrogen is not expected to influence the rate of corrosion. No literature sources identified in this study found evidence that gaseous hydrogen charging alone results in a higher corrosion rate. However, one study by Lee et al. did show a relationship between the electrochemical charging of hydrogen and the rate of anodic dissolution [3]. Whether the degree of hydrogen charging in a gaseous hydrogen environment influences corrosion processes is not known. It should be noted that in aqueous sour service, where hydrogen charging takes place, it is a product of the corrosion process. Regarding external corrosion, no studies evaluating the impact of hydrogen on the effectiveness of cathodic protection (CP) or the disbonding of coating have been identified. It was mentioned that the degree of hydrogen charging associated with cathodic charging is much greater than what takes place in hydrogen gas at typical pipeline operating pressures and temperatures [1], [2]. Further evidence of the benign behavior of hydrogen on corrosion can be gleaned from refinery operations, where vessels and piping transporting hydrogen are ubiquitous. No metal loss attributed to the presence of hydrogen alone is observed in these services, even at very high pressures and temperatures. It should be mentioned that while the presence of hydrogen is not expected to have an impact on the rate of metal loss, locally corroded regions will result in strain concentration that will affect the hydrogen concentration [6].

An indirect effect of hydrogen charging might be related to the possible reduction in burst pressure of locally corroded regions. It is well established that the presence of hydrogen in steel results in a degradation in fracture strain. Data reported by Briottet et al., shown in Figure 4, illustrates this effect [7]. Note that the yield and tensile strength are essentially unchanged, but the fracture strain, particularly at low strain rates, is reduced by as much as 50%. However, even in air, at very slow strain rates, there is a decrease in the stress-strain curve due to primary creep [8], although there is not a significant loss in fracture strain.

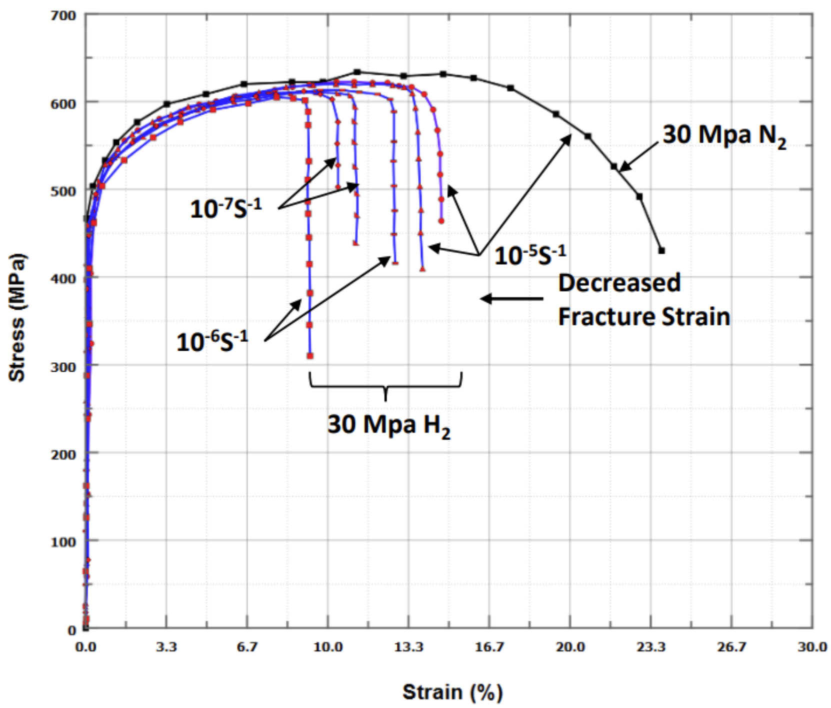


Figure 4 Effect of hydrogen on uniaxial fracture ductility from Reference [7]

As hydrogen reduces the tensile ductility, the burst pressure is expected to decrease accordingly since plastic collapse will initiate at a lower accumulated strain. Typical approaches, such as those in B31.G or RSTRENG, used to evaluate the acceptability of local metal loss are empirical, having been developed and calibrated with the use of burst tests. They relate failure pressure to flow stress, usually taken as the average between the yield and tensile stress [9]. As hydrogen does not significantly affect these properties, as illustrated in Figure 4, the predicted burst pressure would be unaffected by the presence of hydrogen. However, the potential for cracking and failure is related to the accumulation of plastic strain within the local thin area and would be expected to influence the burst pressure. Test data in Reference [10] on notched strap tensile specimens with different notch-tip radii show that as the radii change, the net-section stress as failure changed from average yield and ultimate for a sharp crack to ultimate for a very blunt flaw. This suggests there is a strain limit for the cracking to start, at least in those air tests. Whether the presence of hydrogen is significant enough to affect the burst pressure substantively is presently unknown.

Some insight can be derived from evaluating the accumulation of hydrogen within the corroded region due to the higher local stress and strain field. As the pressure within the pipe increases, there is a corresponding increase in stress within the corroded region. The higher local tensile stress field will provide a driving force for hydrogen diffusion, and the triaxial stresses and plastic strains provide trapping sites, causing the local concentration to increase [11]. The effect of plastic strain within the thinned area will also tend to increase hydrogen solubility by creating additional trapping sites. So, the interaction between stress and strain fields in terms of hydrogen concentration is somewhat complex. The accumulation of hydrogen has been evaluated as part of this study to explore the redistribution of hydrogen in a locally corroded area in a pipeline under pressure. The results of an FEA simulation accounting for both lattice hydrogen, as well as trapped hydrogen, are shown in Figure 5. The model assumptions include the following:

- 36-inch diameter, 0.625-inch wall thickness, X52 steel pipe,
- 3D shape of corrosion from a laser scan of service condition to make 3D FE model – greatest depth = 43.6% of wall thickness, length = ~7 inches, and width = ~4 inches,
- Simulated with and without hydrotest at 1.25 x MAOP (1,795 psig), and operating pressure of 72% SMYS 1,436 psig,
- Lattice hydrogen (C_L) on ID surface set to 2.084x10^{12} atoms/mm^3 (2.5 ppm H_2) and zero on OD, and
- Hydrostatic stresses and plastic strains were evaluated at the deepest location.

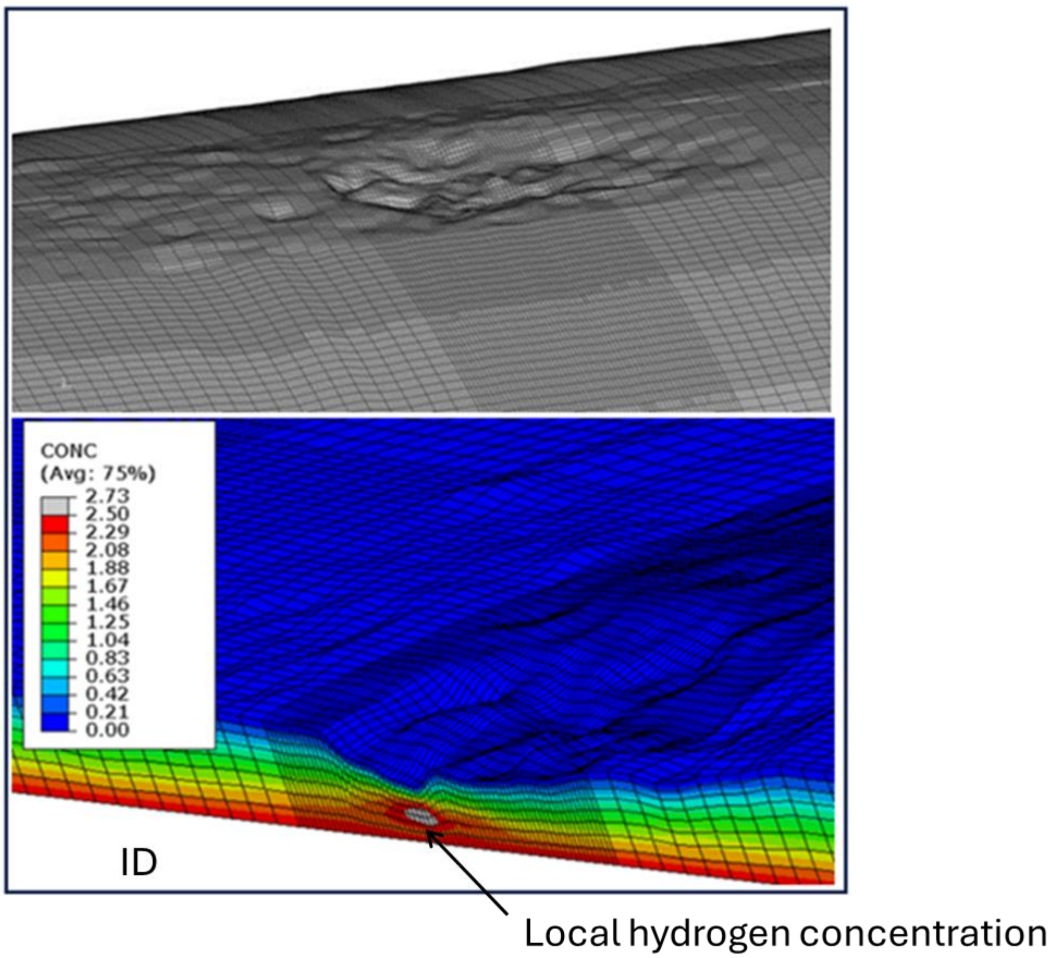


Figure 5 Hydrogen concentration in local thinned area

Due to the increased tensile stress within the corrosion feature, the analysis shows a higher hydrogen concentration compared to the surrounding area. Note the higher hydrogen concentration at the ID of the pipe in contact with the environment. In Figure 6, the stress and strain distribution are shown, including the hydrostatic stress ($3\sigma_H$) and equivalent plastic strain (ε_p).

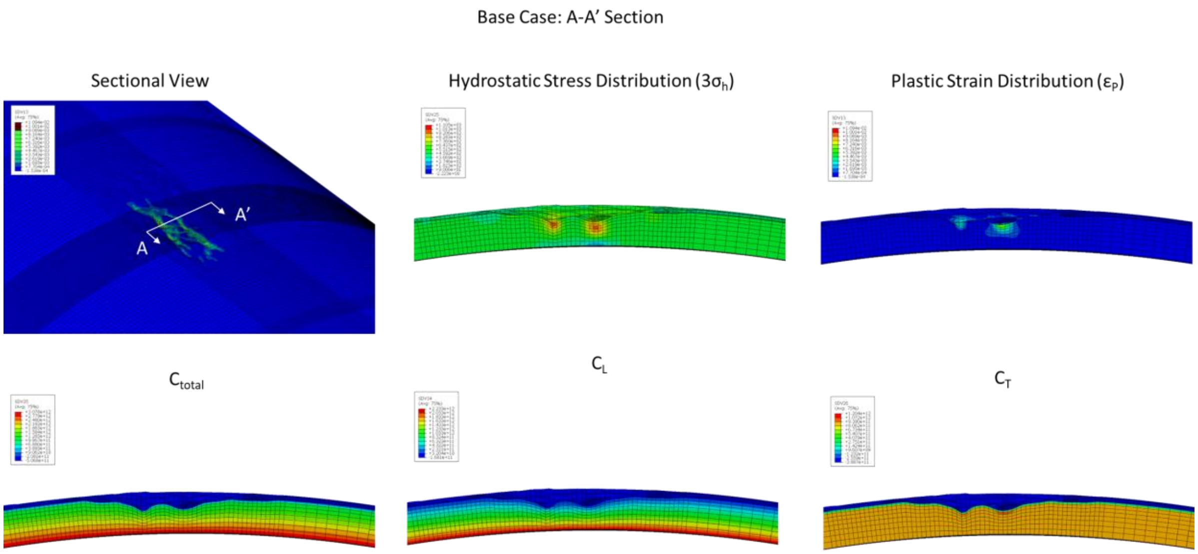


Figure 6 FEA stress analysis of corrosion feature

Note that the locations of peak stress and plastic strain coincide with the locations of high hydrogen concentration.

Work is ongoing in a companion DOT/PHMSA project at Emc^2 to explore this issue in more detail, examining the reduction in failure pressure by associating the presence of hydrogen with damage. This approach, which makes use of phase-field modeling, is becoming increasingly useful for evaluating the integrity limits of structures by incorporating continuum damage-mechanics principles in the analysis, see References [12] and [13].

The approaches used to estimate the burst pressure of corrosion patches all presume the failure mode is plastic collapse. The potential for brittle or elastic-plastic fracture initiation at a corrosion feature is not utilized in these models. From an experience standpoint, this has been the case. Many pipelines operating in the U.S. that were put into service prior to the 1970's can be expected to have a base-metal Charpy transition curve somewhere near ambient temperatures, with the surface-cracked-pipe burst pressure being up to 200°F lower [14]. The transition temperature for some vintage seam welds, however, is much warmer [14]. As hydrogen affects both failure strain and toughness, it is useful to understand if brittle fracture could initiate from a corroded region in the presence of hydrogen. In one study [15], the various burst models were evaluated to determine if toughness had an appreciable effect. They used a statistical model of cleavage fracture to assess the likelihood of brittle fracture initiation at locally corroded regions. This model uses Weibull statistics to evaluate the probability of cleavage by calculating a parameter referred to as the Weibull stress. This methodology assumes that cleavage failure initiates at local defects or inclusions randomly dispersed in the material and that the probability of fracture is related to a critical stress affecting a unit volume of material. This approach has been used for many years to explore various aspects of cleavage fracture (such as constraint effects). The conclusion of the study, which looked at a variety of corrosion geometries, was that current approaches such as B31G are sufficiently conservative to address low-toughness pipe. It should be mentioned, though, that the acuity (sharpness) of the corrosion feature strongly affects the result, which could imply that some forms of damage, such as selective seam weld corrosion, are at increased risk for brittle fracture due to the locally high stresses caused by the irregular nature of the corrosion-patch geometry.

In a separate project for DOT/PHMSA on a novel approach to assessing corrosion [10], experiments on vintage base metal pipes showed that the bluntness of the corrosion flaw decreases the brittle fracture initiation transition temperature compared to a sharp crack. There is a gradual change in the transition temperature differences from a sharp crack with the notch root radius. Even a sharp crack has a much lower transition temperature than in a Charpy test [14]. These results substantiated the ductile initiation behavior of corrosion flaws, even in very old line-pipe base metals in air testing.

While modeling of the type described here suggests that the transport of hydrogen may reduce the acceptance limits of locally corroded areas, the magnitude of this effect is still unknown. Even the application of damage mechanics models, while providing a sense of the magnitude of this effect, still requires validation to substantiate the assumptions inherent in such models. At present, all that can be concluded is that directionally, the presence of hydrogen is expected to reduce the plastic collapse limit of locally corroded areas, probably more so in local regions with smaller notch root radii. In addition, if testing verifies this, models incorporating parameters that take account of the presence of hydrogen will be needed.

The issue of general corrosion can be regarded as less of a concern. Thickness loss associated with uniform corrosion limits stresses to the elastic range, and as the yield and tensile stress are not significantly affected by the presence of hydrogen, the use of the current acceptance criteria should not increase the threat level.

2.1.1.2 Stress Corrosion Cracking

The other form of time-dependent damage identified in B31.8S is stress corrosion cracking. Two forms of SCC are known to affect pipelines – near neutral SCC and high pH SCC. An example of a crack field due to external SCC is shown in Figure 7 [16].

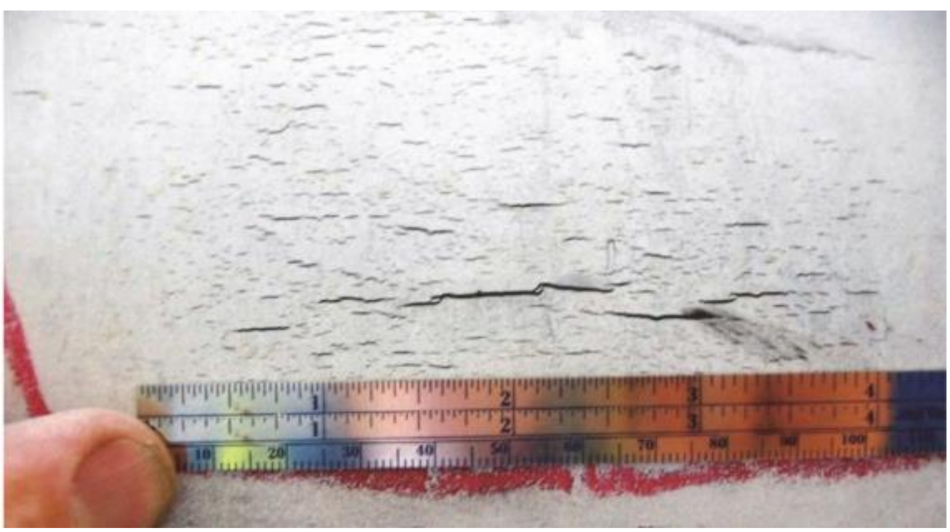


Figure 7 Crack field due to external SCC of a pipeline

Based on the literature search performed for this project, there does not appear to be any data supporting the effect of hydrogen on the crack growth rate in either form of SCC. However, it should be mentioned that hydrogen does play a role in the mechanisms of SCC and is affected by the characteristics of the aqueous environment, i.e., the pH of the aqueous solution. An indirect effect on SCC, however, is the acceptance criteria. As hydrogen reduces fracture toughness, the tolerable size of an SCC field will be smaller. Note that no distinction is made between ID and OD hydrogen distribution through the pipe wall. While some effects may exist, they are difficult to quantify in thin-walled pipes. The typical approach for engineering critical assessment of SCC is to postulate an equivalent single linear crack over the extent of the damaged region in the axial direction, normal to the hoop stress. This equivalent flaw is then evaluated using a fracture mechanics approach. In this sense, the presence of hydrogen will limit the acceptance criteria for SCC due to the lower fracture toughness used in the analysis. However, the development of damage or the rate of growth is not expected to be influenced by the presence of hydrogen. One scenario is if the K value of the SCC growth exceeded K_{IH}, then perhaps there might be an additive effect of hydrogen crack growth on SCC growth, but there is no data to support this postulation at this time. Some full-scale testing by PRCI has been included in a future work plan to assess this behavior.

Other forms of damage associated with hydrogen ingress include hydrogen-induced cracking (HIC), stress-oriented hydrogen-induced cracking (SOHIC), and blistering. These forms of damage can take place when steels are exposed to water containing H_2S, referred to as sour water. Blistering is another form of damage that can take place in either sour water or steels exposed to hydrogen at elevated temperatures and pressures. These forms of damage are all related to the accumulation of hydrogen at inclusions or laminations in higher sulfur steels containing MnS, so-called “dirty” steel. They are generally found in refineries where severe sour water conditions exist or in high temperature-high pressure hydroprocessing equipment. While pre-1970s vintage pipeline plate (skelp) fits into the category of high-sulfur C-Mn steels, the severity of hydrogen charging in gaseous hydrogen at ambient temperature is far less severe than in refinery services. Significantly greater hydrogen charging takes place by the corrosion reaction of steels in low pH aqueous H_2S or at high temperatures, compared to ambient temperature conditions, particularly at lower pressures. These root causes are not identified in B31.8S but are mentioned here as they are known damage mechanisms associated with environments where hydrogen charging occurs. The one possible HSC concern might be hard spots in some vintage pipes. This topic is discussed later in Section 2.2.2.

2.1.1.3 Subcritical Crack Growth

In addition to these damage mechanisms, there is the potential for an additional mechanism not currently identified in B31.8S associated with subcritical crack growth under static loading. It has been shown that the accumulation of hydrogen at the crack tip can reduce the resistance to stable growth under constant load. This is illustrated schematically in Figure 8 showing hydrogen migrating to the near crack tip region.

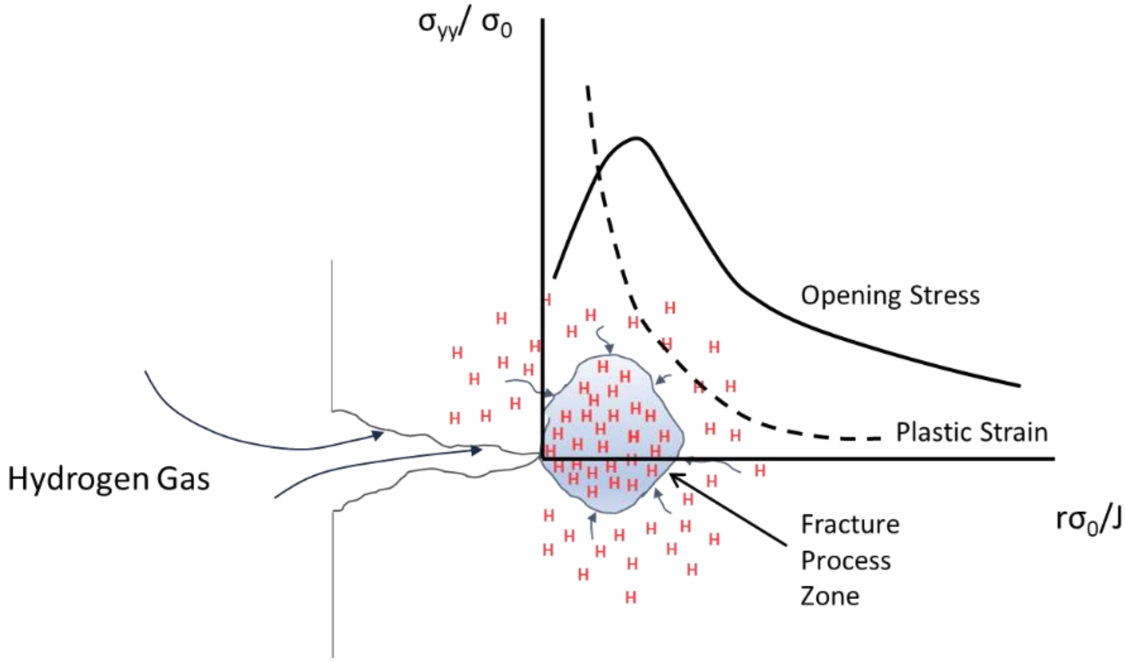


Figure 8 Accumulation of hydrogen at a crack tip

Figure 8 shows the stress and strain fields at the tip of a crack. The high hydrostatic tensile stress just preceding the crack provides a driving force for hydrogen diffusion, and the plastic strain increases trapping sites, increasing solubility. This results in a high concentration of hydrogen within the fracture process zone. Hydrogen interacts with the processes responsible for fracture, reducing the resistance to crack propagation. This possibility is recognized in ASME B31.12, which includes methods for establishing the minimum stress intensity for stable crack growth in hydrogen. This standard provides for a performance-based approach (Option B) where testing in hydrogen gas can be used to qualify materials. It references ASME VIII Div. 3, 2023, paragraph KD-1041, which in turn references ASTM E1681 for determining the minimum stress intensity for stable crack growth. ASTM E1681 is a constant displacement test (decreasing K), where a bolt-loaded specimen is used to apply a predetermined stress intensity on a pre-cracked specimen. The specimen is then subject to a high-purity gaseous hydrogen environment – note that gas purity requirements are provided in KD-1046. The test must be conducted for a minimum of 1,000 hours for ferritic materials. The threshold stress intensity, K_{IH}, is established when the applied stress intensity K_{IAPP} of a test results in less than 0.01 inch (0.25 mm) of crack growth. The value of K_{IH} is then taken to be 50% of K_{IAPP}. It has been shown that the slow-rising-displacement test results in a more conservative estimate of the minimum stress intensity for stable crack growth, illustrated in Figure 9 [17]. However, it is not clear how the acceptance criterion in KD-1040 using a constant displacement compares with a slow-rising-displacement test. ASME B31.12 provides a toughness criterion to resist stable sustained-load (subcritical) crack growth. It specifies a K_{IH} of 50 ksi-√in (55MPa-√m) to resist stable crack growth.

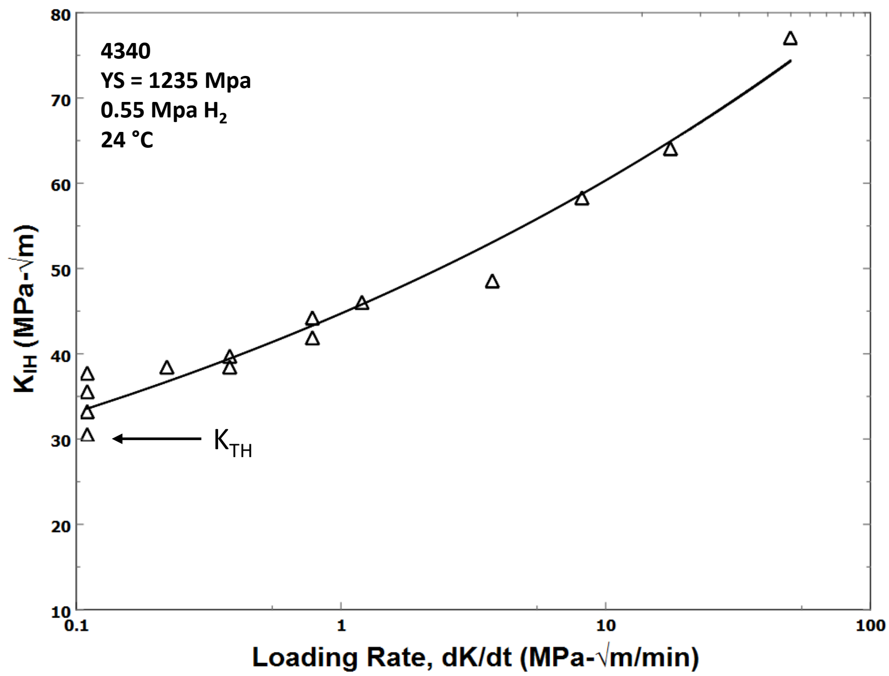


Figure 9 Effect of loading rate on minimum stress intensity (K_{IH}) for hydrogen crack growth [17]

2.1.1.4 Mitigation of Time-Dependent Threats

Time-dependent threats are addressed through periodic inspection, either calendar-based or condition-based. The approach varies according to the nature of the damage and the expected rate of progression. Typically, an ECA is performed to establish the tolerable defect size, such as corrosion thickness or crack dimensions. As discussed, there are some questions regarding the effect of hydrogen on the acceptable thickness loss of corrosion features, but less uncertainty that hydrogen will affect the rate of metal loss. For corrosion, given the general conservatism of most models used to predict burst pressure associated with locally corroded areas, changes to the inspection interval do not appear warranted for corrosion features at this time. Moreover, the capabilities of current ILI tools to size corrosion features are likely sufficient for any changes in tolerable dimensions acceptable to local thinned areas, should that turn out to be the case. However, both from an experimental perspective as well as numerical analysis should be explored further to validate this assumed behavior. Some corrosion-patch pipe tests are in a planned project for a PRCI full-scale testing effort, although details are not known at this time.

For SCC, the introduction of hydrogen into existing NG pipelines may impact integrity management strategies due to the more restrictive acceptance criteria in hydrogen service. While SCC crack fields in NG lines are detected by current ILI tools with acceptable reliability, improvement, and upgrades to ILI tools may be necessary to detect smaller cracks and provide more accurate sizing capability. After identification, excavation for in-the-ditch (ITD) ultrasonic inspection is then performed to refine the dimensions of the anomaly [18]. The tolerable size of the SCC field, however, will be influenced by the presence of hydrogen, as these features are often analyzed by representing them as a single linear flaw. Additionally, if the stress intensity (K) level for the SCC crack exceeds the K_{IH} level, then there may be some hydrogen-induced crack growth component, possibly in addition to the SCC crack growth.

The issue of subcritical crack growth of existing flaws is a new threat caused by hydrogen that needs to be addressed and mitigated when repurposing a pipeline. This threat could be categorized as either a time-dependent or resident threat but is included in this section due to the growth aspect, which takes place under constant load. As mentioned in Section 2.1.1.3 of this report, ASME B31.12 specifies a minimum value of 50 ksi-√in to resist hydrogen-induced crack growth. However, in some existing vintage pipelines, the fracture toughness may be below this threshold, even in the absence of hydrogen. Therefore, the growth of existing cracks is a valid concern. As discussed in Section 2.2.1, the implications for detection and sizing will be addressed in more detail. However, managing the issue of subcritical crack growth using EMAT tools alone may be more challenging in natural gas pipelines with hydrogen added than in liquid pipelines because of lower detection and sizing requirements and the reduced sensitivities of EMAT tools as compared with other ILI tools, such as ultrasonic testing crack detection (UTCD). However, as the critical flaw size is a function of operating pressure (stress), it may be the case that the capabilities of EMAT tools may be sufficient in a specific application. It should be emphasized that an engineering analysis of flaw tolerance, including the potential for subcritical crack growth, should be studied when developing the integrity plan for an NG line converted for transporting hydrogen.

It was also noticed in several probabilistic evaluations for hydrogen pipelines presented at IPC 2024 that only fatigue and reduction in toughness were implemented.

2.2 Resident Threats

Resident threats include root causes associated with original fabrication and construction. Examples include seam cracks, wrinkle bends, defective welds, etc. Hard spots are not specifically mentioned in B31.8S and could be construed to fall under the category of *defective pipe*. In the context of hydrogen transport, the conditions representing the greatest threat to the mechanical integrity of vintage pipelines include:

1) Crack-like flaws in seams and girth welds,
2) Hard spots, and
3) Wrinkle bends and buckles.

The following discussion will describe the potential effects of hydrogen on these forms of damage.

2.2.1 ERW Seam Cracks

Fabrication processes and steel quality are the primary factors affecting seam integrity. Welded pipeline manufacturing involves rolling steel into strips and forming them into a cylinder where the edges are clamped firmly in place. The edges are then joined by the combined action of a clamping force and electrical resistance welding (ERW) to fuse the material at the longitudinal seam. These seams have no filler weld metal, i.e., autogenous welds, which depend on the chemistry of the base metal. Low-frequency electric resistance welding (LF-ERW) was used extensively prior to 1970 and was more prone to defects than modern joining methods. d-c ERW, used by Youngstown Pipe Mill, was more notorious for hook cracks and higher hardness seam welds. Electric flash welds or EFW (i.e., A.O. Smith) can also have hook cracks and high-hardness seam welds. Steelmaking practices for these older steels led to generally lower toughness, and variable chemistry controls sometimes produced hard seams. A review of the general chemistry of line-pipe base metals showed that in the 1950s, there was a tendency to have higher carbon and Mn in the base metal, which led to the higher hardness and lower toughness d-c/LF/ERW and EFW pipes of that time. The failure of an ERW pipeline produced in 1948 is shown in Figure 10. This failure resulted from several factors, including poor toughness, the presence of a hard martensitic microstructure, a hook crack from original construction, and pressure cycling. Hydrogen was also thought to be a contributing factor due to the breakdown of the coating, the presence of wet soil, and

CP potential. As noted earlier, the external hydrogen generation from the wet soil/CP may generate more hydrogen than from a blended hydrogen pipeline.

After 1970, the d-c/LF-ERW and EFW processes were gradually phased out in favor of high-frequency electric resistance welding (HF-ERW) with strip annealing of the seam welds. Overall improvements in manufacturing processes included stricter controls on chemistry like carbon equivalent (CE), reduced tramp element concentration, more consistent post-weld heat treatment, higher hydrotesting pressure in the mill, and improved inspection techniques. During the 1970-1980 timeframe, the practices of pipe mills differed markedly, and the quality of pipe produced led to a significant variability in properties. The manufacturing practices of different mills have been well documented by Kiefner and Clark [19]. Improvements in the manufacturing processes also enhanced the quality of welds, including the use of new non-destructive testing techniques. As a result, it is generally recognized that pipelines constructed prior to 1980, and especially prior to 1970, are more susceptible to fast fracture and potentially brittle initiation toughness.

Figure 10 Brittle fracture of vintage (1948) pipeline along an ERW seam weld

Such pipelines warrant special attention from an integrity standpoint. A good summary of the manufacturing processes, defect types, and history was published by Leis and Nestleroth [20].

Another important factor affecting weld quality was the steel chemistry produced during this era. Older steels were often high in sulfur (>0.02 wt.%), resulting in the formation of MnS inclusions. During the subsequent welding process, the inclusions are deformed due to plastic flow, resulting in curved bands or "fibers" directed towards the inner and outer surfaces. Defects along these inclusion bands are commonly referred to as ‘hook’ cracks. An example of a hook crack that has grown by fatigue and eventually led to fast fracture is shown in Figure 11.

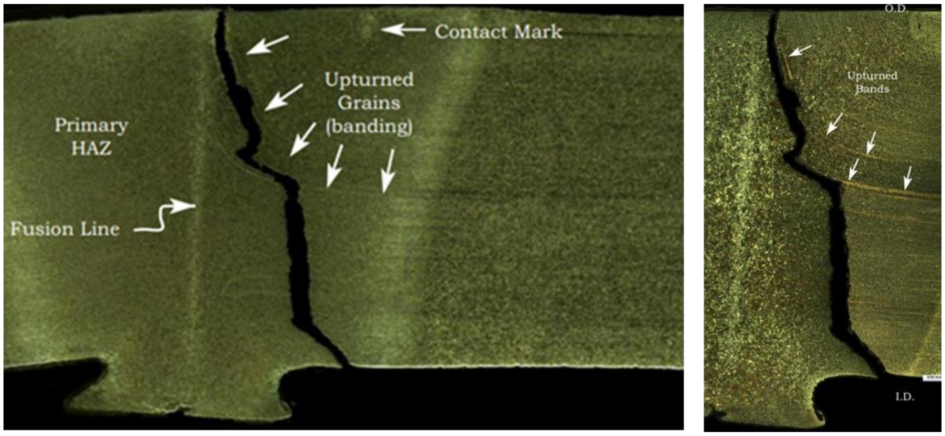


Figure 11 Hook crack in an LF-ERW pipeline

As vintage pipeline steels can have higher carbon and manganese levels, the heat-affected zone (HAZ) associated with the ERW seam can be significantly harder than the surrounding material. In such cases, the seam HAZ will be more sensitive to hydrogen, resulting in poorer toughness. An example of this is shown in Figure 12, which illustrated a high-resolution microhardness map of a seam weld in an ERW pipe.

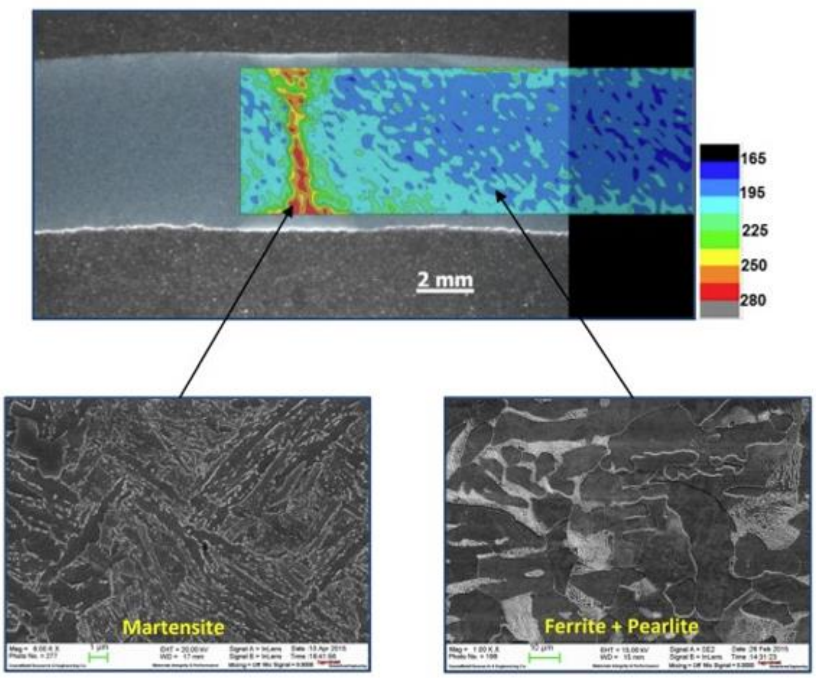


Figure 12 Hardness map of ERW seam weld of vintage pipeline [21]

The pipe segment (a d-c ERW from Youngstown Sheet & Tube, 1948) has a very high hardness region along the seam consisting of untempered martensite. The carbon equivalent was high, so the hard seam was likely a result of a rapid quenching following resistance welding during fabrication. Due to the prevalence of cracks in the seam welds of older pipelines and the degradation in fracture toughness associated with the presence of hydrogen, seam integrity is expected to represent an increased mechanical integrity threat when introducing hydrogen. This is because of the general tendency of toughness loss with increasing steel strength.

A recent study looked at the performance of ultrasonic crack detection (UTCD) tools using a novel “synthetic flaw” approach in which cracks looking like hook cracks in ERW seams were carefully manufactured [22]. This approach has the advantage of measuring performance on real crack geometries as opposed to the use of machined notches typically used by ILI companies. This is illustrated in Figure 13.

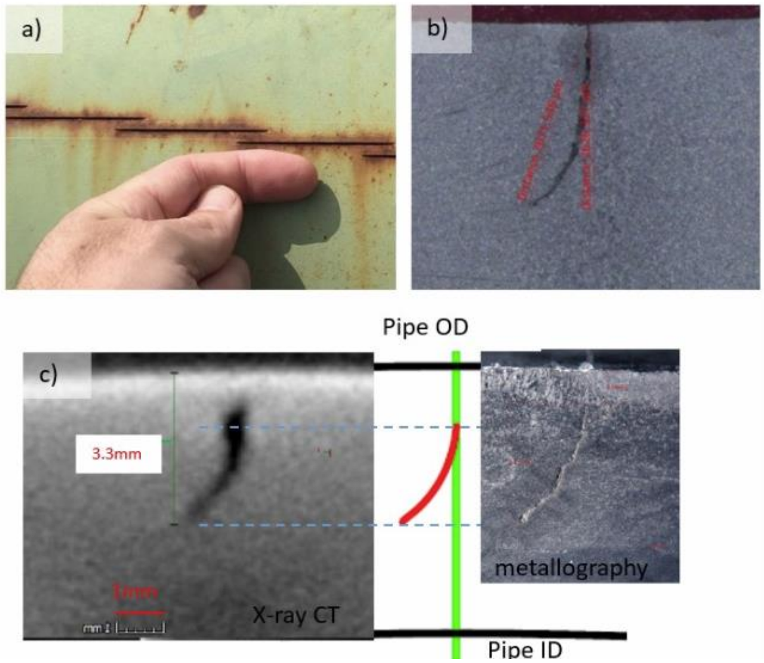


Figure 13 Example of synthetic hook crack used to evaluate ILI performance

In Figure 13, (a) shows the EDM notches cut to various dimensions, commonly used by vendors for evaluating ILI tool performance, (b) is a cross-section of a real hook crack, (c) is an X-ray CT scan of a “synthetic” hook crack, and (d) shows a cross-section of the synthetic hook crack. Using this novel approach, the probability of detection was evaluated. Some results of their study are shown in Figure 14. The data show that a crack with a height of 0.04 inches (1 mm) has a mean probability of detection (POD) of 90%. Note that the blue lines represent the 95% confidence interval on the mean. These results are encouraging.

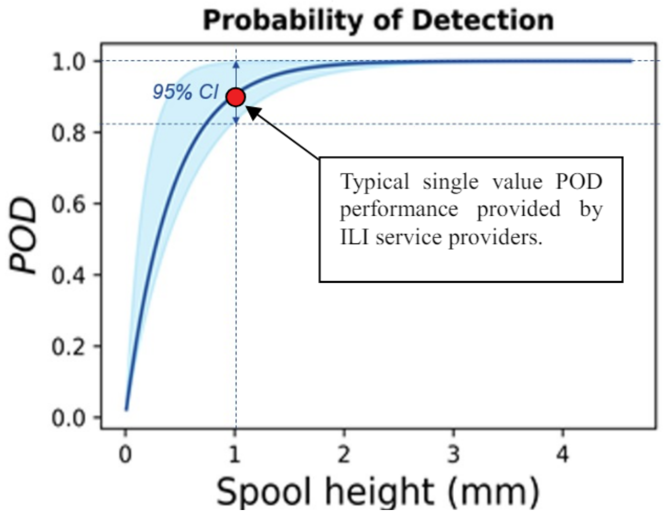


Figure 14 Probability of crack detection of UTCD tool using synthetic hook crack

This is critical information in performing ECA analysis as the tolerable flaw size for pipelines transporting hydrogen will be smaller than for NG service.

To better understand the impact of degradation in fracture toughness on flaw tolerance, consider the following example of an axial OD flaw on a 22-inch diameter pipeline with a 0.312-inch wall thickness. The operating pressure is 750 psi, or about 50% SMYS. The material is assumed to be an X42 vintage pipeline steel. The tolerable crack sizes are plotted as a function of length and depth for various toughness levels in Figure 15[†]. Toughness values from 75 ksi-√in down to 25 ksi-√in are shown along with some typical detection limits that have been reported by ILI vendors. For EMAT, which is a relatively newer technology, fewer studies of crack detection limits have been performed. It is generally acceptable that EMAT crack detection capabilities are less than those of UTCD. One vendor quotes crack detection limits for its EMAT ILI technology as 0.08-inch (2-mm) depth by 1.57-inch (4-mm) length for seam welds.

However, based on the example case shown here, which represents a realistic case study, the use of EMAT tools to manage crack integrity for pipelines transporting hydrogen may be a viable option. Of course, each case will differ, and an analysis of the type performed here will be needed to develop the appropriate actions to manage this threat.

[†] Stress intensity and reference stress solutions from API 579 Part 9.

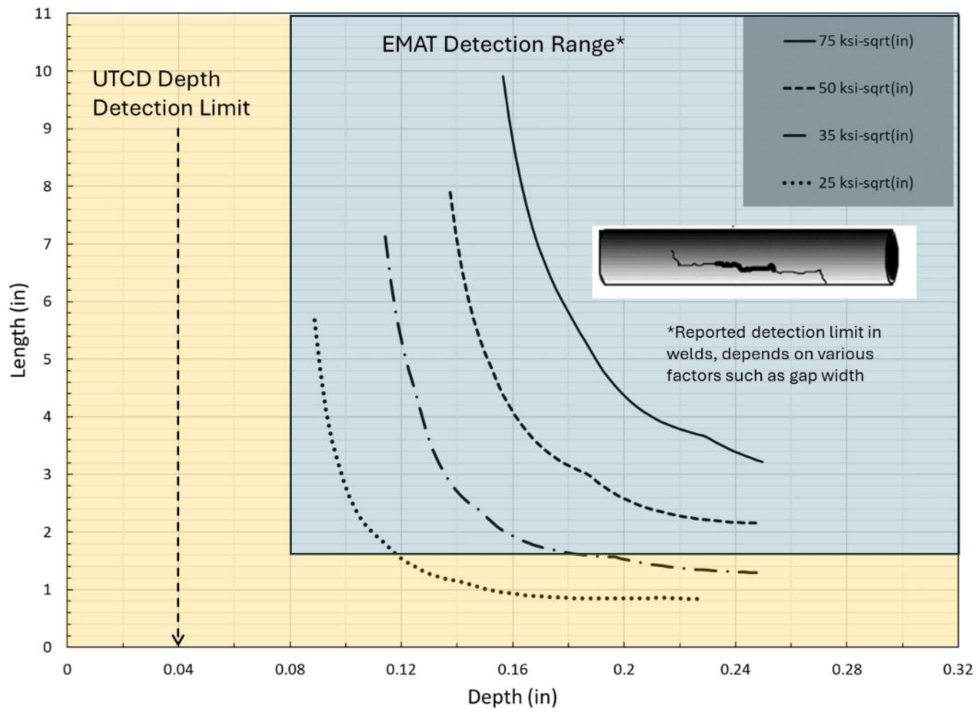


Figure 15 Example of tolerable flaw size for an axial OD surface crack

These results should be put into the context of the toughness of existing vintage pipelines and what could be expected as the toughness when transporting hydrogen.

One large study including over 600 compact tension, C(T), tests of vintage steels produced the distribution of fracture toughness shown in Figure 16, see Reference [21]. The J_{Ic} or J_Q values were converted to K_{Jc} values for the C(T) tests, although some C(T) tests were non-standard sizes, i.e., W/B>2, which elevates the initiation toughness values. The mean value was about 90 ksi-√in. This includes samples from base metal, weld centerline (WCL), and HAZ. If the data from only the WCL is separated out, the distribution produced is shown in Figure 17.

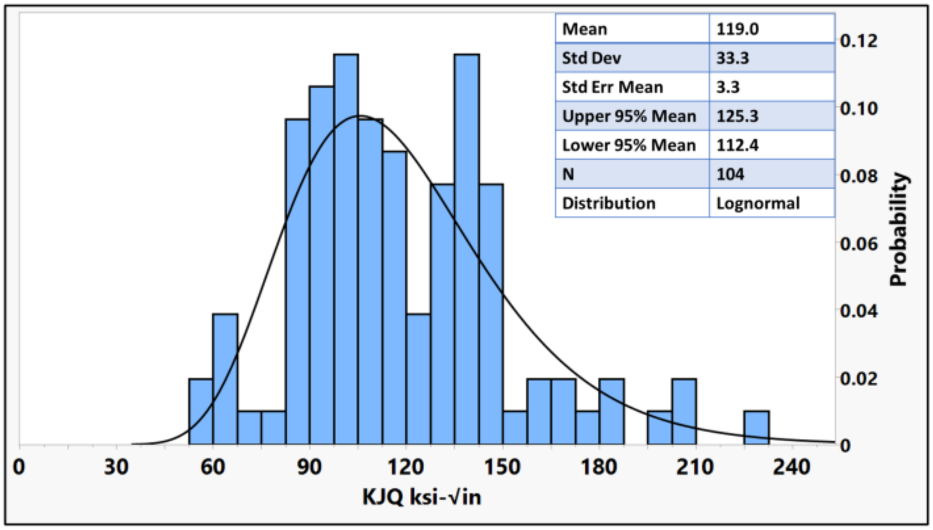


Figure 16 Distribution of fracture toughness of pre-1980 pipeline steel base metals using C(T) and SEN(T) specimens [21]

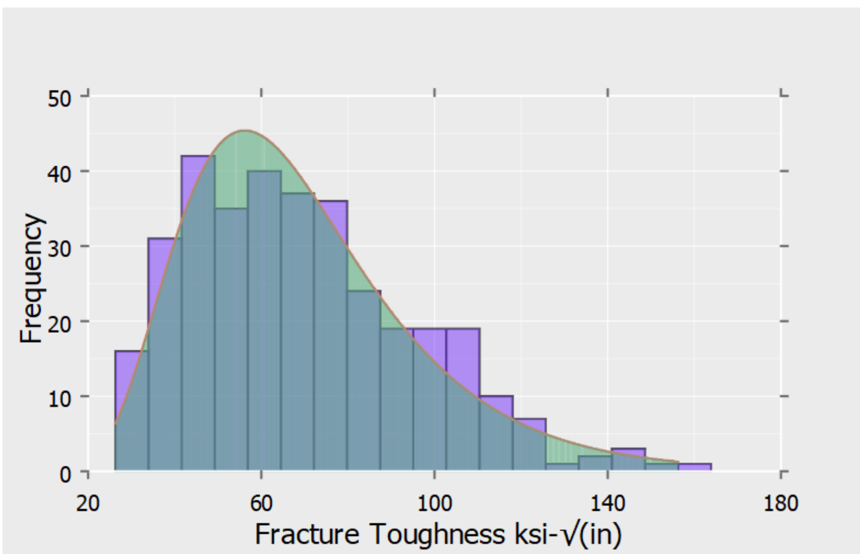


Figure 17 Distribution of fracture toughness of weld centerline using C(T) specimen data [21]

The mean fracture toughness is about 70 ksi-√in. If the effects of hydrogen are now included, then based on fracture toughness tests on vintage pipelines in hydrogen performed by Sandia National Laboratory (using C(T) specimens again, some with non-standard geometries) at low pressure 34 bar (493 psi), the drop in toughness is roughly 30%, and at high pressure 210 bar (3,045 psi) closer to 50% [23]. As discussed later, those air tests are done at a standard ASTM E1820 loading rate, which is considerably faster than the autoclave hydrogen testing rates. Hence, there is some primary creep that occurs due to occurring with hydrogen damage. Even in air, there can be a toughness degradation from the slower loading that causes primary creep [8], so the toughness loss from just hydrogen might be lower than implied in Figure 18.

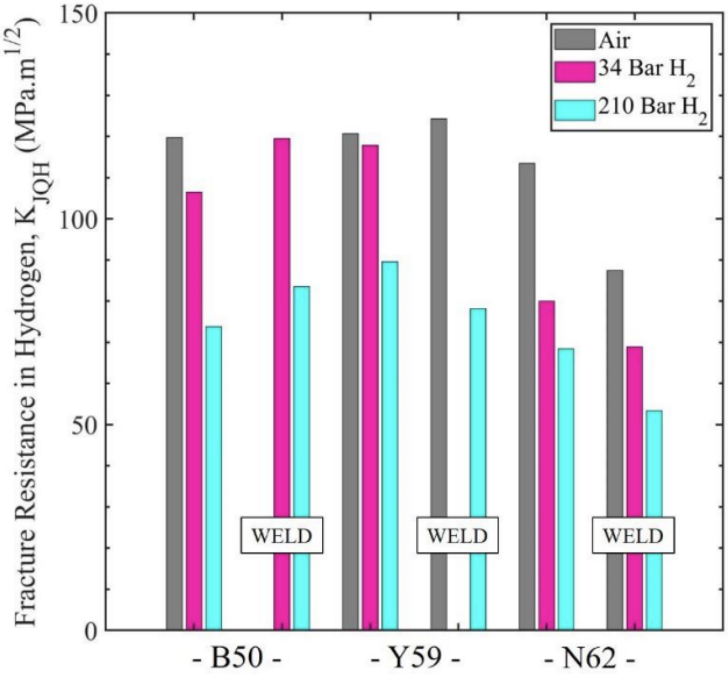


Figure 18 Fracture data of vintage pipeline steels in hydrogen [23]

The Figure 18 data has an average fracture toughness value in the range of 65 MPa-√m (58 ksi-√in). Consulting Figure 14 and Figure 15, and the example data in Figure 18, this would still indicate a detectable flaw with a POD of 90%. It is interesting to note that the average initiation toughness value from Figure 18 is close to the B31.12 stress intensity threshold of 55 MPa-√m for the onset of subcritical crack growth (K_{IH}).

Earlier data by Holbrook and Cialone [24] determined the initiation toughness (J_{Ic}) of a vintage X52 ERW seam weld in hydrogen to be about 49 MPa-√m, which is lower than the Sandia data in Figure 18. This was the same toughness value for a simulated hard spot material. They did some sustained loading tests, and both the ERW seam weld and the simulated hard spot had hydrogen crack growth in 60% hydrogen gas and 40% methane. However, they did not give the applied K values in those sustained loading tests.

Very recent data from SNL focused on vintage pipeline steel FCGR and toughness [25]. Their testing procedures are designed to develop FCGR as well as fracture toughness from a single specimen. The study looks at the effects of hydrogen partial pressure and compares a vintage 1962 pipeline steel to a modern X70 steel. They report that the FCGR for both steels is quite close. This is not inconsistent with past studies, where microstructures of steels often have a secondary effect on fatigue crack growth rates. Regarding fracture toughness, their results are quite interesting. When testing in air, the newer X70 steel exhibits substantially higher toughness than the vintage X52, which is not unusual. Subject to a low partial pressure hydrogen of 1 bar (14.5 psi), a 20% drop in toughness for the vintage X52 is reported. At high hydrogen partial pressure of 34.5 bar (500 psi) and 207 bar (3,002 psi), only a further drop in toughness was found, but only to a modest degree. For the modern X70 steel, a drop in toughness at 34.5 bar (500 psi) is substantial, on the order of 60%, and remains about the same at 207 bar (3,002 psi). This study also reports the J-R curve, which shows the tearing resistance (slope of the J-R curve) with increased displacement. This is often reported as a tearing modulus, where the slope is normalized by the elastic modulus and yield stress: $T_R = \frac{E}{\sigma_o}\frac{dJ}{da}$ to enable a more realistic comparison between steels. The data here comparing vintage to modern pipeline steels shows a shallower J-R curve for the vintage steel compared with the modern steel.

- There were tests done in nitrogen. Frequently, some labs do those tests at standard ASTM loading rates, which are much faster than hydrogen autoclave loading. The results in efforts at Emc^2 on surface-cracked pipes with an air environment and step-hold testing, as well as relatively quick monotonic pressurization to burst, are shown in Figure 19. The fracture initiation toughness (direct from CMOD values) was about 33% larger in the quicker monotonic burst test than under the slow step-hold loading. This is due to primary creep that occurs even at room temperature in line-pipe steels. So, it is desired to know if the primary creep effect is accounted for in the nitrogen testing.
- There are also a number of questions about specimen geometry effects (non-standard W/B specimens in cases, as well as a/W>0.5) and how that affects relative comparisons to tests that may have a standard C(T) specimen size.
- Test data reduction procedures are also another point of uncertainty that needs clarification.

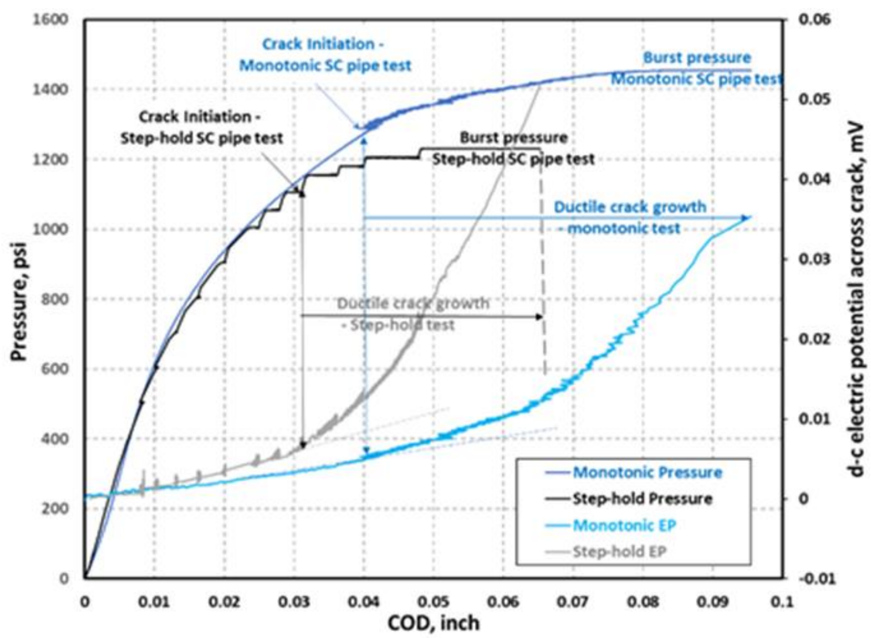


Figure 19 Comparison of axial surface-cracked pipe with identical flaws with air environment in monotonic (relatively quick) pressurization to burst and step-hold testing allowing for primary creep to become stabilized

2.2.1.1 Hardness Effects on Fracture Toughness

Another very recent study looks at the effect of the hardness of vintage and modern pipelines in hydrogen [25]. This dataset provides some extremely useful insight into the likely behavior of hard spots, discussed in Section 2.2.2. Here, the fracture toughness of vintage pipeline steel was measured in hydrogen (210 bar, 3,046 psi) in the as-received state, as well as heat treated to produce a hard hardness. The results from this research are extremely interesting. The as-received vintage steels (hardness < 200 $HV_{0.5}$), which ranged from X42 to X60, showed C(T) specimen toughness with an average of about 70 MPa-√m (63 ksi-√in), with a wide amount of scatter. This result is consistent with the data shown in Figure 16 and Figure 17.

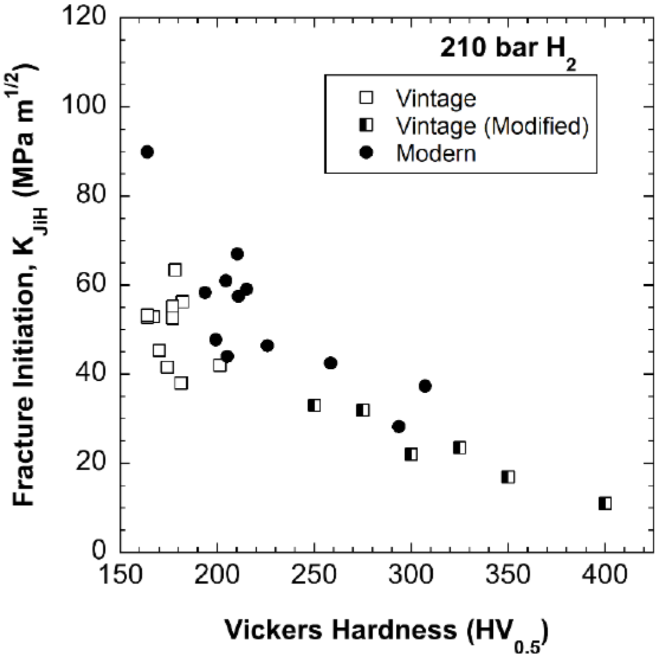


Figure 20 Fracture initiation (K_{JiH}) as a function of Vickers hardness ($HV_{0.5}$) for pipeline steels from modern era, vintage era, and modified vintage to generate higher hardness, from Reference [25]

When heat treated to produce hardness ranging from 250 $HV_{0.5}$ to 400 $HV_{0.5}$, toughness was in the range of 30 MPa-√m. This work also looked at initiation toughness (J_i), as measured using potential drop methods. When done carefully, this value is a more accurate determination of the true value of J at the start of crack extension and is usually slightly lower than the J_{Ic} or J_Q value reported using the definition in ASTM E1820. Here, the initiation toughness for the high-hardness vintage steel was as low as 10 MPa-√m. The authors make an interesting observation here that the initiation toughness between modern and vintage steels is less than the J_{Ic} as reported following the ASTM E1820 criteria. They note that the primary difference is in the tearing resistance, i.e., the slope of the J-R curve. These results are lower than the Battelle data, who performed some limited tests on X42 steel heat-treated to produce high hardness as part of a program looking at pipeline transport of syngas containing hydrogen, summarized in Table 5 [26]. The lowest toughness value of 10 MPa-√m is well below even the ASME Master Curve for steels on the lower shelf and, if validated, would have an effect on the ILI detectability, as illustrated in Figure 15.

Table 5 C(T) specimen toughness data on simulated hard spots [26]

Steel	J_{Ic} Methane (psi-in)	J_{Ic} Hydrogen Addition (psi-in)	K_{Jc} Hydrogen Addition (MPa√m)
X70	1420	320	102.8
X70 replicate	1170	185	78.2
X70 HAZ	1800	280	96.2
X42HT (Rc=38; HV=350)	130	74	49.4
X52 ERW	230	75	49.8

The steel identified as X42HT is a vintage X42 pipeline heat-treated to produce a high hardness microstructure of untempered martensite (HBN~350). This steel showed a drop in toughness of about 40% in the presence of a methane-hydrogen environment. Tearing resistance was also measured and showed an even greater drop. Interestingly, with this higher hardness, at room temperature, there was no cleavage fracture but rather ductile tearing. Higher hardness hard spots in service failure have shown cleavage fracture, so there may be a transition temperature shift with the higher hardness hard-spot materials.

2.2.1.2 Constraint Effects on Fracture Toughness

The toughness data discussed here were all taken from C(T) specimens. Due to constraint arguments, this specimen geometry is known to generally produce conservative toughness values if a preferred specimen geometry is used for pipelines with axial cracks – which is exactly the objective of a standard. Single-edge-notch tension SEN(T) specimens, which is a specimen geometry loaded predominantly in tension, however, more closely match the constraint conditions of a surface flaw in a pipeline. An axial surface crack in a thin-walled pipeline with a large D/t ratio has a crack-driving force primarily from the hoop stress. It has been demonstrated both experimentally as well through numerous numerical analyses that the SEN(T) geometry provides a more accurate fracture toughness when applied to surface cracks in pipelines [27].

At that time, the effect of W/B on the C(T) specimen values was not recognized. Figure 21 shows a recently developed correction factor based on experimental results [14]. For the C(T) tests reported in [21], the average W/B was 5.3. In going to Figure 21, this means that a standard ASTM W/B=2 specimen for these materials would be a factor of 1.75 lower if the constraint effects are the same in hydrogen, as seen in air testing.

Based on the study referred to previously [28], special pin-loaded SEN(T) specimens were designed to closely match the constraint level of pipelines, although the a/W values varied from 0.26 to 0.58. The overall dataset is summarized in Table 6.

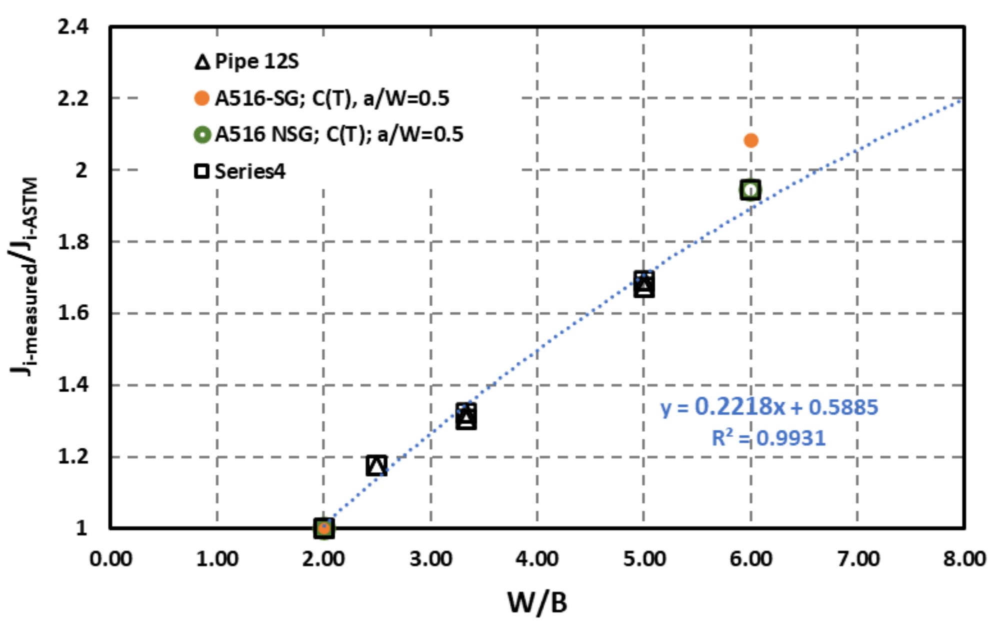


Figure 21 Effect of C(T) and SEN(B) specimen W/B values on the measured J_i values compared to ASTM standard W/B=2 specimens

Table 6 Fracture toughness database of vintage steels [21]

Specimen Geometry	*Notch Location*	*Orientation*	*Samples (N)*	*Mean ksi-√in (MPa-√m)*	*Standard Deviation ksi-√in (MPa-√m)*
C(T)	WCL	Axial	321	64.1 (70.5)	21.6 (23.8)
	HAZ	Axial	66	91.2 (100.32	18.7 (20.6)
	BM	Axial	80	108.4 (119.2)	22.4 (24.6)
SEN(T)	WCL	Radial	61	99.7 (109.7)	29.6 (32.6)
	HAZ	Radial	32	116.5 (128.2)	33.0 (36.3)
	BM	Radial	13	180.1 (198.1)	24.5 (27.0)
SC(T) Modern Steels	WCL	Axial	27	249.5 (274.5)	83.3 (91.6)
	BM	Axial		295.5 (325.1)	39.5 (43.5)
SEN(B)	WCL	Axial	9	122.5 (134.6)	31.2 (34.3)
	BM	Axial	11	51.3 (53.64)	5.4 (5.9)
		TOTAL	620		

Other relevant work has also shown that the SEN(T) initiation toughness (and in surface-cracked pipes) is a function of a/W, see References [29] and [30]. Additionally, it has been shown that the standard ASTM C(T) toughness value can be related to the SEN(T) values as per Figure 22 [14]. Note that the initiation toughness from the standard ASTM C(T) specimen (a/W=0.5; W/B=2) corresponds to the initiation toughness for a SEN(T) or surface crack with a/W (or a/t) = 0.7. (Assuming the thickness of the C(T) specimen is the same as the width of the SEN(T) specimen.) The constraint factors can be determined for different a/t values from this figure.

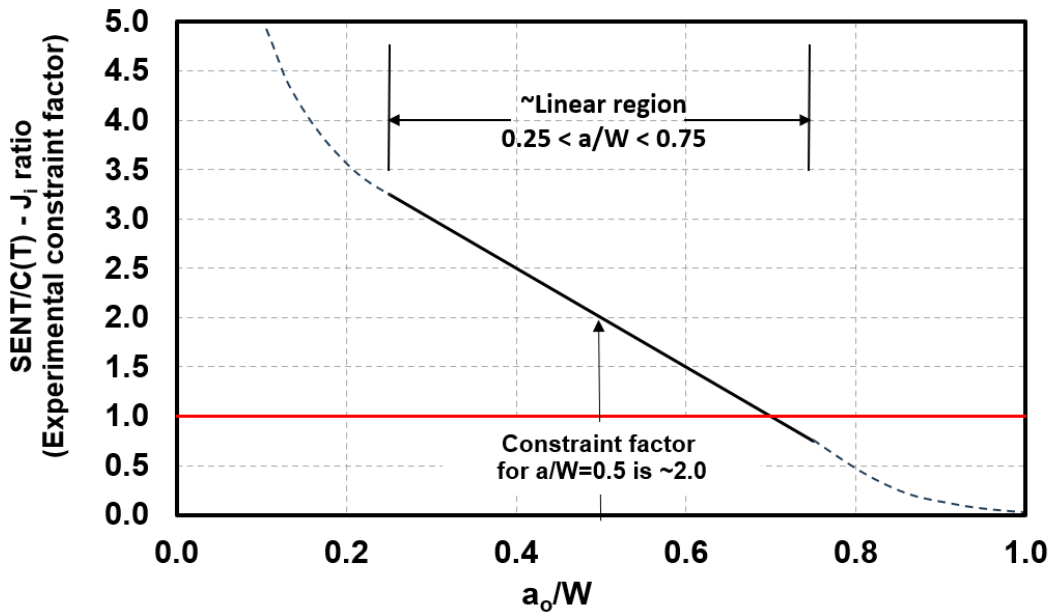


Figure 22 Comparison of J values at crack initiation (J_i) of SEN(T) specimens with various a/t values normalized by the preferred/standard C(T) specimen J_i value

There were both SEN(T) and C(T) tests in air in the database from Reference [21]. The SEN(T) specimens were not on the full dataset of pipes, and the a/W values varied from 0.257 to 0.582. The C(T) specimen database was much larger, but as noted earlier the W/B values were an average of 5.3.

The SEN(T) data show a mean toughness of 99 ksi-√in for the weld centerline (WCL), while for the C(T) geometry, the mean WCL toughness is 64 ksi-√in, but with the W/B correction noted above, the average values for standards ASTM C(T) specimens would be about 48 ksi-√in. Since the datasets are not exactly the same, it can be pointed out in this data that the SEN(T) toughness with shallower flaws is considerably greater than the standard C(T) specimen J_i value. The trend is correct, but this exercise points out the need for careful constraint corrections in both C(T) and SEN(T) results in air. The constraint corrections are probably more complex in a hydrogen environment since higher crack-tip plasticity (higher toughness values) will have higher hydrogen concentrations.

2.2.1.3 Influence of Hydrogen on Ductile to Brittle Transition Temperature

Another fracture-related question deals with the effect of hydrogen on the ductile-to-brittle transition temperature. Cleavage fracture is inherently a statistical phenomenon, where failure is triggered by inclusions residing in some unit volume subject to critical stress. The probability of cleavage increases as the temperature is lowered into the transition region. A typical base metal Charpy transition curve for vintage pipeline steel is shown in Figure 23.

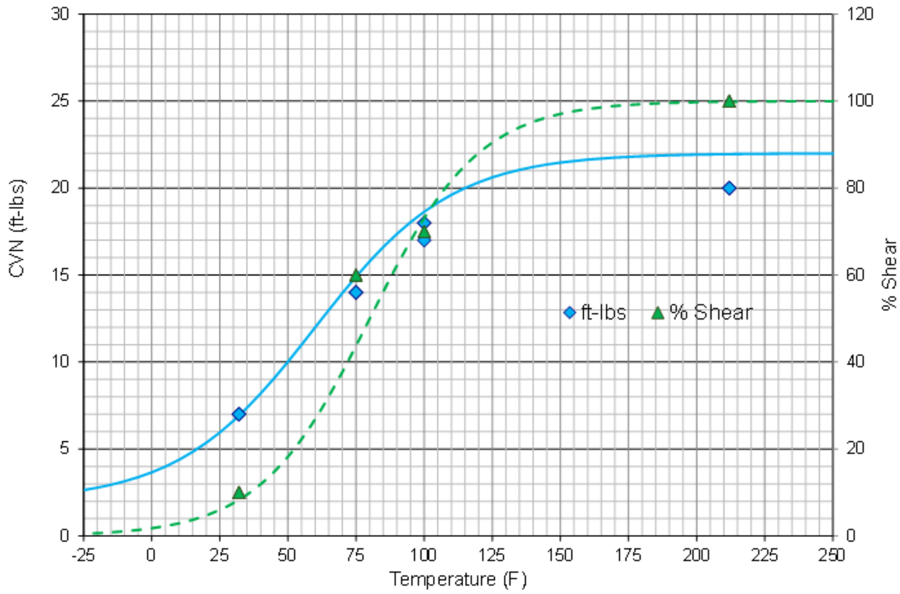


Figure 23 Charpy base-metal transition curve for vintage LF-ERW pipeline steel [21]

At operating temperatures in the range of many pipelines (50°F to 75°F), the Charpy impact energy of this steel is clearly within the transition region. It should be recalled that unlike fracture toughness tests of the type shown in Figure 16 and Figure 17, Charpy impact tests are conducted at a very high strain rate on a notched (not pre-cracked) bar. This high strain rate tends to obscure the effects of hydrogen, generally resulting in no apparent shift in the transition curve in the presence of hydrogen. (Frequently, Charpy specimens are put in a hydrogen pressure container to charge them; however, there is no loading on the specimen to attract the higher hydrogen concentration to the notch region.) This is often attributed to the inability of hydrogen to diffuse to the region of high stress and participate in the fast fracture process, unlike quasi-static fracture toughness tests. A compounding factor deals with the fact that due to the nature of the Charpy test, it must be conducted ex-situ, meaning they are pre-charged with hydrogen (but not under load), then removed from the environment, and impact tested in air. Due to the high diffusivity of hydrogen in steel, it is likely that the hydrogen content has diminished largely before the test is performed for a specimen requiring cooling. The same can be said regarding all ex-situ fracture testing. An example of tests conducted on an X65 pipeline steel with and without hydrogen is shown in Figure 24. There is clearly little difference between the curves and certainly within the data scatter. J-R tests on the same steel, however, performed under quasi-static (very slow) loading show a distinct reduction in the resistance curve[‡]. This behavior is shown in Figure 25.

So, one favorable conclusion for the impact testing results is that the dynamic fracture toughness of the steel is probably not changed for a hydrogen pipeline since the hydrogen does not have time to diffuse to the crack tip when the crack is running at 300 to 2,000 feet per second.

Another interesting aspect is that all the autoclave J-R curve testing is done in displacement control to allow for the hydrogen to get transported to the crack tip. For an axial surface crack in a pipe, the loading is load-controlled, so as approaching the unstable crack condition, the crack growth rate is increasing, which might increase the material tearing resistance. This aspect would be seen in pipe tests, but not the

[‡] J-R curve refers to the resistance curve developed during a fracture toughness test when stable crack growth is observed prior to unstable fracture. Such tests are run using standards such as ASTM E1820.

current autoclave testing procedures. However, it is possible to run an autoclave test at slow loading rates in load-control to see how the tearing resistance changes as the crack growth accelerates to the instability condition (like a surface crack in a pressurized pipe). To our knowledge, this has not been done yet.

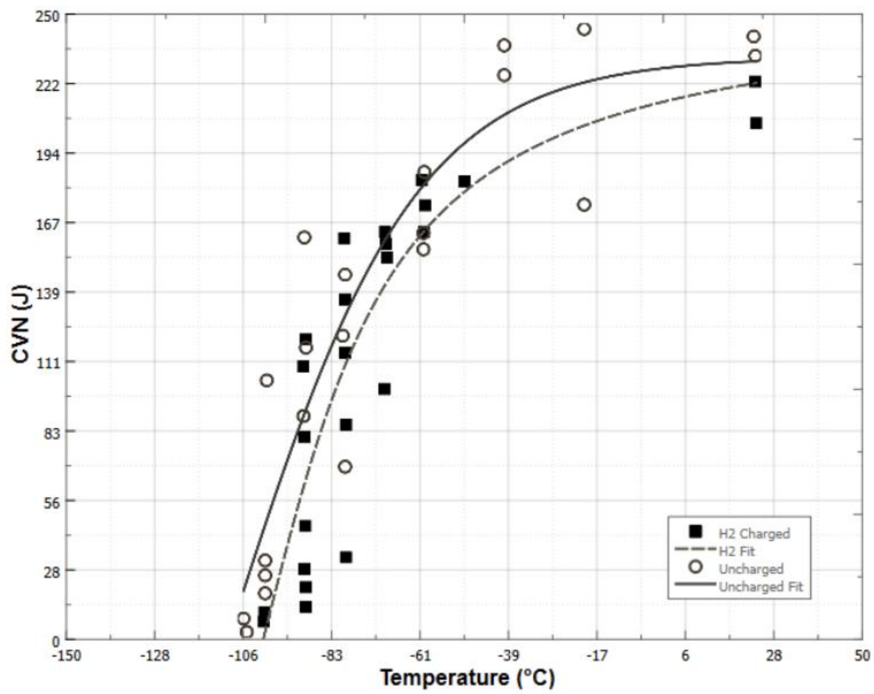


Figure 24 Charpy transition curves for an X65 steel with and without pre-charging

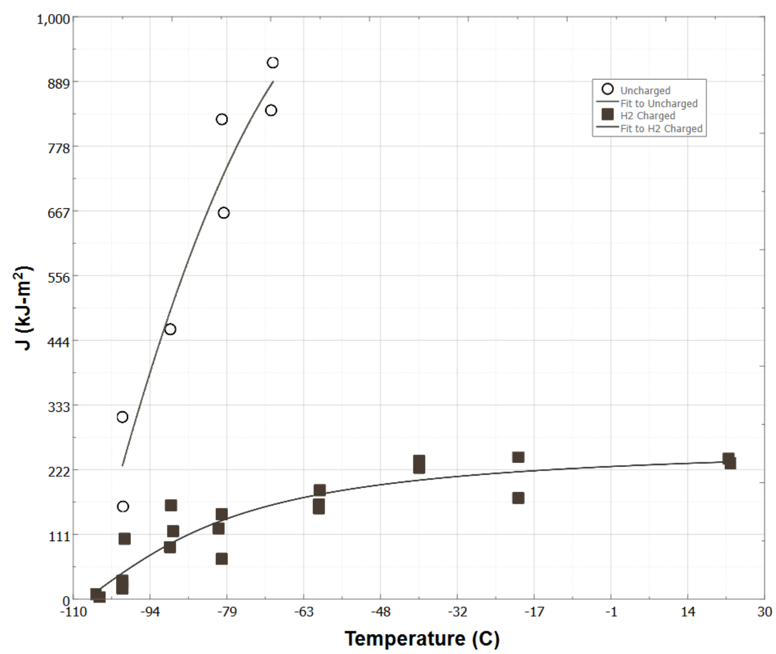


Figure 25 Fracture toughness as a function of temperature

The data in Figure 25 clearly suggest a relationship between test temperature and hydrogen charging. Another set of tests, shown in Figure 26 performed by Zafra et al., show the effects of displacement rate on the J-R curve [31].

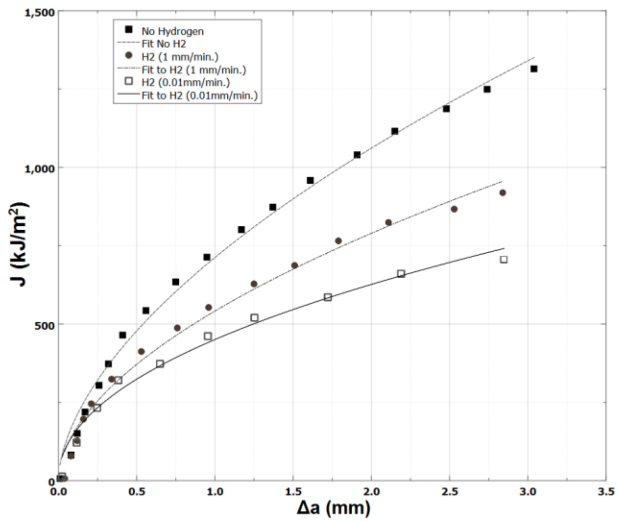


Figure 26 Effect of displacement rate on J-R curve [31]

This raises an interesting point regarding loading rate and the determination of fracture toughness in a hydrogen environment. It is well known that a slow loading rate is required to fully capture the effect of hydrogen on fracture due to the time required for hydrogen to reach the crack-tip region, where the fracture process (either ductile or brittle) takes place. As illustrated in Figure 9 for the onset of subcritical crack growth. Currently, there are no standards for testing steels in hydrogen outlining important testing procedures such as loading rate, constraint effects, data reduction procedures, and many other variables that affect the result. It is common practice to compare fracture toughness tests performed in hydrogen at a very slow loading rate to tests conducted in air at a much faster rate consistent with standards such as ASTM E1820. In air at the slower rate, steel will experience primary creep that reduces its toughness, while the hydrogen test has hydrogen environmental effects and primary creep effects together. Ideally, an air test would be done at the same loading rate as the hydrogen test to see just the hydrogen effect. The ASTM rate testing in air is done for practical reasons to minimize the time required for conducting tests. While this may well be a valid approach for relating toughness data to Charpy testing, it is an example of the need for standardization in testing procedures for fracture toughness in hydrogen to get only the hydrogen degradation aspects. Other examples include test environment (e.g., oxygen content), specimen pre-conditioning, surface finish, use of preload, fatigue precracking before or while in hydrogen, etc. As noted previously, specimen geometry and dimensions can affect fracture toughness in air. Due to the thickness of typical line-pipe, specimens with a thickness on the order of 0.25” or less (“B” dimension in C(T) testing) are not uncommon. Width on the order of about 1” generally permits machining C(T) specimens without flattening for larger diameter pipe. The database shown in Table 6 consists mainly of pipe ranging from 0.2” to 0.312” and planform width of 1”, giving W/B ratios for many of the thinner specimens of about 5[§]. However, based on other work done recently looking at validity criteria for small (mini-CT) specimens, it is reasonable to assume that the data generated within this thickness range provide reasonable J values [28] if tested with the standard W/B=2 and a/W=0.5 geometry.

§ ASTM E1820 recommends W/B between 2-4 but permits other sizes if other validity criteria are met.

2.2.1.4 Fatigue Crack Growth

Another aspect of crack integrity deals with the potential for growth due to pressure cycling. In many cases, the severity of fatigue loading for current transmission gas pipelines is far less aggressive compared with liquid lines and, consequently, has been regarded as a lower concern. There may be some special new hydrogen pipelines where large pressure cycles may occur, i.e., a green hydrogen pipeline may make hydrogen by solar cells and electrolysis, but in the evening, the hydrogen is not made, and the hydrogen in the pipeline is depleted resulting in daily larger pressure cycles; similarly, if hydrogen is made at a nuclear power plant when the normal electric demand is down, then the pressure in the hydrogen pipeline will cycle daily. Studies have consistently shown that fatigue crack growth rates (FCGR) are accelerated in hydrogen, by as much as an order of magnitude, potentially making crack growth under low amplitude cycles a possibility. An early study on X42 performed by Battelle is shown in Figure 27 [24].

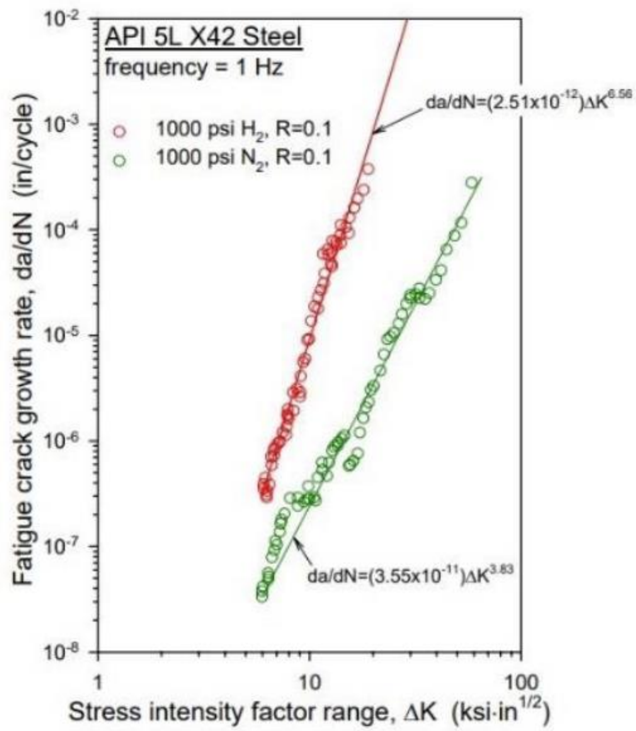


Figure 27 Fatigue crack growth rate of X42 in hydrogen from [24]

ASME B31.12 incorporates models specific for pipelines in hydrogen service in a Code Case developed on the Sandia recent data.

Data reported by DVWG (a recognized standardization body for the gas and water industry) as part of a German study to evaluate repurposing existing pipelines compared an older 1961 vintage ERW X42 base metal with HAZ and found the FCGR to be in very close agreement with the B31.12 curve as shown in Figure 28 [24].

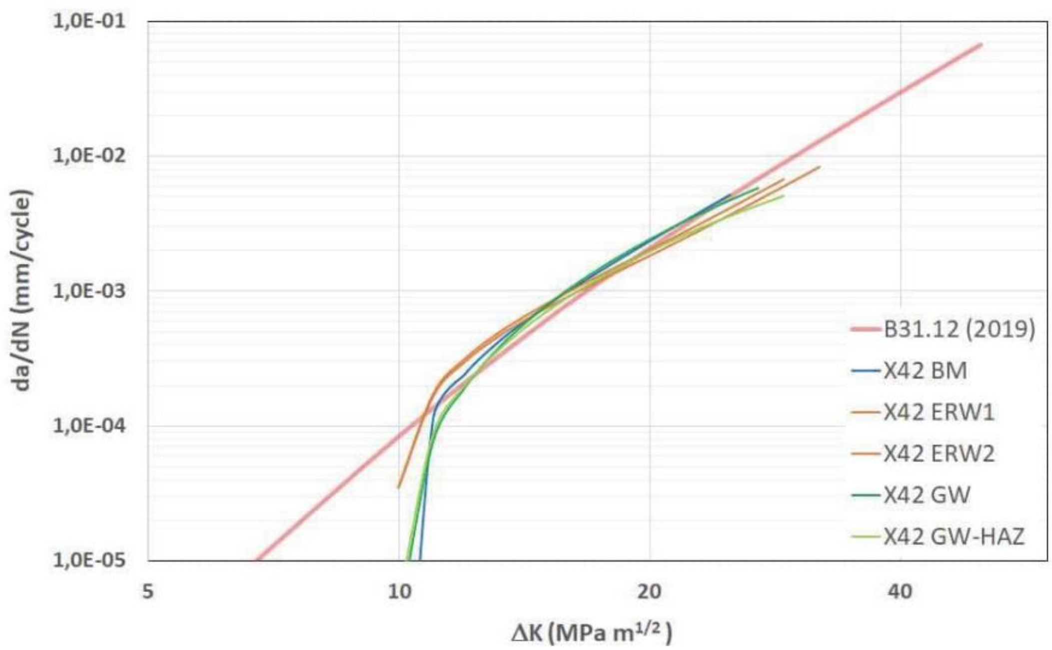


Figure 28 DVWG study on FCGR of European vintage pipeline steel

Sandia National Laboratory has done extensive testing on the effects of hydrogen on FCGR for line pipe, looking at both modern and vintage steels. In the study reported in Reference [23], the FCGR of a vintage X52 steel was compared with that of a modern X70 steel at various hydrogen partial pressures (or fugacity). The tests show that the vintage steel behaves consistently with the FCGR design curves in ASME B31 Code Case 220. Here, they make an important distinction, pointing out that the FCGR depends on fugacity (not partial pressure).

2.2.1.5 Effect of Hydrogen Pressure on Fracture Toughness

An important and frequently asked question regards the minimum amount of hydrogen required to have a significant impact on mechanical integrity. This is a complicated question and inevitably relies on the specifics of each pipeline. Factors such as MAOP, fatigue demand, propensity for hard spots or hard seams, presence of seam cracks, dents, gouges, corrosion features, etc., will all have a bearing on the safe amount of hydrogen that can be blended into the line. Closely related to this question is the ability to successfully integrate operator actions into the IMP to maintain an acceptable risk. Prior to blending hydrogen, a number of steps are clearly required, some of which are outlined in a later section dealing with integrity management plans.

To explore the question of hydrogen blending on pipeline integrity, it is necessary to look at some of the available data relating material property changes to hydrogen pressure (or partial pressure or fugacity). In one study, the effect of hydrogen pressure on the toughness of an X42 steel was evaluated and indicated a reduction from about 150 MPa-√m to about 50 MPa-√m over a pressure range from 0 MPa to 15 MPa, shown in Figure 29 [32].

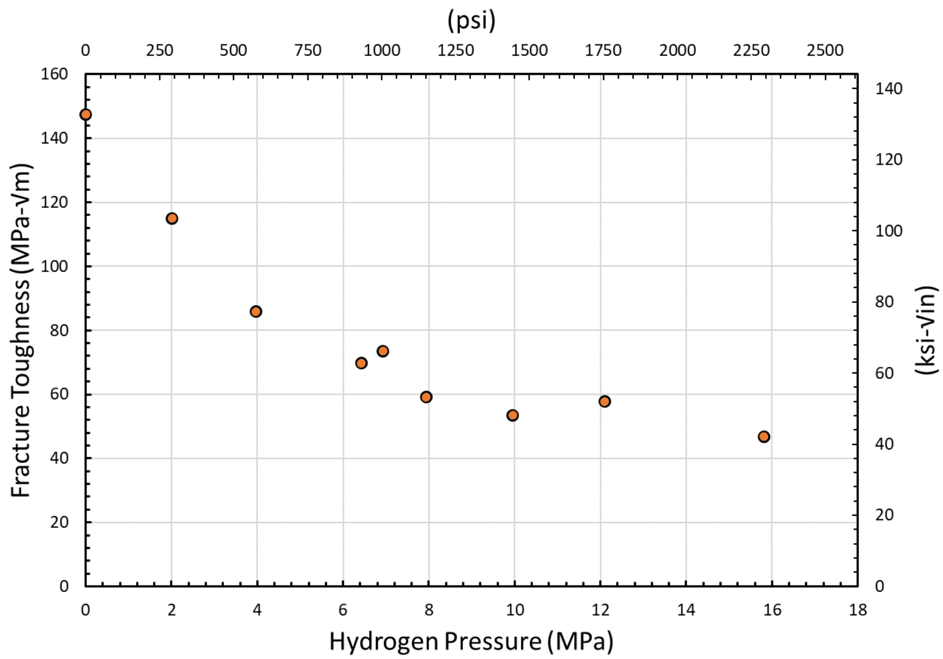


Figure 29 Fracture toughness of X42 as a function of hydrogen pressure [32]

These experiments suggest a rapid decrease in fracture initiation toughness from C(T) specimens with hydrogen pressure. This question will be revisited in further sections dealing with other forms of damage.

Such data is collected using machined test specimens in an autoclave filled with hydrogen gas so the hydrogen can enter the steel from all directions. The cleaner (fresh machined) steel allows quicker hydrogen entry for absorption and transport to the crack from all surfaces. In a pipeline there will be an ID corrosion layer that will slow the hydrogen adsorption into the steel. These scales are often porous and loosely adherent, and therefore, it must be assumed that they are not an effective barrier to hydrogen ingress for the life of the pipeline. At the 2024 IPC conference, two papers presented results of ID and OD surface cracks in pipes with internal hydrogen gas. The paper by Sandia [33] on fatigue crack growth of ID and OD surface cracks in small-diameter A53 pipe gave evidence that the internal hydrogen affects both the ID and OD surface crack fatigue growth behavior. The other paper by Cosham [34] showed results on larger diameter, very low Charpy energy base metal pipe tests with internal hydrogen and long-time hydrogen pressurization prior to testing. He also showed ID versus OD surface crack test data, but it was for burst pressure no fatigue crack growth. The burst test data showed there was no effect of hydrogen on the OD flaw, but there was an effect on the ID flaw. Hence, the question of ID surface condition and the effect on external flaws remains unclear.

An aspect perhaps not yet considered from the autoclave testing is that in a pipeline, there may be regions with plastic straining (dents, gouges, wrinkle bends, crack-tip strains from a prior hydrotest, weld regions, etc.) and residual stresses (seam and field welds, all the plastic strained conditions, and hard spots). Those pipeline plastic strain and residual stress conditions do not exist in the autoclave test specimens. However, the plastic strain and residual stresses may give rise to higher hydrogen concentrations. So, for these more pragmatic pipeline conditions, some care is warranted to compare the local hydrogen concentration relative to the local hydrogen concentration in test specimens. Such results may suggest that an effectively higher hydrogen partial pressure from the autoclave testing is representative of certain pipeline hydrogen partial pressures (or fugacity). Determining the magnification of the hydrogen concentrations from these factors is a doable task but quite complicated [11].

2.2.2 Hard Spots

While not specifically identified as a root cause in B31.8S, hard spots represent a damage mechanism that can be grouped with other manufacturing-related defects, which are termed *resident threats*. Due to the increased sensitivity to hydrogen embrittlement, hard spots are identified in this report as one of the primary threats likely to increase due to the addition of gaseous hydrogen without the wet soil, CP, and loss of coating conditions that are known to affect NG pipe hard-spot failures.

Hard spots are caused by inadvertent quenching of the steel while in the austenitizing region during plate manufacturing (prior to pipe forming). This inadvertent quenching produces untempered martensite which has a very high hardness (tensile strength) with high sensitivity to hydrogen embrittlement. For some older vintage pipelines, poor chemistry control led to heats with a high carbon equivalent (especially from about 1948 to 1960) that promoted martensite formation. A known issue exists with flash-welded pipe produced by A.O. Smith [20] which accounted for about 66% of the current incidents, while there are much fewer cases for Bethlehem, National Tube, Republic Steel, Youngstown Sheet & Tube, Kaiser, Consolidated Western, as well as a few other pipes made in the 1950s when the average carbon and Mn were higher [35]. Hard-spot failures have led to serious incidents, including a recent one in 2019 in Danville, Kentucky [36]. This incident was attributed to a hard spot of approximately 6” by 3” in combination with hydrogen charging from coating loss, wet soil, and CP. Hardness values measured were reported to be between 362 and 381 Brinell. The pipe was made by A.O. Smith in 1957.

There exists a correlation between tensile strength and the degree to which mechanical properties (primarily fracture strain, toughness, and FCGR) are affected by hydrogen. This has been recognized for many years. The data in Figure 30 illustrates this relationship [37]. Here the reduction in area for notched bars of steel with varying ultimate tensile strengths (UTS). The data show the decrease in RA is more severe depending on the UTS.

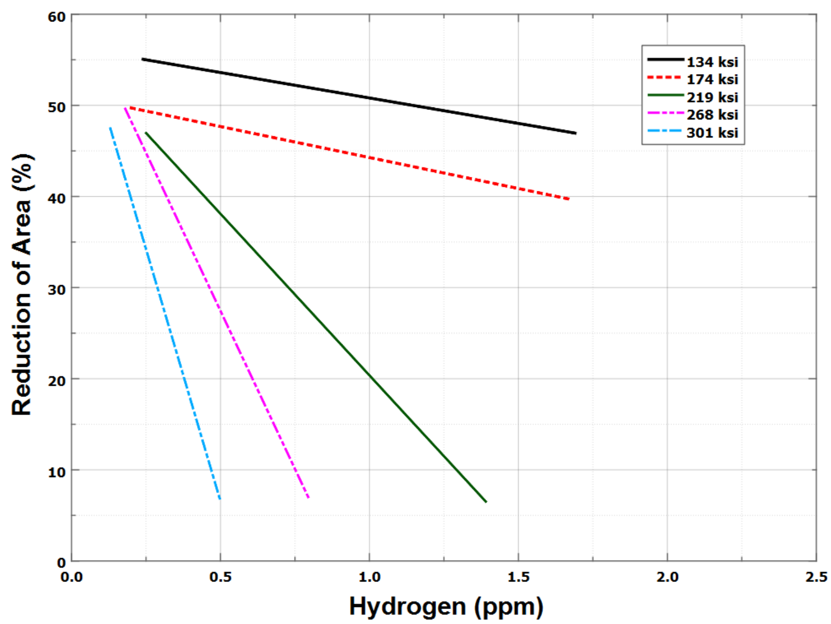


Figure 30 Effect of tensile strength on notch sensitivity [37]

As hardness is correlated to UTS, hard spots are effectively regions of high tensile strength and high sensitivity to hydrogen embrittlement, and there can be significant residual stresses from the creation of the hard spot. Cracking at these locations is often described as hydrogen stress cracking (HSC). Figure 31 is an example of a hard spot on a pipeline showing hard regions and cracking in the untempered martensite.

Figure 31 Hard spot containing martensite exhibiting cracking

Failures resulting from hard spots have been experienced in pipelines where the following conditions coexist: coating loss, wet (higher pH) soil, sometimes with CP hydrogen-enhancing trace elements in them, and cathodic protection (CP) greater than about -1,200 mV. Generally, the degree of hydrogen charging by electrolytic means is significantly greater than for gaseous hydrogen when the coating is damaged. Nevertheless, cracking at hard spots due to gaseous hydrogen should be considered a viable threat without the contribution from CP since it may affect hard spots with no external coating damage or in dry soils. Additionally, hard spots (which are created when the steel is in plate form) could be on the ID surface as well. The hardness is generally greater on the accidentally quenched surface of the plate, but there are cases of the hardness being greater subsurface than on the surface, which may be attributed to the accidental quenching before the final rolling pass to get the desired plate thickness. Reference [35] has a wealth of information on hard spots (the report is to be published in the fall of 2024). Data presented in Section 2.2.1.1 previously showed the significant impact of hydrogen on the fracture toughness of harder steels.

There are some additional efforts ongoing at Emc^2 to assess hydrogen stress cracking and fracture toughness changes in different hardness hardspots (in vintage steel) when subjected to hydrogen generated from wet soil and different CP levels with single-side charging. The toughness evaluations in that effort will use SEN(T) specimens that better reflect the transition temperature and toughness of surface-cracked pipes. When that data is developed and published, it will be additionally useful for hydrogen pipeline integrity evaluations, although C(T) specimens typically have a brittle-ductile transition temperature of about 55°F warmer than surface cracks in base metals.

To study the effects of hard spots on mechanical integrity in more detail, the pipe fabrication process is first reviewed to understand the loading conditions that should be applied. If some inadvertent quenching occurs during the plate rolling process, a localized martensite region will rapidly form. At the rolling temperature, the plate is in the austenitizing region. During controlled cooling, the microstructure of vintage line pipe transforms to ferrite and pearlite. Due to the differing specific volume between martensite and ferrite/pearlite of about 8 to 9%, there is both thermal and microstructure transformation shrinkage of the hard spot relative to the remainder of the plate, resulting in residual stress within the hard spot region. The plate is then rolled into a cylinder by a pipe mill and is fabricated into a pipe. This operation is done at ambient temperatures, so there is cold working/straining of the plate material. As the hard spots have a higher yield strength, the pipe deforms around these regions, resulting in flatter spots. The flatter region may experience more through-thickness bending when the pipe is pressurized, giving additional tension on the OD surface where a hydrogen crack can form with soil exposure. As part of a companion project, a finite element analysis examined a circular hardspot containing a crack oriented in the axial direction. The initial analysis included a perfectly flat spot in the hard spot region, which can induce a through-thickness bending stress during pressurization. The higher strength of a BHN=350 hard spot was included, but the residual stresses were not included. Surface cracks of various depths and lengths were included in that study, and the estimated toughness for those hard spots was used to determine critical surface crack sizes and compare them to simple pipe burst pressure analyses, see Reference [38]. The trend of the results for the FE analyses and several burst pressure analyses for a 36-inch diameter pipe with a 6” diameter hard spot with BHN=350 is shown in Figure 32. However, this does not include any residual stresses from the accidental quenching of the plate material. It was instructive in this effort to find that the original LnSec equation, when using the strength of the hardspot, tended to be overly conservative for longer cracks relative to the FE results and the CorLAS predictions. This trend in the original Ln-Sec equation is why the Modified LnSec equation was developed, but the Modified equation is known to have problems with lower-toughness materials, so it can’t be used for a critical crack in a hard spot. The CorLAS equation for the BHN=350 case had the same trend as the FE results. When trying to go to higher hardness (higher strength) cases, there was an equation that caused negative failure pressure to be calculated. So, the CorLAS equation has limits on how high the strength can be increased. The Emc^2 FE-based J-estimation scheme was assessed, knowing that the strength of this hard spot material is beyond the validation of that method. Nevertheless, it was conservative relative to the FE analyses and had the same trend with crack lengths.

Another interesting observation was that for BHN=350 hard-spot material, the test data in Reference [26] showed there was some ductile tearing in C(T) tests, which seems to agree with having larger cracks surviving in hard spots and having that hardness (proprietary data). However, some higher hardness hard spots appear to have brittle fracture and smaller crack sizes. We suspect that as the hardness increases, not only is the ductile fracture toughness reduced, but there could also be an increase in the brittle-to-ductile fracture initiation transition temperature of the steels.

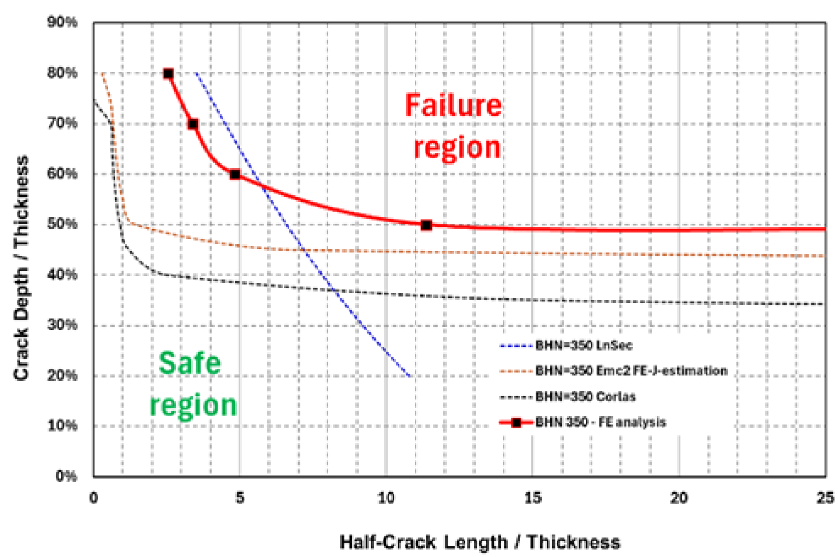


Figure 32 Comparison of initial FE calculated critical crack sizes to the simple pipe burst test model for BHN=350 with hydrogen degraded toughness and pressure of 72% SMYS in the 36” by 0.440” X52 pipe (no residual stresses included in the FE analyses)

The next evaluation assessed residual stresses from the thermal plasticity and the microstructure phase-change effect in the hard spot. This is a complicated evaluation, even though it is somewhat similar to a weld residual stress analysis. The phase-transformation aspects would be important and require a calibrated LeBlond constitutive law in the FE evaluation, where the proper constitutive law coefficients for that phase transformation in the vintage line pipe steel did not exist. Even then, there may be creep in the material surrounding the cooled hard spot while still surrounded by red-hot austenite, and the time duration between the hard spot creation and the cooling of the whole plate is unknown. However, there was an opportunity to experimentally measure the residual stresses by trepanning a hard-spot region in a pipe with strain gages on the hard spot; see Reference [39] for more details. The peak stresses with this ~BHN=360 hard spot was 19.4 ksi with a through-thickness bending. It was anticipated that the residual stresses might increase as the hardness increases for the same size hard spot, which was crudely approximated using a simple linear extrapolation, see Figure 33.

It was thought these were first-of-a-kind residual stress data for hard spots since inquiries to literally hundreds of people and literature searches showed no other results. However, while looking through a 1972 NG-18 report [24], some additional residual stress data on the OD of hard spots was found for hard spots that were much larger circumferentially, although about the same axial length. These data are also shown in Figure 33, where the stress is a bending stress through the thickness and is tensile on the OD surface (the hard spot was created on the plate surface that corresponded to the OD of the pipe).

The next step in our companion DOT/PHMSA project is to include those residual stresses in the FE model and see what the differences are in the critical crack sizes compared to the results shown in Figure 32. For the more typical case of the hard-spot creation on the plate surface corresponding to the OD of the pipe, there would be compressive residual stresses on the ID surface, and the flat-spot-induced stress from the pressure loading would also be compressive. So, ID-created hard spots might not be that challenging for a hydrogen pipeline since the higher hydrogen concentration would be on the ID surface with lower stresses. The additional FE analysis results will not be available in time for the final report on this project, but they illustrate the increasing knowledge of understanding hard spots. Some numerical calculations of the hydrogen density with these residual stress components appear warranted for future efforts. The potential for cracking could be examined by the phase-field hydrogen cracking numerical evaluation procedure being examined in Reference [39].

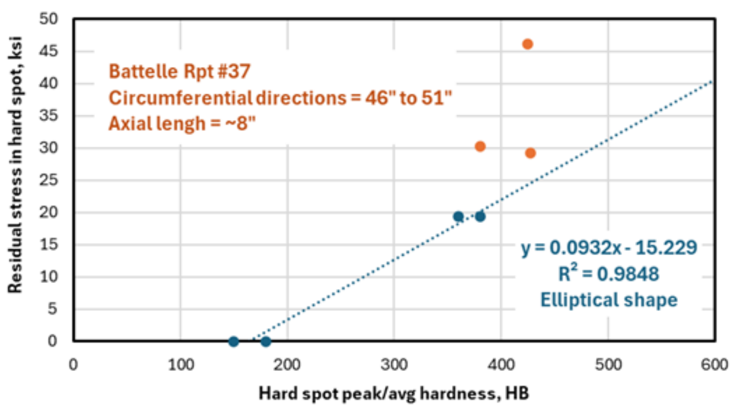


Figure 33 Measurements of OD residual stresses in hard spots

2.2.3 Wrinkle Bends and Buckles

The practice of using wrinkle bends to lay pipe was common in vintage pipeline construction. While not permitted in current codes, these features exist in some vintage pipelines, and it is important to consider the impact hydrogen may have on the threat level they represent. There is considerable plastic strain in a wrinkle bend. Service thermal cycles can cause circumferential cracking in the peak of the wrinkle bend. PRCI is planning on some wrinkle bend pipe tests, but the details are not known at this time. Buckles in pipe should have a similar behavior with internal hydrogen.

2.2.4 Fabrication Welds

Field welds made during the construction of pipelines will be susceptible to fracture in a similar manner to seam welds, with the addition of the weld residual stress (WRS). Girth welds, branch connections, fittings, etc., are all locations vulnerable to fracture due to weld-related defects. To explore this, calculations like the ones performed for axial seam cracks were made for a girth weld with the inclusion of WRS. Fracture toughness values of 75-35 ksi-√in were evaluated. Residual stress distribution following ASME-API 570 2001.

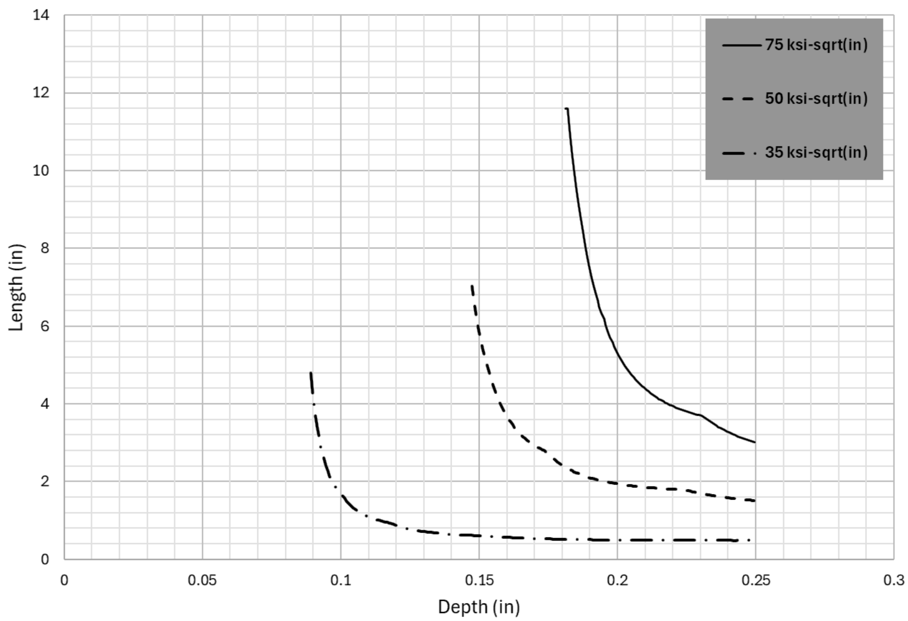


Figure 34 Tolerable crack size for circumferentially oriented flaws using API residual stress profile and assumed operating stresses

Cracks oriented in the circumferential direction at girth welds have a lower crack-driving force from primary stress (axial pressure stress) compared with longitudinal cracks. However, for pipelines, girth welds impart weld residual stress that adds to the crack-driving force. This is unlike ERW seams, which are autogenous welds. The example case presented here assumes identical conditions discussed in Section 2.2.1, with the addition of a residual stress profile following API 579 Part 9. The tolerable crack size calculated in Figure 34 shows that at a toughness of 35 ksi-√in, flaws as deep as about 25% of the wall thickness (0.08”/0.312”) are stable for long cracks in the range of 4”. While cracking at girth welds or other fabrication-related welding, such as branch connections, fillet welds to various fittings, etc., is of increased concern. This is related to the fact that the weld centerline (bond line) and HAZ of vintage pipeline steels generally have low toughness, combined with many flaws. There are also a variety of geometric conditions (flash heights, mismatches, over-trimming, etc.) that are challenging to the ILI inspection. During this era, inspection techniques for seams in the pipe mill were not particularly sensitive, so there was significant reliance on pressure testing.

While flaws are undoubtedly present in field welds, the ability to conduct quality assurance is likely somewhat better. In addition, the orientation of flaws parallel to girth welds is subject to a pressure stress that is half of the hoop stress acting on an axial flaw in a seam[**], although other geotechnical loading factors could give rise to higher longitudinal stresses. The same argument also applies to the driver for fatigue crack growth. It is also known that the stop-start location of a girth weld can impart high through-thickness tensile stresses that may induce hydrogen cracking [40].

2.2.5 Mitigation of Resident Threats

Resident threats encompass many forms of damage, from crack-related to dents and gouges. Potential mitigation steps are outlined in Table 7.

Table 7 Mitigation of resident threats

B31.8S Root Cause	Threat Level	Description	Primary Concern	Mitigation Approach
Seam Crack	High	Cracks located in ERW seams are often associated with pipe manufacture, e.g., hook cracks and lack of fusion. Susceptible to subcritical crack growth depending on applied stress and crack size.	Crack growth to critical size, causing leak or rupture. Affected by fatigue	ILI tools such as UTCD, EMAT, or hydrotesting are used to identify and estimate size. ECA is based on fracture mechanics analysis to determine mitigation strategy. Hydrotesting can establish maximum survivable flaw to help validate ILI results. Higher hardness ERW/EFW seams in vintage pipes are an important aspect, especially since recent Sandia data suggest very low toughness in higher hardness linepipe steels.
Hard Spot	High	High degree of sensitivity to hydrogen. History of cracking due to hydrogen. Susceptible to subcritical crack growth depending on applied stress and crack size.	Depending on size of hard spot, HSC could result in a critical sized flaw leading to longitudinal rupture.	Detection by ILI tools is the primary approach, followed by removal. Concern for reliability of detecting hard seams due to the small volume of material affected. Are closely associated with manufacturer (A.O. Smith and a few other manufacturers of pipe in the 1950s). Further research on hard spot detection is needed, particularly for hard seams.
Wrinkle Bend	Medium	Location of high strain and complex stress state. Location that could have higher hardness due to work hardening and greater sensitivity to hydrogen.	Crack initiation and grow by fatigue leading to circumferential leak or rupture.	Identification and characterization of deformation. ECA limits may be based on dimensions, finite element analysis, estimation of strain, and assessment of fatigue life.
Fabrication Welds	Medium	Weld related defect density is likely compared to ERW seams. Flaws oriented normal to principal stress, but crack driving force from weld residual stress present. Lower driving force for fatigue crack growth.	Crack growth to critical size. Low driving force for fatigue crack growth. Better properties and fewer weld related defects compared to seam welds. Failure likely circumferential, leak or rupture.	Identification by ILI tools such as UTCD and potentially EMAT tools designed with probes detect cracks in the circumferential orientation. MFL tools have the potential to screen for cracks with openings on the order of a millimeter. Cracks may be more likely to start at stop-start locations in girth welds.
Nonmetallic Materials	Medium-Low	Degradation of seals/packing in valves, meters and various fittings or components.	Likely failure mode is a leak. Primarily only non-pressure boundary materials effected.	Identifying and retrofitting certain components with appropriate materials.

2.3 Third-Party Damage

One of the most frequent failure root causes of pipeline failures is due to third-party damage. Pipe struck by farm equipment, backhoes, or other excavation methods can cause considerable damage, resulting in

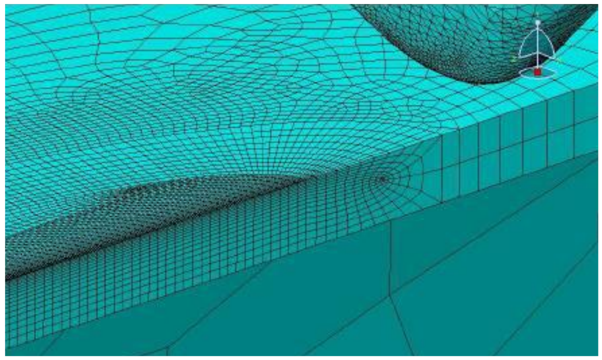
[**] More precisely about 30% of the hoop stress for buried pipe without any geotechnical induced loads.

either immediate failure or after some period in which the damage progresses to some critical size. Some illustrations are shown in Figure 35.

Figure 35 Illustration of third-party damage to pipelines

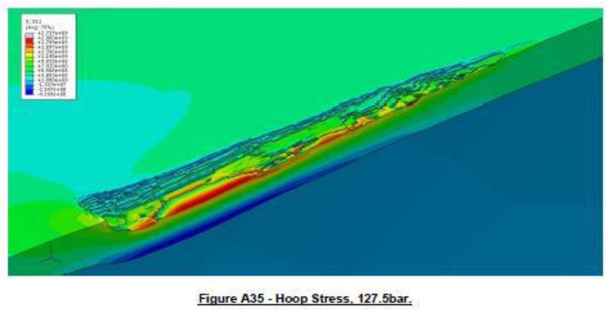
Little is currently known regarding the influence of hydrogen on the probability of failure at the time of impact, but it is logical to assume that prior to the impact, there is little hydrogen accumulation. Directionally, as hydrogen reduces the tensile ductility, it would be expected that the amount of strain that could be accommodated after impact would be reduced, but not at the time of the damage creation. This observation is only supported by the tensile test data reported here and the prior literature review. Test data examining the effect of more complicated stress-strain states caused by this form of damage have not been studied to any significant degree and likely require full-scale testing to determine the increase of this threat. Following deformation, however, data suggest that significant damage would be more likely to initiate cracking, and once formed, crack growth would be accelerated. Failure would occur sooner (at a smaller defect size) than in NG service unless there was wet soil/CP-generated hydrogen (the coating would be lost during the damage creation).

The full-scale dent-and-gouge testing efforts in the past examined the damage with an air environment around the damaged region [41]. That might be sufficient for the immediate failure, but the longer time failures could be affected by the presence of hydrogen. The hydrogen for existing pipelines could come from the coating damage along with wet soil and CP. For a hydrogen pipeline, plastic deformation is the internal denting of the pipe that might enhance the diffusion of hydrogen concentration to the damaged region. Numerical evaluations in a more recent PRCI project simulated the dent-and-gouge damage [42], where such analysis results could be used in future evaluations of how the hydrogen concentration might occur in such a region. Results for one case are shown in Figure 36, where the hoop stress and plastic strains would determine the hydrogen concentration. Clearly, such time-dependent behavior is difficult to model without validation tests with hydrogen exposure and hold times to see the differences in the failure pressure with hold times with hydrogen and without hydrogen. We suspect that the hydrogen from possible wet soil and CP might be more controlling on the failure times, but there is also the possibility of not having wet soil in the vicinity of the damaged region where the internal hydrogen might be controlling the failure time for a given gouge-and-dent defect.

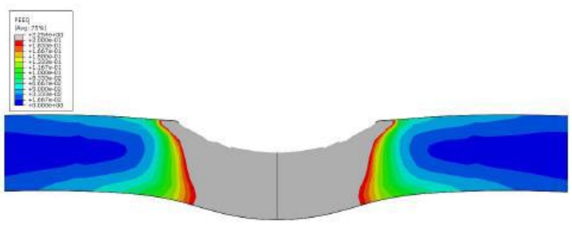


(a) View of the FE mesh through the thickness of the region to be damaged

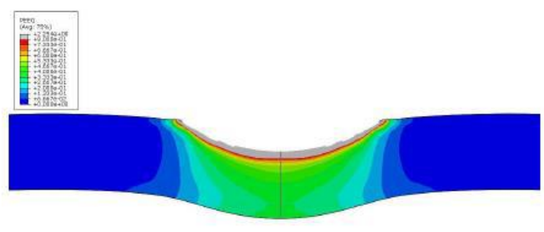
(b) Hoop stress after damage at 0 pressure



(c) Hoop stress at 127.5 bar internal pressure



(d) Plastic strains along the gouge at 20% strain limit)



(e) Plastic strains along the gouge (80% strain limit)

Figure 36 FE mesh used in past dent-and-gouge simulations, along with some results of the hoop stresses and plastic strains

2.3.1 Dents and Gouges

For dents, a strain-based criteria like 6% equivalent strain are used following ASME B31.8 and API RP 1183. Other limitations like proximity to welds, presence of gouging or cracks, etc., or other locations of low ductility limit dent acceptance criteria further. It can, therefore, be inferred that as the presence of hydrogen degrades tensile ductility, more restrictive acceptance criteria for dents may be needed in hydrogen service. This is consistent with a couple of general trends. The first is that hydrogen will migrate to locations of high tensile stress. In particular, the hydrogen concentration is increased on a local scale by the presence of high hydrostatic (tensile) stress $\sigma_H = \left(\frac{\sigma_1+\sigma_2+\sigma_3}{3}\right)$ as well as plastic strains. At these locations, the Fe crystal lattice dilates from the hydrostatic stresses and can accommodate a greater number of hydrogen atoms. Conversely, compressive hydrostatic stress has the opposite effect. Plastic deformation (strain) also increases hydrogen solubility due to higher dislocation density, which gives more hydrogen trapping sites. The hydrogen concentration would therefore be expected to exceed that of the surrounding undeformed pipe based on the local strain concentration, and degree constraint (stress triaxiality). The second trend is the reduction of fracture ductility due to constraint. It has been known for many years that constraint affects tensile ductility, and many codes and standards reflect this by limiting strain. Many models have been used to describe this effect, typically relating the uniaxial tensile strain to the multiaxial strain though some function of $\frac{\sigma_H}{\sigma_e}$. Figure 37 shows the change in tensile elongation of a vintage X42 steel as a function of hydrogen pressure. The data indicates that at a pressure of 5 MPa (725 psi) hydrogen, there is a decrease in the range of 30%. At 20 MPa (2,900 psi), the elongation has dropped over 50%.

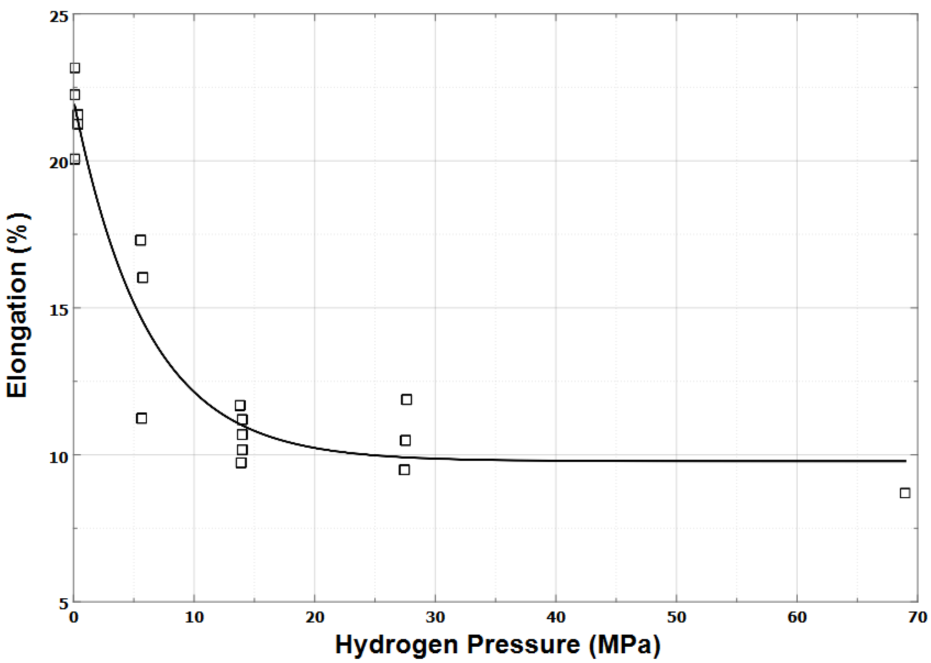


Figure 37 Tensile ductility of X42 in hydrogen

Data compiled by Sandia National Laboratory on a variety of steels tested at 1,000 psi, showed a drop in reduction of area of about 20% for an X42 steel, and 45% for X60 [32].

Some insight on multiaxial effects can be gleaned from notched-bar tests. Notched tensile bars can be machined with various acuities, giving a range of stress triaxialities, albeit somewhat limited. Data on notched bars is shown in Figure 38. In this study, the stress-displacement (strain) is plotted as a function of hydrogen content for an X80 steel [43]. At 5% by volume, there is a drop of about 12% in elongation, and at 50% hydrogen, a 25% drop is observed.

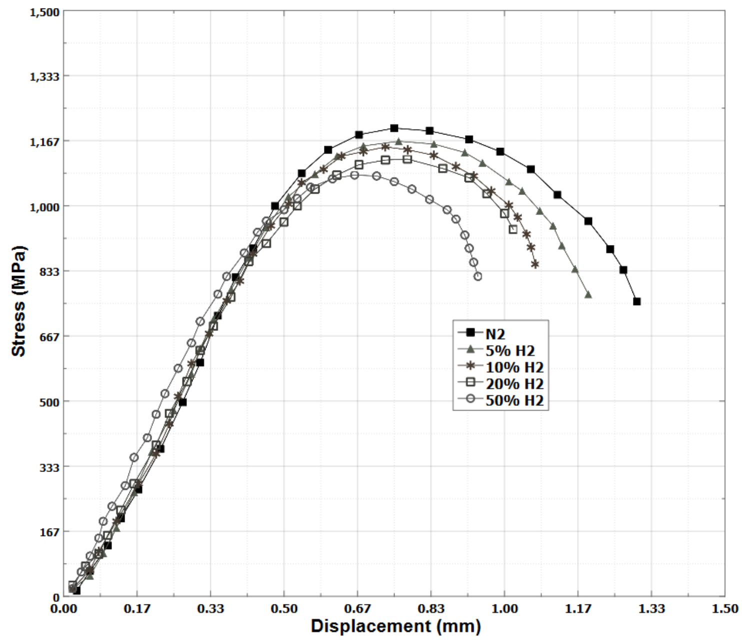


Figure 38 Effect of hydrogen blending on tensile ductility of notched bars

Looking at the effect of notch acuity, where the degree of stress triaxiality differs due to the notch radius, provides additional insight into the role multiaxiality plays in defect tolerance. The data in Figure 39 show the relationship between the net fracture stress σ_{net}, lattice hydrogen C_L, and notch radius (ρ) decreases [44].

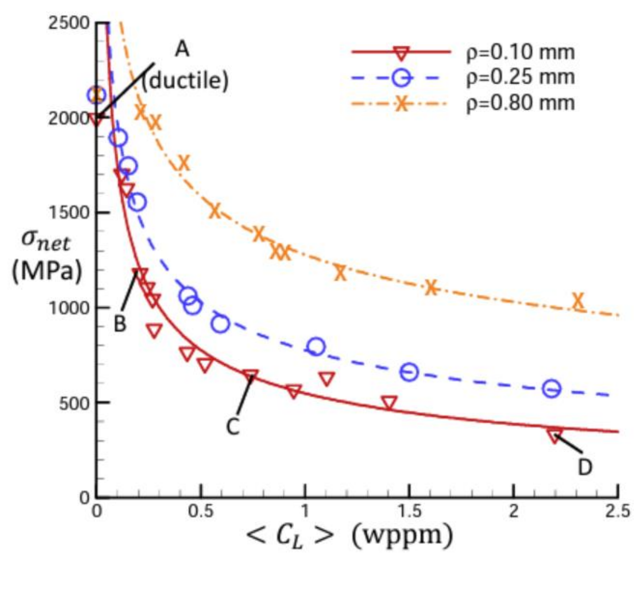


Figure 39 Effect of notch acuity on net-section fracture stress [44]

This suggests that as triaxiality increases, notch sensitivity in hydrogen also increases. This result implies that geometry plays a strong role in the severity of these types of defects. Now, this is not a new observation, but the relationship between hydrogen concentration and the local stress-strain field is important and makes existing features that have remained dormant more vulnerable to cracking after the addition of hydrogen.

It is important not to overstate this issue, but directionally this trend would be expected. To explore this further, several steps can be taken to understand the impact of hydrogen on dents, gouges, wrinkle bends, and similar types of features.

- Small-scale testing of blunt-notched bars of vintage steels in various heat-treatment conditions and determining failure strain as a function of triaxiality,
- Full-scale tests with sufficient instrumentation to validate models or to guide the development of acceptance criteria, and
- Numerical analysis to support model development, calibrated by small-scale tests and full-scale tests.

These data show a relationship between stress triaxiality and hydrogen sensitivity. This trend *may* be extended to damage features like dents or gouges, where the stress state may result in a higher concentration of hydrogen and a decrease in tensile strain. This may be compounded by the fact that in some features, particularly gouges, significant work hardening and even a local phase transformation also takes place during the damage process. As has already been discussed, there is a clear relationship between hardness and properties such as fracture toughness.

Collectively, the data indicate that the strain tolerance of dents would likely be more restrictive in hydrogen. Current strain limits on dents found in ASME B31.8, or API RP 1183 are 6%, where no material property data are available. This is also reflected in ASME B31.12, where dents in newly constructed pipelines are limited to 2% strain. Dents in girth welds and long seams are regarded as injurious if they exceed a depth of 2%.

Data from the Battelle study referred to previously also showed that a reduction in low-cycle fatigue life in a hydrogen-methane environment [26]. Tests were conducted on notched specimens at 1 Hz at an R ratio of 0.1. The pipeline steels in the study included X52, X60, X65, and X70. Gas compositions varied the hydrogen-methane ratio from pure methane to a 60:40 ratio hydrogen to methane mixture. In some tests, carbon monoxide and water vapor were present to explore their inhibiting effects on hydrogen embrittlement. Results of this work showed under the most severe conditions of stress amplitude and hydrogen mixture, LCF life was reduced by an order of magnitude so that the ASME Boiler and Pressure Vessel Code traditionally adds a safety factor of 2 on stress to conservatively cover the damage effect, but the safety factor of 20 on cycles did not always conservatively bound the methane-hydrogen S-N fatigue data, see Figure 40 from Reference [45].

In a very recent study, the endurance limit and FCGR of vintage X52 pipeline steels were investigated to look at the effects of hydrogen at low and high pressures [46]. Cycles to crack initiation, as well as failure, were measured at various pressures and compared with air and nitrogen tests. As with the Battelle study [26], the tests were conducted at 1 Hz and an R value of 0.1. Results from this study showed similar trends to the Battelle work, where a high-pressure hydrogen gas mixture decreased both the cycles to crack initiation and the cycles to failure.

The implications of the fatigue life testing in hydrogen suggest that features such as dents, gouges, wrinkle bends/buckles, or other forms of deformation may be more likely to initiate cracks. Once a crack is formed, the growth rate is likely to be accelerated relative to NG service.

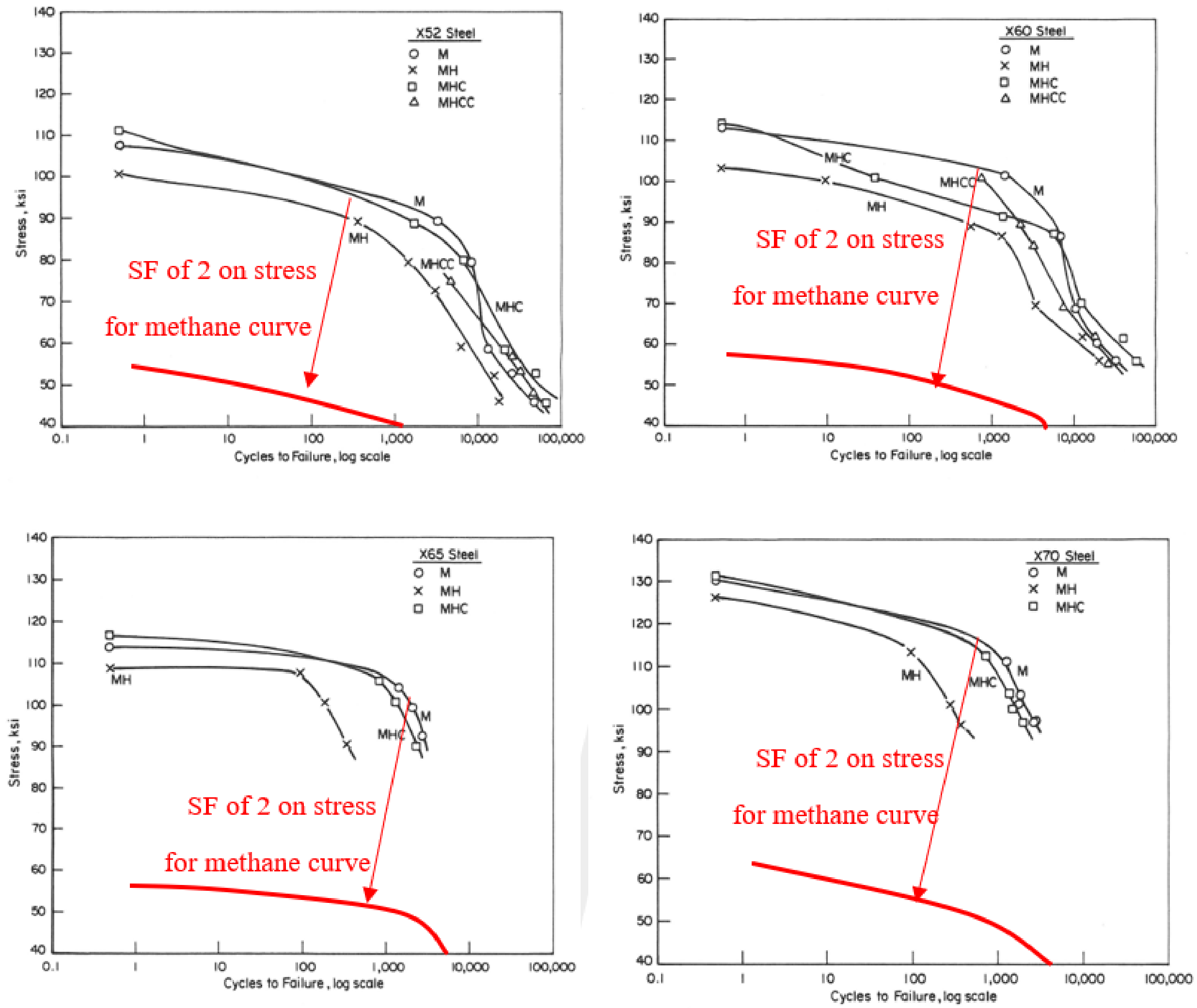


Figure 40 S-N fatigue curves for pre-1985 line-pipe steels in: pure methane (M); 60% hydrogen and methane (MH); methane, 60% hydrogen and 24% CO (MHC); and methane, 60% hydrogen, 25% CO and 10% CO_2 (MHCC) and margins with SF=2 on stress – from Reference [45]

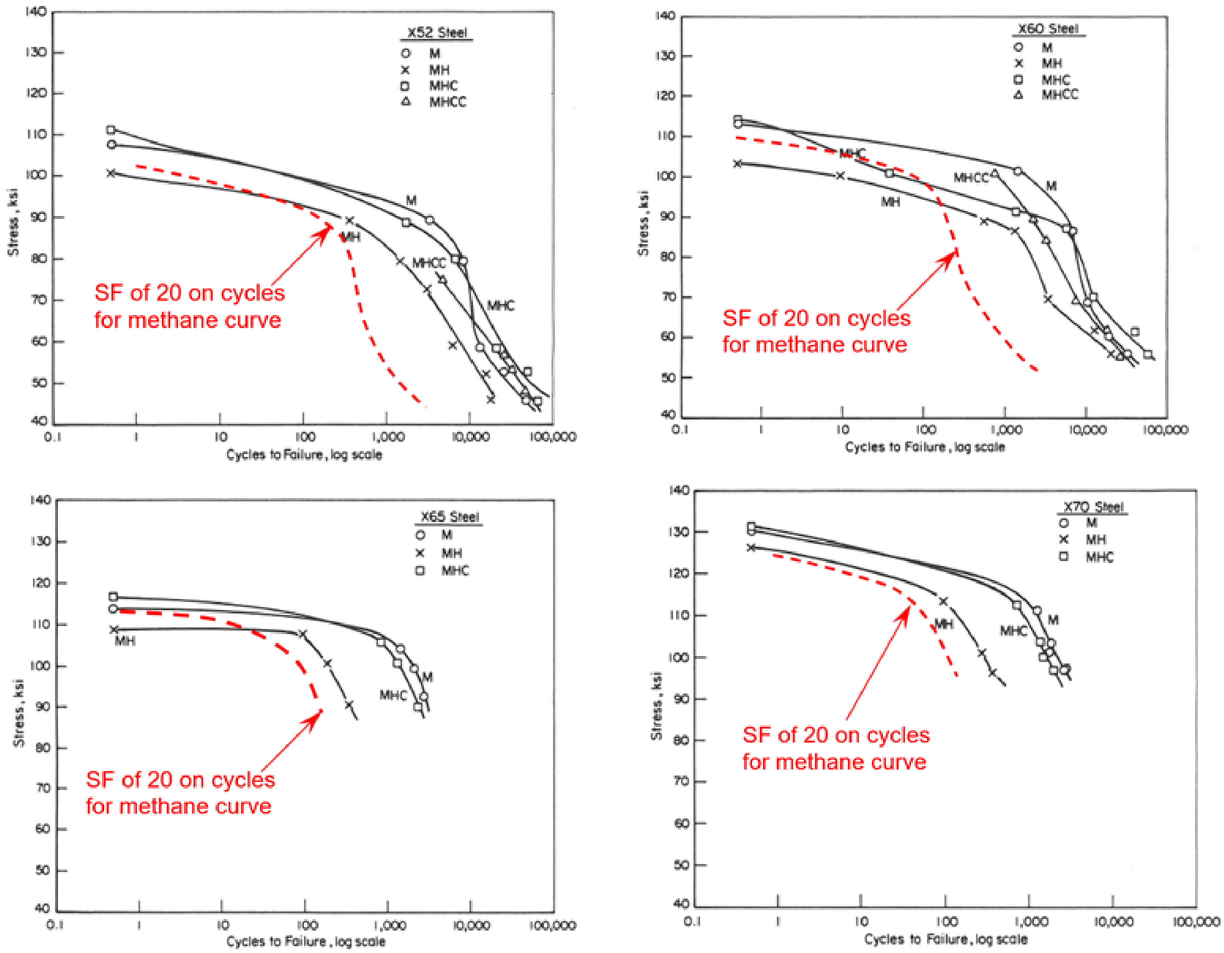


Figure 41 S-N fatigue curves for pre-1985 line-pipe steels pure methane (M); 60% hydrogen and methane (MH); methane, 60% hydrogen and 24% CO (MHC); methane, 60% hydrogen, 25% CO and 10% CO_2 (MHCC) with margin of 20 on cycles – from Reference [45]

2.3.2 Natural Force: Weather, Water, Ground Movement

Natural force damage caused by water, ground movement, seismic activity, etc., can result in significant levels of plastic strain, as suggested in Figure 42.

Figure 42 Illustrations of natural force damage to a pipeline

As with other forms of damage that combine significant plastic deformation and high local stresses, it can be expected that strain tolerance is reduced in the presence of hydrogen. The magnitude of this impact is not known currently, and the steps outlined in Section 2.3.1 apply equally to these threats. Examples of the type of effort required include the study performed by Battelle in 1986, “Outside Force Defect Behavior” [41], and the more recent PRCI study “Mechanical Damage Instantaneous Failure Model – Numerical Simulation of Physical Tests” [42].

2.3.3 Miscellaneous Random Threats (Effects on Nonmetallic Materials)

The other threat integrity challenges that must be addressed in this report involve the compatibility of nonmetallic components with hydrogen. The compatibility of non-metallic materials with hydrogen is an important aspect of safe and reliable transport and distribution systems. Non-metallic materials are currently used in a variety of components in natural gas networks. Examples include [47] the items listed in Table 8.

Table 8 Application of nonmetallic materials in pipeline networks

Component	Description	Example materials[a]
Compressed hydrogen pressure vessels	Type III	Metallic liner; composite vessel: glass fiber or carbon fiber, epoxy resin
	Type IV	Polymer liner: HDPE, nylon; composite vessel: glass fiber or carbon fiber, epoxy resin
Pipelines	Multi-layer construction for high-pressure distribution (>10 MPa)	Polymer liner: HDPE, nylon; composite vessel: glass fiber or carbon fiber, epoxy resin
Piping, tubing	Monolithic construction for low-pressure distribution (<10 MPa)	HDPE, PP, PVC, CPVC
Mechanical compressors	Seals and coatings	Teflon composite, PEEK
Dispensing hoses		Proprietary/unknown material
Flange connections (low pressure)	O-rings, gaskets	Nitrile rubber, Viton, Teflon
Threaded connectors (high pressure)	O-rings	Nitrile rubber, Viton
Valves (manual, actuated, check, velocity, relief devices)	Pistons	PEEK
	O-rings, fittings, etc.	Nitrile rubber, Viton, Teflon
	Seals and gaskets	Teflon, Viton, nitrile rubber, EPM, fluorosilicone, silicone, Neoprene, Nylon, PEEK
	Valve seats	Nylatron, Vespel, PCTFE, Teflon

Of primary importance is pressure boundary equipment, which largely consists of distribution piping made of high-density polyethylene (HDPE) and medium-density polyethylene (MDPE). In the U.S., there exists over 1.5 million miles of plastic pipe with 98% consisting of PE, data from PHMSA's as well as the Plastic Pipe Database Collection Initiative. Data from the latter indicate the following primary causes of failure (reproduced from Reference [48].

Table 9 Causes of polyethylene failures

	Component			Overall
Cause	Pipe	Fitting	Joint	
Installation Error	6.2%	26.9%	56.0%	21.6%
Material Defect	12.3%	15.8%	10.4%	13.7%
Point Loading	9.8%	1.9%	2.2%	13.7%
Other	9.6%	2.6%	4.4%	10.3%
Unknown	48.4%	24.0%	17.7%	33.5%

Based on a survey of current literature, there are no indications that hydrogen has a measurable effect on the integrity of polyethylene. Data from the European Industrial Gases Association (EIGA) provides useful guidance on the application of various nonmetallic materials in hydrogen [49]. A broad study on the implication of hydrogen addition to pipelines and distribution networks sponsored by the European Pipeline Research Group (EPRG) provides a good summary of nonmetallic compatibility [50].

2.3.4 Mitigation of Random/Time-Independent Threats

The primary mitigation of random or time-independent threats relies on periodic inspection and surveillance programs. In some cases, environmental factors such as weather impacts could trigger the need for surveillance. The approach can vary depending on the form of damage, such as weather impacts. Some broad guidance is provided in Table 10.

Table 10   Inspection guidance on various threats [51]

Integrity threats	Method				
	Direct assessment	In-line inspection	Pressure test	Visual	Operating & maintenance procedures
Time-dependent threats					
Corrosion:					
Internal		X	X		X
External underground	X	X	X	X	
External aboveground		X	X	X	X
Stress corrosion cracking (SCC)	X	X			X
Hydrogen embrittlement		X	X		X
Stable threats					
Manufacturing defects:					
Pipe		X	X [1)]		X
Pipe seam		X	X [1)]		X
Construction defects:					
Girth weld		X	X [1)]		X
Buckle/Dent		X	X [1)]		X
Wrinkle bend		X	X [1)]		X
Equipment:					
Control/relief valve					X
Time-independent threats					
Third-party/mechanical damage	X	X	X		X
Incorrect operation:					X
Including cold embrittlement					X
Weather and outside forces:					
Cold weather					X
Lightning	X				X
Flooding/Erosion				X	X
Subsidence				X	X
Landslide				X	X

[1)] Refers to postconstruction.

3 Task 4 – Determine the Effects of Hydrogen/Natural Gas Blends on Threat Levels

3.1 Results of Subject Matter Expert Elicitation

In this task, 25 subject matter experts (SME) identified in Task 2 were assembled for an elicitation workshop. Elicitation is a process of gathering expert opinions from different but related viewpoints, i.e., there were selected experts on a wide range of expertise in pipeline integrity management, hydrogen embrittlement, ILI/NDE, pipeline codes and standards, FEA, and fracture mechanics. Before conducting the workshop, which was held in Columbus, OH, in March of 2023, the SME team was asked to respond to various questions related to the changes in mechanical integrity resulting from hydrogen addition to an existing NG pipeline. This information was obtained using an online tool developed for this purpose. The data were compiled and evaluated so that the results could be discussed and a consensus reached on some topics. The questionnaire took considerable time to formulate and get additional opinions on whether topics/questions were missing, clarifying questions, and whether the questions were unbiased. The Emc^2 project team members were not part of the SME team but rather acted as facilitators of the discussion. In addition to responding to specific topics, the SME team was also asked to rate their confidence in their answers so that some weight could be given to the data.

A screenshot of the tool used to gather the SME data is shown in Figure 43.

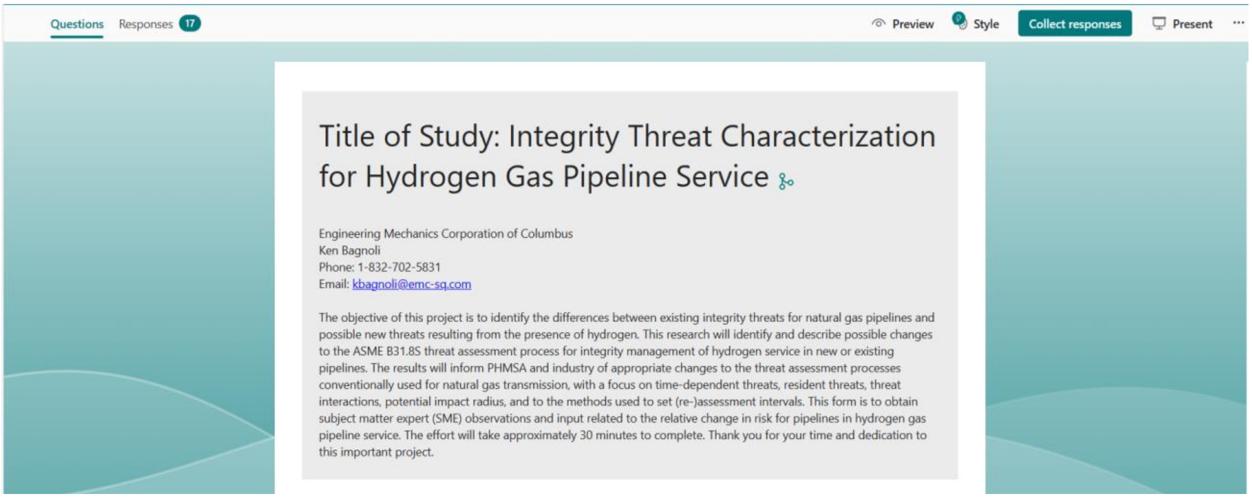


Figure 43 Screenshot of online SME team opinion gathering tool

The topics included in this elicitation process are summarized as follows:

- SME Elicitation questions structured around 16 categories:
    - Material properties
    - Crack growth
    - Crack initiation
    - Effect of fabrication method
    - Effect of construction
    - Fatigue demand
    - Operating pressure
    - Time-dependent threats
    - Effect of hydrogen concentration
    - Stress corrosion cracking
    - In-line inspection
    - Threat mitigation
    - Repair procedures
    - Flaw assessment
    - Non-metallics
- There was a total of 65 questions, and
- Several questions inquired about SME level of confidence (limited confidence <40%; somewhat confident 40%-70%; high confidence >70%) and rationale for responses.

Out of the 25 SME experts invited, 17 people responded to the opinion gathering exercise. To illustrate the manner in which the opinions were input, a screenshot of the response to a question about the impact of various blending levels on material properties is shown below. None of the project team members provided input to this elicitation effort since the project team efforts are a separate consideration in the recommendations, as well as ongoing efforts from other organizations.

2. What impact would a 5% to 20% hydrogen blend have on the following **material properties** compared to 100% natural gas pipeline transport?

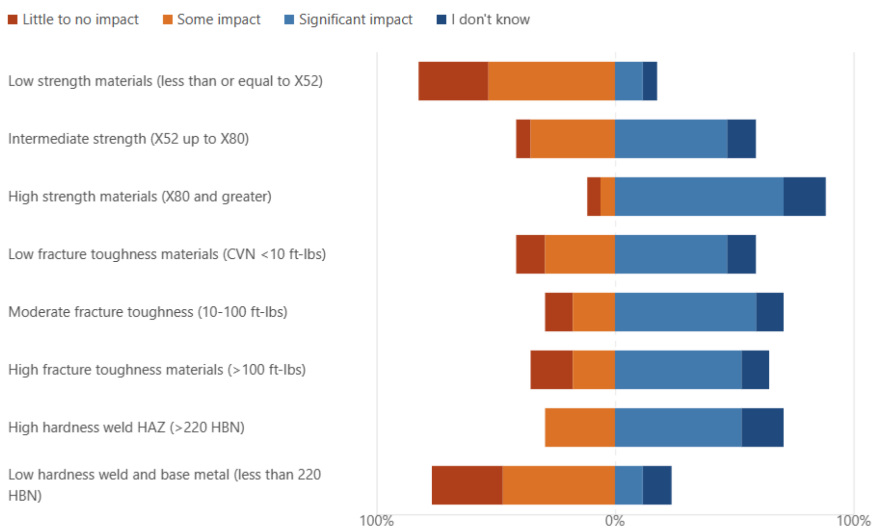


Figure 44 Example of an online opinion gathering question format

In this example, about 80% of the respondents had high confidence or were confident in their answers, and only 18% had low confidence. (Note: if their response was "I don't know," they might still be highly confident they didn't know.) In addition to the structured input, the SME experts had the opportunity to add clarifying comments captured for discussion purposes during the workshop. Key results from the elicitation process are summarized here. In order to contextualize the questions, it was indicated that a range of 5-20 vol% hydrogen would be blended into a hypothetical vintage pipeline now in NG service. All the opinions are provided in Appendix II.

The self-rating of expertise showed 95% consider that they have a high or good understanding (16/17), and one respondent indicated a limited understanding. The following summarizes the general themes of the study. Note that the characterization here is a generalization of the opinions. For more details on the actual responses to each topic, see Appendix I.

1. The opinions were that there would be some significant impacts on material properties.
2. Significant impact on FCGR was the main opinion, some to moderate impact on HCF/LCF, little to moderate effect on SCC, little or no impact on corrosion.
3. The opinions were that there is moderate to significant impact on subcritical crack growth, but several responses indicate unknown effects. A similar response to the effect of stable crack growth during hydrotest conducted at normal code pressures.
4. Opinions on the impact of manufacturing methods:
    a. LF-ERW – High effect of hydrogen on properties
    b. HF-ERW – Moderate effect
    c. Lap Welded – High effect, with almost half responding they did not know

d. Flash Welded – High effect
e. DSAW – Moderate to low effect
f. Seamless – Low effect
g. SMAW Girth Welds – Moderate effect
h. Automated Girth Welds – Low effect

5. Construction Aspects opinions:
    a. Hot Taps – Moderate to high effect of hydrogen
    b. Type B Sleeve High effect, with a large number of responses indicating unknown
    c. Fabricated Fitting – Moderate effect with a large number of respondents indicating unknown
    d. Base Metal Repair – Moderate to low effect
    e. Arc Strikes – Moderate effect
    f. Compression Sleeves – Low to unknown effect
6. Fatigue Demand opinions (increase or decrease with hydrogen blending) – Split opinions between yes and maybe
7. Operating Pressure Changes needed opinions – Maybe to yes there is an effect of hydrogen
8. Time-dependent Threats opinions
    a. External Corrosion – no effect of hydrogen
    b. Internal corrosion – no effect
    c. MIC corrosion - no effect
    d. Selective Seam Weld Corrosion – no consensus
    e. Axial SCC – no consensus
    f. Circumferential SCC - no consensus
    g. Pressure Cycle Fatigue (FCGR) - large effect
    h. Low-Cycle Thermal Fatigue - Moderate effect
9. SCC affected by hydrogen opinions
    a. Near Neutral SCC Growth Rate – Split between no effect and increased rate
    b. High pH SCC Growth Rate - Split between no effect and increased rate
10. Consequences of Failure Increased – Opinions were maybe to yes
11. Effectiveness of ILI opinions
    a. MFL – Same effectiveness for hydrogen pipeline to no knowledge
    b. UT ILI – Equally split between less effective, same effectiveness, and don't know
    c. EMAT ILI – same opinions as UT ILI
    d. Caliper Tools – Same effectiveness for hydrogen pipelines
    e. IMU Tools – Split between same effectiveness and don't know
12. Threat Mitigation opinions
    a. Hydrotesting – Same usefulness
    b. Direct Assessment –Same usefulness
    c. Pressure Cycle Management – More useful
    d. Thermal Cycle Management - More useful
    e. Pressure Reduction – Split between same and more useful
    f. Leak Detection – Unknown
    g. Routine Maintenance – Same usefulness
    h. Field NDE – Same effectiveness
    i. Controller Response to Abnormal Condition – Same to more useful
13. Repair Procedures opinions
    a. Welded Sleeve – Same usefulness

   b. Composite Sleeve – Same usefulness
   c. Clams – Same usefulness
   d. Grinding – Same usefulness
   e. Field NDE – Same usefulness
   f. Hot Work Restrictions – Same to more useful
14. Frequency of Integrity Assessment opinions – Most indicate yes, increase in assessment frequency needed for hydrogen pipelines
15. Flaw Assessment Procedures changes needed for hydrogen – all opinions indicate same or don't know. Assessment procedures ranged from cracks, corrosion, FCG, dent analysis, design factors
16. Non-Metallics integrity with hydrogen:
   a. Seals - generally same to 20% hydrogen, above 20% these responses indicate somewhat of an impact, but a significant number of "I don't know" responses
   b. Gaskets – Significant impact on "I don't know" responses
   c. Pressure and Temperature Sensors – Most indicate "I don't know"
17. Codes and Standards Update Required – Significant majority indicate updates are needed

3.1.1 Examples of Failures Attributed to Hydrogen Embrittlement

Some examples of hydrogen related failures compiled during this project and a prior PRCI project on "Why Crack Fail" are summarized in the below table [52].

Table 11 Examples of hydrogen related pipeline failures

Liquid/Gas	Failure Mode	DISCOVERY	Year	Grade	Pipe Manufacturer	Seam Weld Type	CRACK LOCATION	GEOMETRY FEATURES	MECHANISMS
Gas	Rupture	In-Service	1968	X60	National Tube	DSAW	GW	n/a	Hydrogen Assisted Cracking (HSC)
Gas	Rupture	In-Service	1960	X52	AO Smith	FW	Base Metal	n/a	Hydrogen Assisted Cracking (HSC)
Gas	Rupture	In-Service	1962	X52	n/a	n/a	GW, Base Metal	Weld Defect	Hydrogen Cracking
Gas	Leak	In-Service	1961	X52	n/a	DSAW	Base Metal	Hard Spot	Hydrogen Embrittlement, High-pH SCC
Liquid	Rupture	In-Service	1949	X46	Youngstown	dc-ERW	LSW	Hard Spot	Hydrogen Induced Cracking (HIC)
Liquid	Leak	In-Service	1952	n/a	n/a	n/a	GW, Fitting	Weld Defect, Hard Spot	Hydrogen Induced Cracking (HIC)
Gas	Rupture	In-Service	1957	X52	AO Smith	FW	Base Metal	Hard Spot, Mill Defect	Hydrogen Induced Cracking (HIC), Lamination
Gas	Leak	In-Service	1969	X60	n/a	n/a	Base Metal	Bottom-Side Dent	Hydrogen Stress Cracking (HSC)
Gas	Leak	In-Service	1967	X60	n/a	ERW	Base Metal	Hard Spot	Hydrogen Stress Cracking (HSC)
Gas	Rupture	In-Service	1957	X52	Bethlehem Stee	DSAW	Base Metal	Hard Spot	Hydrogen Stress Cracking (HSC)
Liquid	Rupture	Hydrotest	1948	X46	Youngstown	dc-ERW	LSW	Weld Defect, Hard Spot	Intergranular Fracturem Hydrogen Assisted Cracking (HAC)
Liquid	Rupture	Hydrotest	1948	X46	Youngstown	dc-ERW	LSW	Weld Defect, Hard Spot	Intergranular Fracturem Hydrogen Assisted Cracking (HAC)
Liquid	Leak	Hydrotest	1952	X52	n/a	n/a	GW	Weld Defect	Partial Weld, Fatigue Crack, Hydrogen Induced Cracking (HIC)
Liquid	Rupture	In-Service	1948	Grade B	Youngstown	LF-ERW	LSW	Weld Defect	Hook Crack, hard seam, hydrogen charging from CP

3.1.2 Recommendations for Integrity Management Plans

The impacts of hydrogen outlined in this report clearly suggest that operators would need to update their IMP prior to the addition of hydrogen to existing NG pipelines. The impacts on material properties will affect mitigation plans from various perspectives and will likely require revisiting inspection approaches and intervals. There may even be cases of vintage lines that perhaps should not be converted to hydrogen service. No single document currently contains comprehensive guidance on the specifics needed to address this issue. However, the application of existing ECA methods accounting for changes in properties such as fracture toughness, FCGR, and loss in ductility for strain-controlled forms of damage is clearly warranted. Along with this, reassessment of ILI technologies for potential applications that have the capability for smaller defect detection and more accurate sizing will be important to ensure that critical defects can be detected and assessed. Hard spots, which may be an increased threat, should be evaluated, particularly for lines in which such features have already been identified, prior incidents have occurred, and ones manufactured from pipelines associated with hard spots [35]. The presence of hard seam welds is another potential issue where the threat is cracking, and accelerated FCGR could be an issue.

Establishing new tolerable flaw sizes based on both fast fracture as well as application of a K_{IH} limit on subcritical crack growth should be addressed. At present, there is insufficient data to recommend changes to programs looking at dents, gouges, or other forms of pipe deformation, so it is impossible to provide guidance on these aspects of the IMP.

Shown below in Table 12 and Table 13 are some selected resources that may be used to assist operators in revising IMPs for blending hydrogen.

Table 12 Selected codes and standards that address hydrogen and pipeline integrity

Document Reference	Title
ASME B31.12	Hydrogen Piping and Pipelines
ASME B31.8S	Managing System Integrity of Gas Pipelines
EIGA Doc 235/21	Industrial Gas Pipeline Integrity Management
EIGA Doc 247/24	Hydrogen Overview – Distribution, Storage, Applications
EIGA Doc 121/14	Hydrogen Transportation Pipelines
ISO 11114-2	Transportation gas cylinders – Compatibility of cylinder valve materials with gas contents, Part 2 Non-metallic materials
ISO 13623:2017/Amd 1:2024	Amendment 1: Complementary requirements for the transportation of fluids containing carbon dioxide or hydrogen
EIGA TB 42/22	Technical Bulletin: Welded Gaseous Vessels and Hydrogen Compatibility
ASME API 579 FFS-1	Fitness-For-Service Evaluation
API RP 1183	Measuring and Assessing Dents in Pipelines
API RP 1176	Recommended Practice for Assessment and Management of Cracking in Pipelines
API RP 1184	Pipeline Facilities and Construction Inspection
API Bulletin 1178	Integrity Data Management and Integration
API RP 1110	Pressure Testing of Steel Pipelines for the Transportation of Gas, Petroleum Gas
EPRG Project 221/2020	Hydrogen Pipeline – Design and Materials Challenges and Mitigations
AS/NZS 2885-2024	Pipelines - Gas and liquid petroleum (in the process of being updated for hydrogen pipelines)
Sandia Report SAND2013-8904	Polymers for Hydrogen Infrastructure and Vehicle Fuel Systems: Applications, Properties, and Gap Analysis
Sandia Report SAND2012-7321	Technical Reference for Hydrogen Compatibility of Materials
SA TR 15916	Basic considerations for the safety of hydrogen systems

Table 13 Selected online resources on hydrogen effects on pipelines

Technical Reference for Hydrogen Compatibility of Materials	https://www.sandia.gov/matlstechref/
U.S. Department of Energy Office of Scientific and Technical Information	https://www.osti.gov
Pipeline Research Council International	https://www.prci.org
European Pipeline Research Group	https://eprg.net
Sandia Hydrogen Effects Database	http://granta-mi-sandia.gov/mi/index.aspx
DOT/PHMSA	https://primis.phmsa.dot.gov/comm/hydrogen.htm
DOT/PHMSA, R&D Database	https://primis.phmsa.dot.gov/rd/
EIGA Publications	https://www.eiga.eu/publications/
National Research Council Canada	https://nrc.canada.ca/en/research-development/research-collaboration/programs/advanced-clean-energy-program-hydrogen
U.S. Federal Code of Regulations	https://www.ecfr.gov/current/title-49/part-192
Pipeline Distribution	https://hydelta.nl/research-programme

3.1.3 Impact on Codes and Standards

As outlined in this report, there remain significant gaps in knowledge regarding the effects of hydrogen on pipeline integrity. The small number of pipelines currently operating with hydrogen is reflected in the lack of codes and standards that address integrity issues. The primary reference code in the U.S. for operators to base integrity decisions is currently ASME B31.12, which is focused on new construction. B31.12 is being reorganized so that the hydrogen pipeline requirements will become a section within B31.8, and the facility piping may become part of B31.3.

While operating data are limited, numerous research efforts are ongoing around the world, and valuable information is rapidly becoming available. The EIGA document "Hydrogen Transportation Pipelines" is the other main consensus document providing valuable guidance on design. Various codes address pipeline damage, but none include relevant material property or ECA procedures specially geared toward the effects of hydrogen on various threats. In Section 2.1, a qualitative analysis gained through feedback from a wide variety of sources provided the anticipated change in various threats identified in B31.8S, and an additional threat posed by stable crack growth. At this point, sufficient research has been accomplished to begin the development of a new standard, or modification of existing ones, to help operators evaluate the feasibility of repurposing existing lines to hydrogen and guide the modification of integrity management plans to maintain risk to an acceptable level. The development of such a standard should include input from major stakeholders as well as recognized experts in the fields of materials compatibility in hydrogen as well as pipeline design, operation, inspection, and maintenance. A decision on the path forward must first address whether a new standards development effort should be initiated or whether modifications to existing standards are the best course of action. It would appear from the work done in this study that a single document providing recommendations for repurposing existing pipelines would be warranted. The appropriate state and federal regulations could then reference such a document.

4 Task 5 – Review of Threat Algorithms, Tool Selection, Repair Criteria, and Acceptance Limits

4.1 Ranking Integrity Threats

It is important to emphasize that while hydrogen causes degradation in material properties for steels as well as some non-metallic materials, the presence of hydrogen may not represent a significant change for some threats. For example, the rate of metal loss due to corrosion is not expected to be significantly impacted by the addition of hydrogen to NG. Likewise, the dynamic crack propagation and arrest properties should not be affected due to the higher crack propagation rates that preclude hydrogen transport to the crack tip, which is a slow process. Hydrogen has a faster decompression wave, so dynamic crack arrest is actually easier in a hydrogen pipeline than in a natural gas pipeline. However, the criticality or tolerable size for crack initiation may be decreased, but the salient point is the severity of this impact. It is important to consider the threat as well as the form of damage when assessing the overall impact of converting an existing pipeline to hydrogen.

The development of a threat algorithm follows from the data and analyses in Tasks 1, 3, and 4 of this project. This included a methodology for estimating the change in the probability of failure associated with various threats with the addition of hydrogen and the effectiveness of various mitigation strategies. For example, the addition of hydrogen has been demonstrated to increase the fatigue crack growth rate for steels. Mechanical testing has shown that the fracture toughness of steel decreases in hydrogen relative to air/inert environments. With the data published, it is possible to evaluate the crack growth rate and tolerable flaw size for pipeline steel in hydrogen and air/inert and assess the change in the probability of failure. As it is not within the scope of this project to conduct a numerical probabilistic assessment for POF for each threat (nor is it possible with the currently available data and deterministic models), a qualitative process was derived based on the input gained from the SME panel from the Tasks 3 and 4 efforts. This process is intended to inform the user of changes in threat level and strategies/effectiveness of mitigation procedures such as in-line inspection, changes to operating pressures or cycling, etc.

Another pragmatic margin may come from the fact that the hydrogen fracture toughness testing is done in displacement control at terribly slow rates. For an axial crack in a pipe, the loading is load-controlled, not displacement-controlled. So, the crack in a pipeline may initiate at the autoclave toughness levels (adjusted for constraint effects), but as the crack starts to tear ductile, the loading rate increases because the system is load-controlled, not displacement-controlled. So, the crack growth resistance (J-R curve) may increase back towards the non-hydrogen condition. The benefits of improving the burst pressure depend on the amount of stable tearing that the cracked pipe can tolerate. Such evaluations have not been done to date.

The next steps in this process included evaluating the elicitation results, comparing the data to published work, and developing a final report and recommendations regarding changes and additions to the threats identified in ASME B31.8S.

4.2 Relative Ranking of B31.8S Root Causes in Hydrogen

Based on the results of the industry feedback, a ranking scheme was developed to create a seriatim of the threats resulting from the introduction of hydrogen. The ranking is necessarily qualitative and not intended to be interpreted quantitatively. It is only intended to indicate the relative impact of each threat. Each threat was evaluated relative to three factors related to risk: probability, consequence, and mitigation. The definitions are shown in Table 14.

Table 14 Definition of factors related to risk

Probability	Consequence	Mitigation
1 – same as NG	1 – same as NG	1 – usually not effective
2 – 2 times NG	3 – more severe	3 – sometimes effective
5 – 5 times NG	5 – significantly more severe	5 – highly effective

The algorithm to calculate the score is:

$$Rank = \left(\frac{Probability\ \cdot Consequence}{Mitigation}\right) \cdot 10$$

Ranges between 6-20 were judged little or no impact, 12-20 as medium, and above 20 as high. The results are shown in Table 15.

Table 15 Relative ranking of B31.8S threats resulting from hydrogen blending

Threat Category	Root Cause	Potential Effect of Hydrogen	Probability Factor	Consequence Factor	Mitigation Factor	Rank
(a) Time Dependent	1. External Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse limit of local thin area. (M)	2	30	5	12
	2. Internal Corrosion	Not likely an effect on corrosion rate. Decrease in plastic collapse limit of local thin area. (M)	2	30	5	12
	3. SCC	Not likely an effect on SCC, but decrease in fracture toughness reduces critical flaw size (M)	2	50	5	20
(b) Resident	4. Seam Crack	Decrease in fracture toughness results in smaller tolerable flaw size. Higher fatigue crack growth rate, potential for subcritical crack growth under constant load, particularly during hydrotesting. (H)	5	50	3	83.3
	5. Defective Pipe: Hardspot	Decrease in fracture stain and toughness but overall high impact (H)	5	50	1	250
	6. Girth Weld, Fillet Weld, etc.	Decrease in toughness and concentration of hydrogen in HAZ reduces tolerable flaw size (H)	5	30	5	30
	7. Fabrication Weld	Decease on toughness results in smaller tolerable flaw size (M)	2	30	5	12
	8. Wrinkle Bend/Buckle	Decreased in fracture stain and concentration of hydrogen could result in cracking and failure (M)	2	50	5	20
	9. Stripped Threads, etc.	No impact (L)	1	10	5	2
	10. Gasket O'ring Failure	Moderate impact (L)	1	30	5	6
	11. Control/Relief Equipment Malfunction	No impact (L)	1	30	5	6
	12. Seal/Pump Packing Failure	Moderate impact (M)	2	30	5	12
	13. Plastic Pipe	No impact (L)	1	30	5	6
(c) Random/Time Independent	14. Third Party Damage	Decrease in toughness and fracture strain results in potential for fast fracture (H)	5	30	3	50
	15. Previous Damage: dents/gouges	Decreased in fracture stain and concentration of hydrogen could result in cracking and failure (H)	5	30	5	30
	16. Vandalism	Low impact (L)	1	30	5	6
	17. Operating Temperature	Low impact (L)	1	30	5	6
	18. High Wind	Decrease in fracture stain, but overall low impact (L)	1	30	5	6
	19. Water-related	Decrease in fracture stain, but overall low impact (M)	2	50	5	20
	20. Geotechnical	Decrease in fracture stain, but overall low impact (M)	2	50	3	33.3
	21. Lightning	Low impact (L)	1	30	5	6

5 Task 6 – Develop a 5-year Field-Testing Plan to Validate IM Challenges

This task involves identifying important knowledge gaps and making recommendations to help address them over a five-year time horizon.

5.1 Knowledge Gaps

The first objective of this task is to identify significant knowledge gaps. There are several general categories that will be defined here to organize the discussion:

- Experimental Data,
- Testing Procedures Standardization,
- Engineering Critical Assessment Procedures,
- Capabilities of ILI technology, and
- Operating Experience.

5.1.1 Experimental Data

Experimental data are currently being generated at a rapid pace by government and industry-led efforts around the world. Operators are also funding private studies to develop data on their pipelines. Organizations such as PRCI in the US and EPRG in Europe are focused on this topic, with PRCI launching an Emerging Fuels Institute several years ago to oversee industry research. Nevertheless, there is still the need for additional data, particularly on vintage pipeline steels that comprise the majority of the NG pipeline network in the U.S. The procedure for the testing to gain data of direct use for piping integrity evaluations includes accounting for hydrogen and constraint aspects consistently for fracture toughness. Too much of the recent data has ignored the constraint aspects by using non-standard test specimens that are convenient for autoclave testing but can give misleading results compared to standard testing procedures for flaw evaluation. The standardization of test specimens, procedures, and data reduction is an effort just incubating on the European and US fronts. Data reduction techniques can lead to a much larger error than even improper test procedures. This section highlights some of the most important areas where data are needed to better assess the various threats. The focus here will be on threats identified in Section 4.2 as having the most impact on integrity.

5.1.1.1 Fracture Toughness

The threat of leak or rupture from cracks is clearly one of the most significant issues associated with blending hydrogen in NG pipelines. Lines constructed prior to about 1970 are known to have cracking issues in the ERW seam, as discussed in Section 2.2.1. This, coupled with generally low toughness, makes seam integrity an even greater integrity threat. In inert environments, some vintage seam welds may have axial surface cracks that may initiate in a brittle manner. Hence, the hydrogen effects of such materials with the proper constraint conditions representative of a surface crack in a pipe are critical for determining the ILI requirements and suitability of such materials. Over the last 10 years or so, a significant amount of toughness data on vintage steels has been generated, see References [10], [21] and [53]. This information has led to significant insight into the statistical characterization of the toughness of vintage steels, including seam welds. Data on the toughness of vintage steels in hydrogen service has become available only recently for only a few welds, and data on the scale of References [21] and [14] will be needed to characterize base material as well as seam-weld properties in hydrogen.

A significant issue that will affect fracture toughness is hardness. It is well known that high hardness is vulnerable to cracking, generally referred to as hydrogen stress cracking (HSC) [36]. Data have shown that some vintage manufacturers have been associated with producing line pipe with hard spots – the most often cited is A.O. Smith [20], although there are several others during the 1950 pipe production era [35].

Typically, the source of hydrogen causing these types of failures has been attributed to cathodic protection systems, where a combination of coating failure, wet soil (sometimes with trace CP hydrogen enhancing elements), and CP current results in hydrogen charging. The combination of these three aspects is a relatively low probability. In the future, as hydrogen is blended into NG lines, the potential for HSC will increase as the entire pipeline will now be subject to hydrogen charging, even with good external coating. Whether hard spots created in the plate end up with higher hardness on the ID surface currently seems less probable from current experience, but it might still be possible. Also, there are cases of the hardness being greater subsurface, so the hydrogen getting to that subsurface region will depend on the stress gradient from the pressure stresses, residual stresses from the accident quenching/creation of the hard spot, and the bending stresses from pressurization of the pipe with a flatter region in the hard spot.

In addition to hard spots, hard seam welds with low toughness have also been identified as a contributor to pipeline failures. Very limited data are available relating fracture toughness to the hardness of vintage pipe. As discussed in Section 2.2.2, data from Battelle published in the 1970's is still one of the few sources of such data. In Reference [39], it was also pointed out that for a surface crack in a hard seam weld, the strength of the weld metal affects the crack-driving force (reducing it), which is not included in any of the burst pressure models to date.

5.1.1.2 Notched Tensile Testing

The use of notched bar testing with varying acuities can be very useful in exploring the effect of stress states on hydrogen embrittlement. It is thought that high hydrostatic tensile stress regions and plastic-strained regions will have a higher hydrogen concentration, influencing fracture strain. Notched bar testing offers the most economical means of studying this experimentally. The use of various notch radii provides the ability to vary the stress state. These test results will be quite useful for the evaluation of integrity challenges involving plastic straining of line-pipe steels, i.e., dents, dents and gouges, wrinkle bends, buckles, etc.

5.1.2 Testing Procedures Standardization

Conducting fracture toughness tests in gaseous hydrogen has become more widely practiced in recent years, compared with the more common approach of cathodically charging hydrogen. In-situ tests in gaseous hydrogen are more complex and costly but provide the ability to assess materials by replicating the intended environment for pipelines as closely as possible. These tests are conducted following the general requirements of either ASTM E1820 or ASTM E1681. The latter involves using a bolt-loaded specimen to impose a static load (constant displacement) to determine subcritical hydrogen crack growth, which is different than the start of ductile tearing by E1820 used for critical crack size evaluations. The results of the E1681 test provide a means of determining the threshold stress intensity K_{TH} for environmentally driven cracking mechanisms. It has been demonstrated that the use of this type of test, compared with an active loaded one following ASTM E1820, can lead to non-conservative results for subcritical crack growth evaluations. In B31.12, Option B, a performance-based test is permitted for qualifying steel for hydrogen pipeline transmission in the final heat-treatment condition. It refers to the testing procedures in ASME VIII-3, paragraph KD-1040, to determine the threshold stress intensity for crack initiation, K_{IH}. The testing procedure referenced in KD-1040 is ASTM E1681, *not* ASTM E1820. Here, the terminology becomes confusing. This reference to "K_{IH}," as used in ASME VIII-3 KD-1040, is *not* to be confused with the onset of crack growth but rather K_{TH}. These two parameters are determined in a different manner. The value of K_{IH} is established by conducting a specimen test, i.e., a C(T) specimen (preferably in a high-purity gaseous hydrogen environment) with a very slow rising displacement rate. Sufficiently slow loading is needed so that hydrogen can migrate to the crack tip (see Section 2.2.1). The load at which crack extension begins is used to calculate the K_{IH} value. When a similar test is conducted under constant displacement (ASTM E1681), the point at which crack growth stops is usually referred to as the K_{TH} limit. Therefore, K_{TH} is really a stress intensity factor where the subcritical hydrogen cracking stops and can be much lower than K_{IH} [54].

One of the most important factors in evaluating toughness in hydrogen is the displacement rate (see Figure 9). Standardizing this parameter would enable data from different labs to be compared. Another important factor that influences toughness testing in hydrogen is gas purity. It has been shown that even small traces of oxygen can impact the test results, as illustrated in Figure 45 [26].

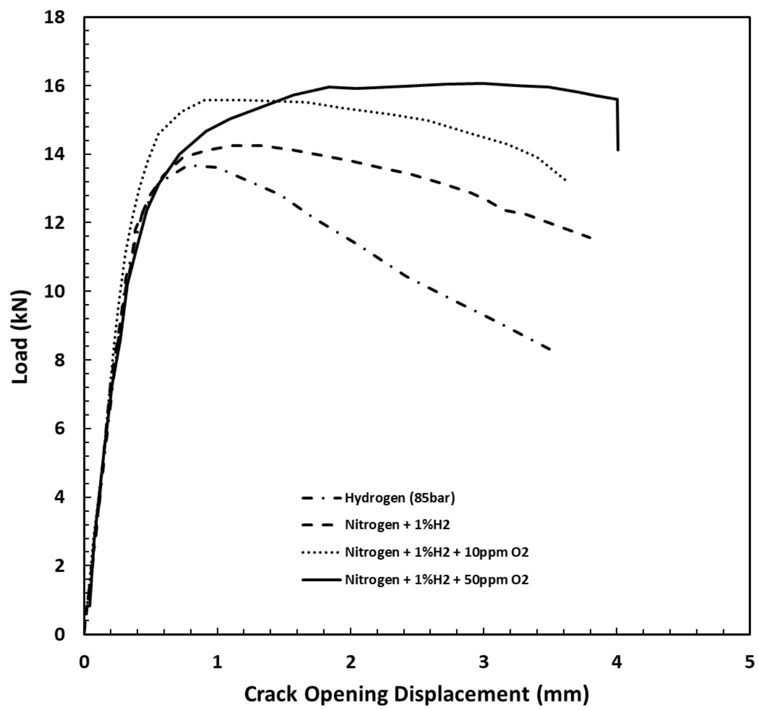


Figure 45 Effect of gas purity on load-displacement curves

Specimen geometry is another important factor in fracture toughness testing. The influence of geometry and mode of loading on measured fracture toughness is well known. This has been demonstrated by the observation that testing the same material using specimens with different dimensions or loaded in a different manner produced significantly different results. This effect on changing the fracture toughness values is referred to as constraint, where one school of thought is the degree of stress triaxiality at the crack tip, often described by the ratio of hydrostatic to effective stress. However, new constraint parameters are still under development, even for inert toughness testing. The magnitude of stress triaxiality affects the size and shape of the plastic zone, which in turn strongly influences fracture resistance. Understanding constraint effects on testing has practical importance in addressing the transferability of lab results to engineering structures. An important aspect of standardized fracture toughness testing following ASTM E1820 is that results with preferred specimen geometries[††] that are

[††] For a C(T) or SEN(B) specimen, the preferred geometry for plane strain conditions is W/B=2 and a/W=0.5. Higher W/B values will give higher measure toughness values due to more of a plane-stress condition being achieved. Similarly, having different a/W values can change the measure toughness as well.

independent of specimen geometry and can be applied generally without loss of conservatism [28]. To accomplish this, specimens are deeply notched and loaded predominantly in bending to ensure plane strain conditions along most of the crack front. In addition, limits are placed on certain specimen dimensions such as thickness and ligament length (B, b_o, or W/B), crack depth to width ratio (a/W) and extent of permissible crack growth (Δa), see Section 2.2.1. Most test data reported for pipelines in gaseous hydrogen use the compact tension, C(T) geometry, which is a high-constraint test specimen. However, cracks found in pipelines are subject to a very low level of constraint, and therefore, the application of C(T) or other bend specimen geometries is conservative when applied to cracks in pipelines. This is demonstrated in Table 6, where the mean fracture toughness for single-edge-notched tension, SEN(T)), specimens taken from the same pipeline is considerably higher than as measured using C(T) specimens [14], [21], [27], [29], and [30]. This issue will become important when considering the tolerable flaw size for cracks in pipelines – particularly as the detection limits of ILI crack tools may be stretched. It should be mentioned that pipelines have a high diameter-to-thickness (D/t) ratio, with thickness often in the range of 0.2" to 0.3" thick C(T) specimens. When machined, C(T) specimens often have a W/B value above the preferred specimen geometry of ASTM E1820; see Figure 21. The higher W/B specimen will have a lower constraint than the preferred specimen required by the standard [28] with a higher apparent toughness. Similarly, SEN(T) specimens have a lower constraint similar to a surface-cracked pipe, but the measured toughness changes with the a/W of the crack, see Figure 22. A recent study at the end of this program showed that for SEN(T) specimens with different a/W values in a vintage base metal, the hydrogen concentration will change with the a/W of the crack, which occurs due to the higher plastic strains in the shallower flawed specimen that has higher toughness, see Figure 46. The displacement continued up to the values where ductile tearing occurred in air. SEN(T) testing is not done in hydrogen autoclave testing to date to assess the potential toughness changes with crack depth, so future efforts are needed to evaluate if the toughness change with a/W (or a/t of a surface crack) may flatten due to the difference in the hydrogen concentration, as illustrated in Figure 47.

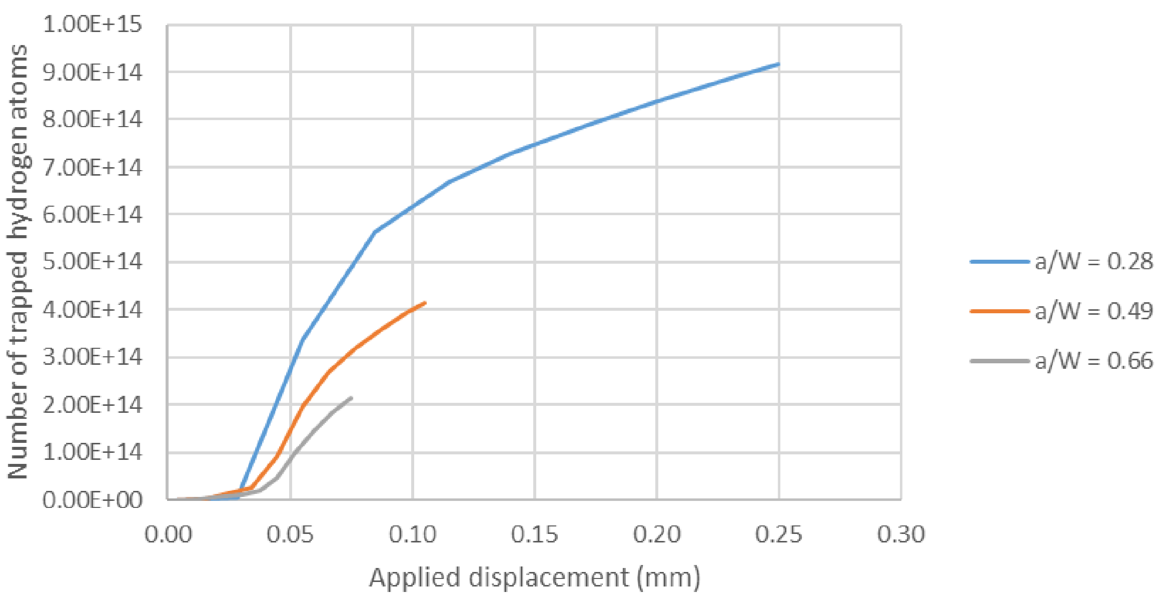


Figure 46 Number of trapped hydrogen atoms in the plastic zone as a function of applied displacement for the SEN(T) specimens with a/W = 0.28, 0.49, and 0.66 (displacement stopped at the displacement where ductile tearing started in air environment tests)

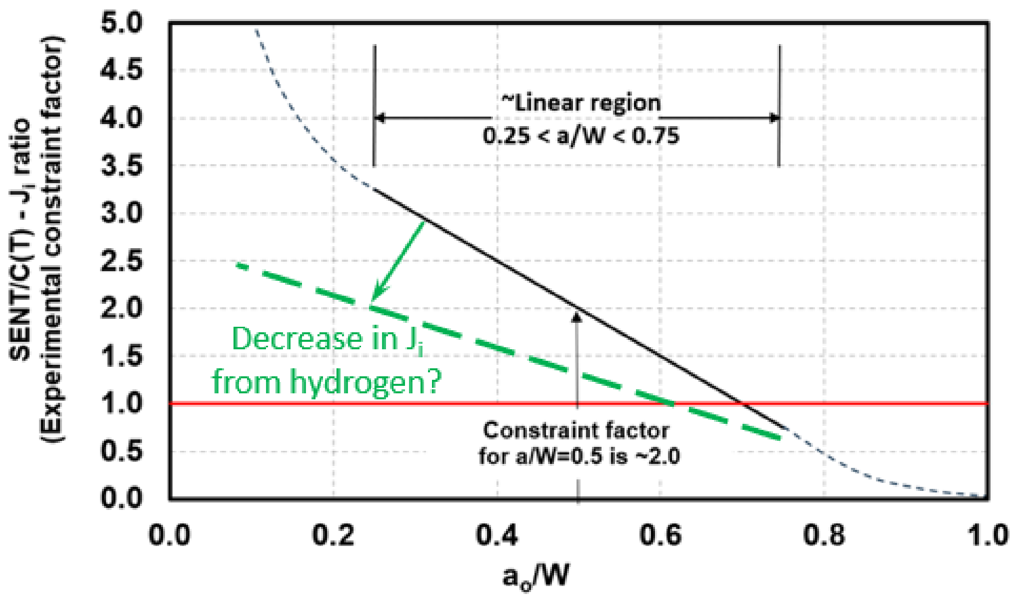


Figure 47 Relationship between standard C(T) specimen initiation toughness (J_i) and SEN(T) specimen J_i values as a function of a/W in the SENT specimens for air testing and possible change in the SEN(T) J_i values in hydrogen

Interpretation of toughness data also varies. In ASTM E1820, fracture toughness (measured by the J integral and frequently converted to K for use in ECA analysis) defines the critical J_{Ic} using an offset crack growth approach like that used in defining the 0.2% offset yield stress in tensile tests. The value of J_{Ic} is taken from the intersection of a power-law regression curve of the J-R data and an offset line at 0.2-mm crack extension. This is an engineering definition aiming at consistency in approximating the initiation of crack growth since crack length monitoring techniques like unloading compliance can have difficulty in detecting the very start of ductile tearing. However, the application of d-c electric potential difference (DCPD) technique provides a more accurate measurement of the point of crack initiation, typically at a lower value of J. The "Experimental Key Curve Method" of defining the onset of crack growth is also useful as well [55]. In characterizing toughness in hydrogen, as in all fracture toughness reporting, it is important to identify clearly how the value of J_{Ic} was developed. The DCEP method is most frequently used in hydrogen autoclave testing but requires experience in data reduction techniques since the electric resistivity changes linearly with plastic strain. Hence, there is an offset in the DCEP signal from the start of the test, where blunting stops and ductile tearing commences. Some published papers reduce this data quite differently, which, from our review in this project, can change the calculated "toughness" values at the start of ductile tearing by a factor of 10 to 20. In addition to the fracture toughness, reporting the full J-R curve is also valuable as this is a measure of the tearing resistance with increased displacement.

As noted earlier, several other aspects of specimen testing in hydrogen need further evaluation. For instance, all autoclave testing is at room temperature, whereas some vintage seam weld testing at the minimum operating temperature would be desired. C(T) tests not only give conservative upper-shelf toughness values compared to shallower surface cracks, but the transition temperature for cleavage initiation is about 55F warmer in the C(T) test than a surface crack or SEN(T) specimen with a/t (or a/W) values greater than 0.38 [14]. As noted earlier, the SEN(T) test and surface-cracked pipe have toughness increasing as a/W decreases. However, the associated plastic strains near the crack tip will have a higher hydrogen concentration, so this interaction of constraint and hydrogen has yet to be explored. It was also noted that the autoclave testing is at a very slow constant displacement rate. A surface crack in a pipe is under load-controlled loading. So, once a crack starts to grow near the instability condition, the crack growth rate increases, which in turn may decrease the effect of hydrogen on the J-R curve of a surface-cracked pipe relative to autoclave testing. The margins gained from this are not known at this time.

Another aspect of testing in hydrogen is the way the hydrogen pressure is reported. At low pressures, it is acceptable to assume that hydrogen behaves as an ideal gas, and the partial pressure and fugacity are essentially equal. However, at high pressures this is not a valid assumption, and it is more appropriate to report a fugacity instead of partial pressure [56].

These aspects represent just a few of the considerations that can be important for characterizing the fracture toughness of pipeline steels in gaseous hydrogen in a manner needed for consistent surface-flawed pipe assessments. At present, as there are no standard test procedures, and data reported in the literature may be somewhat difficult to interpret for evaluating fracture tolerance, as well as inconsistent from pipe material to pipe material since different W/B specimens may be used for different thickness pipes. This last point makes it more difficult to get a constant hydrogen degradation factor for different materials. Also, as noted, even the data reduction procedure for detecting the start of ductile tearing in a hydrogen test might lead to underpredicting the J_i and J_Q values by a factor of 10 to 20.

5.1.3 Engineering Critical Assessment

As discussed in the previous section, the selection of fracture toughness as well as the use of a criterion for initiation of subcritical crack growth are the two critical components in crack assessment procedures. Otherwise, the way the calculations are made remains unchanged, except in some special cases (i.e., cracks in hard seam welds or hard spots). Regarding other forms of damage, such as dents, gouges, and local thin areas, it is not yet clear whether changes to existing ECA procedures will be warranted. It should be noted that crack assessment procedures where an explicit value of fracture toughness (e.g., API579, BS7910, R6, MAT8, and the Emc^2 FE-based J-estimation procedure) is used will be more straightforward in accounting for the effects of hydrogen. For empirical crack assessment methods that have been calibrated to burst tests conducted by hydrotesting in water, one approach might be to take the J_{IcH} and calculate an equivalent Charpy energy. Knowing a toughness degradation factor on J_{Ic} from hydrogen and implementing that through a Charpy energy adjustment would be extremely beneficial to operators that have established Charpy energy databases for line-pipe steels in their lines for addressing the DOT/PHMSA MegaRule toughness requirements [14].

An interesting aspect uncovered in this program was that when including the strength of a high hardness weld in the FE analysis, the higher hardness drops the crack-driving force, which is not included in any burst pressure evaluation procedures. This same trend was observed in nuclear pipe flaw evaluations, where the weld-metal strength decreased the crack-driving force. One could define an effective stress-strain curve for the crack-driving force from FE analyses that is a function of the weld and base metal stress-strain curves, see References [57] and [58].

For other forms of damage that are related to strain-induced damage and failure by plastic collapse, it is less clear whether assessment procedures need to be revised nor what failure criteria to use [9]. For some forms of damage like dents, research continues to refine assessment approaches and outline issues with current practices [59], [60]. Based on the considerations outlined in Section 2.3.1, the strain limits for dents should be revisited to determine if more restrictive acceptance criteria are needed, and fatigue crack growth in a dented pipe should be affected by hydrogen.

For gouge-and-dent defects, it is likely that the time to failure after the damage is reduced and that the failure pressure is also reduced. This is a complicated evaluation that is more likely to need full-scale testing to guide evaluation procedures.

5.1.4 Capabilities of ILI

The effects of hydrogen on flaw tolerance raise some important implications for ILI. As has been discussed, the acceptance criteria for many threats are reduced and, therefore, may require improved performance from ILI tools. For NG pipelines, there is a natural preference for use of crack-detection tools that do not require a couplant, i.e., EMAT. Since EMAT systems are generally less capable in terms of detection threshold and sizing accuracy than ultrasonic testing crack detection (UTCD) systems, the suitability for managing a crack-related threat with technology needs to be included based on an ECA analysis. If the toughness decrease in higher hardness steels is as severe as suggested in Figure 21, then the critical crack sizes might be below the UTCT or EMAT capabilities.

5.1.5 Operating Experience

While the mileage of pipelines containing hydrogen is very limited, experience has demonstrated safe and reliable performance to date. Data available pipelines in hydrogen service regulated by PHMSA is shown in Figure 48.

Source: U.S. Pipeline and Hazardous Materials Safety Administration

Database accessed July 20, 2016

Operator Name	Intrastate Miles	Interstate Miles	Total Miles
AIR LIQUIDE	328.4		328.4
AIR PRODUCTS	77.2	536.4	613.6
AKZO NOBEL	0.5		0.5
BUCKEYE	45.8		45.8
CITGO	9.2		9.2
EQUISTAR	23.0		23.0
EXXONMOBIL	0.4		0.4
HOLLY ENERGY	5.8		5.8
HUNTSMAN	1.9		1.9
KOCH	24.8		24.8
LAFITTE	5.9		5.9
LINDE	32.5		32.5
MARATHON	0.02		0.02
MARKWEST JAVELINA	5.3		5.3
MOBIL	3.1		3.1
OCCIDENTAL	1.9		1.9
OLIN	6.0		6.0
PHILLIPS 66	43.3		43.3
PRAXAIR	131.4	244.8	376.2
SASOL	1.0		1.0
DOW	11.0		11.0
TPC GROUP	0.9		0.9
US AMINES	20.1		20.1
VALERO	5.1		5.1
WESTLAKE	1.2		1.2
Air Liquide, Air Products, Linde, Praxair	569.6	781.2	1,350.7
Other Companies	216.1	0.0	216.2
Totals	**785.7**	**781.2**	**1,566.9**

Figure 48 Mileage of pipelines operating with hydrogen service

The total mileage of pipelines in hydrogen service total only about 2,823 miles. To date, experience has been good; however, as the total mileage is so small, there is not a large dataset from which to draw definitive conclusions. In addition, some of these lines were designed for hydrogen, and the operating stresses are generally much lower than those of NG transportation Class 1 piping systems.

5.1.6 Full-Scale Testing

The use of burst testing is valuable for validating models for estimating the failure pressure of pipelines containing cracks. Research by Robinson at Sandia in the late 1970s looked at the failure pressure of line pipe with axial surface flaws. This study was an early investigation of blending hydrogen into existing pipeline networks. Tests were conducted in nitrogen and hydrogen-nitrogen gas mixture with hydrogen partial pressure of 1,000 psig. Surface flaws were introduced on both the ID and OD of each pipe near the center. Crack depths were in the range of 18-25% of the wall thickness. (The fracture toughness is elevated with shallower surface flaws; see Figure 22.) The results of the tests are shown in Figure 49, which is a plot of the normalized hoop stress versus crack length. The experiments indicated a reduction in burst pressure of about 15% when hydrogen is present for these flaw sizes. Recent full-scale testing is being conducted by EPRG and is focused on the fatigue crack growth of axial flaws. Future tests are also planned and underway by EFI funding at CFER. There were also two papers at the 2024 IPC conference with some pipe test results. The Sandia paper [33] tested small-diameter A53 pipe with ID and OD axial surface cracks in pressure cycling with hydrogen. The results showed that both the ID and OD surface cracks had a significantly reduced number of cycles to leakage with internal hydrogen. An implication was that since the ID surface was not cleaned, the hydrogen was adsorbed into the steel through this barrier. The full-scale hydrogen test results reported by Cosham [34] had ID and OD axial surface cracks in larger diameter pipe with hydrogen. They cleaned the ID surface, but only the ID flaw burst pressure was reduced with hydrogen. This had the opposite suggestion that the hydrogen effect on OD flaws (burst pressure) was negligible. So, the data to date is somewhat inconsistent.

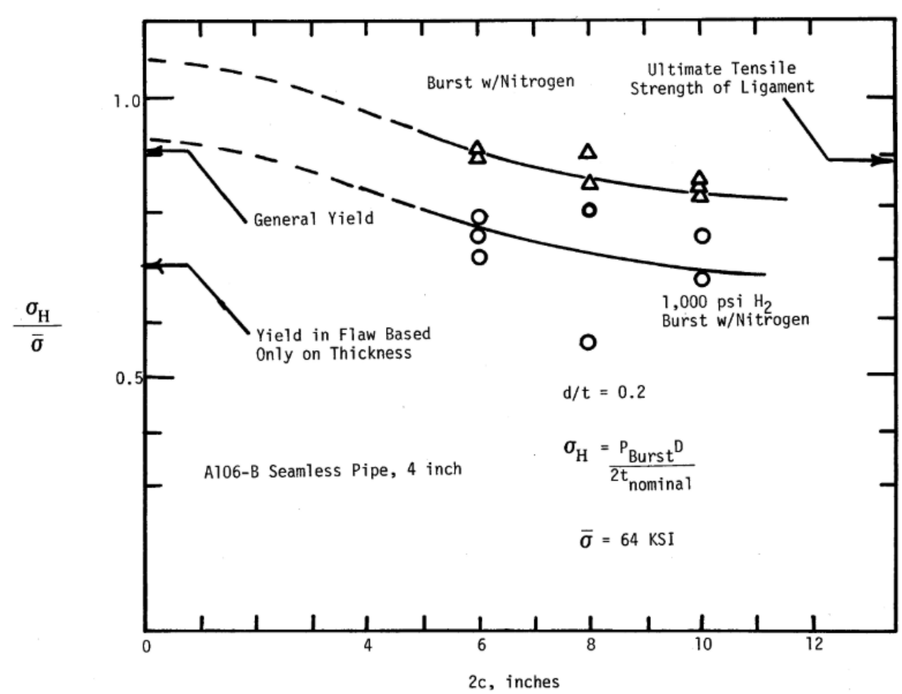


Figure 49 Full-scale burst tests of line pipe in hydrogen and nitrogen by Robinson

5.2 Five-Year Plan

For this task, we have been assembling data and information for the entire duration of the project. We have reviewed each of the 33 topics (related to the topics in the SME Elicitation efforts) in greater detail and ranked them on a scale of 1-5 (5 being the most important).

This 5-year plan contains many topics on material properties, pragmatic integrity challenges, repairs, inspection, metallic and non-metallic components, fitness for service evaluation procedures, codes and standards, etc. Most of these topics came from the elicitation workshop, where we had input from ~20 SME independent participants who answered 65 different questions. (Ms. Stephanie Flamberg of RSI was of great assistance in this effort.) We also examined efforts in the US and elsewhere around the world, some of which were discussed in the two Emerging Fuel Symposiums over the last 2 years, as well as papers from IPC conferences and ASME PVP conferences. The PRCI/EFI efforts have also been accounted for, and there were perhaps hundreds of helpful emails/discussions from those involved. We have also been in contact with EPRG and Australian efforts. Some of the information from other private JIP efforts was known, although some efforts are much more confidential. There is also work at the DOE labs and other DOT-funded projects that were reviewed as well. One of the topics on repairs was higher on our initial higher-level evaluation group but was lowered in priority since DOT/PHMSA sent out requests for proposals for that topic in May 2024. Hence, the repair topic is getting DOT/PHMSA attention from that soon-to-be-funded effort (funding might be in September or October 2024), although the adequacy of the workscope from this project's recommendations is not yet known. Finally, there is an abundance of technical papers that include efforts in other related industry applications involving hydrogen embrittlement in pressure systems, as well as more detailed evaluations conducted in this project and a companion project on hydrogen pipelines at Emc^2 being conducted for DOT/PHMSA [39]. The initial Task 1 in this project involved a "literature review," and there was a complimentary "literature review" in our companion DOT/PHMSA project focusing on vintage pipelines. These "literature reviews" were written as more of a tutorial summary on either material property changes with hydrogen or analysis procedures to understand the hydrogen degradation aspects in materials and pipeline systems. There are separate reports available on the DOT/PHMSA project website; see References [4] and [61].

Greater weighting was, of course, given to the topic's importance to the overall industry and regulatory needs and whether the various deterministic aspects would be sufficiently addressed to do the whole pipeline system evaluations within that same 5-year time period. (The table is limited to a 5-year plan recommendation.) Some might argue that a relative probabilistic evaluation could show the desired sensitivities; that is true if the deterministic relationships used in the probabilistic evaluation reasonably captured the sensitivities and failure modes.

Finally, the importance of the overall pipeline network was considered, not just new or vintage pipeline systems. It might be that a specific problem might be limited to a smaller population of pipeline systems, and because of the lower overall impact, the ranking might be lower. (However, if you owned that system, it might be a high-importance topic.) One specific integrity concern that comes to mind is wrinkle bends. Some older systems might have wrinkle bends, and if they have one, they might have hundreds. But that might be the lower percentage of the overall pipeline network. On the other hand, challenges like dents, general corrosion patches, and mechanical damage can affect all piping systems, so they have a higher ranking.

Of the 33 topics, there were five groups, and within a subgroup, there was an additional ranking. That subgroup ranking is not shown in the table below but was used to create the overall ranking order. For the highest ranking (a value of 5), there were 11 topics. For a ranking of 4, there were 3 topics. For the ranking of 3, there were 8 topics. For the ranking of 2, there were 7 topics. For the ranking of 1, there were 4 topics. As one SME stated during the SME Elicitation Workshop, the hydrogen integrity challenges may be like peeling an onion – attack the higher priority items first, then the next layer becomes the subsequently higher priority layer.

For this table, with 33 topics, it was only possible to put in a few lines on “Discussion and Need,” as well as whether there is “Any Ongoing work” on that topic or suggestions. The topics are not just “Field Testing” but include the associated analyses to design, validate, and extrapolate the results to other pragmatic situations.

Table 16 Suggested 5-year program on the various topics for hydrogen pipeline integrity evaluations in order of their ranking

Item #	Topic	Discussion and Needs	Any on-going work on this topic?	Priority rating
1	Evaluation of fracture toughness constraint effect interactions with hydrogen	From a MegaRule viewpoint, the toughness reduction relative to data in the existing air toughness database is needed. The autoclave testing to date is too variable in specimen sizes, which can significantly affect the J_i values. Some constraint adjustments (for W/B of CT and SENB being different than 2, and a/W different than 0.5) exist in air but require starting with a reference specimen size specimen (i.e., W/B=2 and a/W=0.5 in C(T) and SEN(B) testing. These correlations need to be validated in hydrogen to make adjustments to the significant existing data. Included in the constraint effect interactions is the fact that in air, shallow flaws have more plasticity at failure, so they should absorb more H+ than deeper flaws. Hence toughness changes with surface flaw depth may differ with H+ concentration. This result may also affect the leak-rupture boundary. This item affects all toughness evaluation items below and is given the highest priority because of that.	Some minor work on this topic was done in Emc^2 projects for DOT/PHMSA. Current autoclave data need adjusting to give J_i values relative to critical surface crack size evaluations in pipe, and determine adjustments to Charpy and fracture toughness databases for pipeline made to address the DOT/PHMSA MegaRule requirements should they be extended to converting existing pipelines to hydrogen-blended pipelines. Some round-robin efforts by EPRG and PRCI are just starting up with the objectives still being formulated at the time of this report writing. Testing procedures and data reduction can drastically change toughness values calculated.	5
2	Fracture behavior of steels with CVN<20 ft-lb	This topic applies to some lower toughness vintage base metals or ERW/EFW seams where; da/dn, S-N, stress-strain curve, and toughness data are needed. It is desired to know how much reduction is there in upper-shelf toughness (J_i) with H+ partial pressures (see discussion on Topic 11). Will the brittle initiation transition temperature change with hydrogen is an important question for vintage welds that have warmer transition temperatures.	To our knowledge, there is no autoclave testing with gaseous hydrogen as a function of temperature to date, especially for cases with warmer transition temperature materials. There is a little electrochemical testing at temperature. We haven't seen vintage ERW/EFW seam weld data yet, other than an early Battelle NG-18 report #151 in the 1980s.	5
3	Material properties for vintage steels	This topic includes X42 to X60 vintage pipe with ERW/EFW/DSAW and girth welds – pre-1970 steels; da/dn, S-N, stress-strain curve, toughness data are needed. Overlaps with Topic 2.	Sandia and SwRI have developed a small amount of such data, but there is not much public data to date. There are a number of private JIP projects developing such data.	5
4	High hardness welds (HBN>220)	This topic includes older girth welds, higher hardness ERW/EFW, and hard spots where fracture toughness data is needed. Overlaps with Topic 3.	There are a few tests in the older Battelle/NG-18 Report 151 data on simulated hard spot, and ERW fusion line. Some girth weld data in a SwRI private report. Sandia presented a paper at IPC2024 on hardness effects on fracture toughness, although the toughness values seem quite low.	5
5	Flaw assessment standards or FFS tools	Some guidelines on acceptable flaw sizes with hydrogen degradation are still needed. Many full-scale tests are just barely starting or not even in the planning stage yet. Material testing is further along, but not yet with some of the materials of higher concern for repurposing existing pipelines. Probably more of a change to the inputs is needed than the analysis procedures themselves, although the existing analyses do not calculate the crack-driving force well for cracks in welds that have higher strength than the base metal.	Need to relate hydrogen toughness changes to the database of air material toughness as an input. This is eventually a probabilistic evaluation.	5
6	Mechanical damage - gouges in dents	Plastic deformation and residual stresses in the damaged region can significantly affect the H+ concentration around the damaged region. That hydrogen concentration should affect the sustained load or delayed failure time, and perhaps the fatigue crack growth in the damaged region.	EFI is planning some mechanical damage fatigue tests, but this is a very difficult problem since the hydrogen concentration may be much larger in this type of flaw from the local plastic straining. Mechanical damage is a higher concern integrity challenge for current pipelines.	5
Item #	**Topic**	**Discussion and Needs**	**Any on-going work on this topic?**	**Priority rating**
7	Updating of Codes and Standards	Hydrogen pipeline standards are in the infantile stage at this time. The B31.12 pipeline aspects are to be moved to an annex in B31.8. Emc^2 staff are planning to get involved with that effort to communicate the results of this and a companion DOT/PHMSA project. EFI has a project to identify threats and then pare them down to be addressed with this new B31.8 hydrogen effort. That EFI effort will not be completed before the end of this project. There might also be some efforts in API-1176 in the future.	EFI project is to develop a threats list for the new B31.8 group to consider how the standards should account for those threats. Emc^2 is to contribute findings from this program to the B31.8 group. Next meeting in September 2024 is at the end of this project. Progress to date in the B31.8 group is that they will not include hydrogen effects in B31.8S in time to be in the 2026 Edition. Continued interaction and monitoring is needed of this activity.	5
8	HSC in hardspots	A question of concern is if H+ concentration in a hard spot from hydrogen gas transmission is less detrimental than external generated H+ from CP/soil and coating loss?	Some toughness data from old Battelle/NG-18 program on simulated hardspot material with BHN=350 exists. Higher hardness tests needed. PRCI has started some efforts on "Optimizing Cathodic Protection to Avoid Cracking" in hard spots, which should be helpful. Sandia just pubished soem resutls at IPC2024, but the values look very low.	5
9	Inspection intervals	May need shorter duration inspections with lines more sensitive to pressure cycling (green hydrogen, service to gas turbines, nuclear power electrolysis during off-peak electrical survive demands, etc.)	Needs probabilistic evaluations with update of integrity management plans.	5
10	Dents	Should guidelines for dent dimensions (% of diameter and sharpness of dent) change due to plastic deformation attracting hydrogen concentration? Will the higher H+ concentration from the plastic strain affect the dent fatigue performance?	PRCI/EFI is doing some full-scale dented pipe fatigue testing in future. Difficult to assess in lab testing, although specimen testing with different amounts of cold working are needed for the modelling.	5
11	Growth under sustained loading	There are two aspects to this topic for pipe-fracture evaluations. The 1st is for subcritical crack growth; the 2nd is the effect on the burst pressure and ductile tearing toughness. A question to be answered for a technical basis is "does the isochronous stress-strain curve change with hydrogen?" K_{IH} from autoclave testing is important, which is different from sustained loading reductions of burst pressure. Some efforts on looking at K_{IH} are ongoing, but we are not sure how that might affect long duration hold-pressure burst test margins, i.e., sustained loads drop the burst pressure by about 15% in inert environments, but the trend in H+ environment is unknown. This may require some step-hold test comparisons – lab and pipe. From a lab specimen testing viewpoint, the typical autoclave testing in hydrogen gas is at very slow rates to allow for hydrogen transport to the crack tip, while fracture toughness tests in air are done at higher loading rates. This loading rate difference contributes to the difference in J_{Ic} in air versus having small amount of hydrogen. We suspect that much of the difference is from the primary creep that is occurring in the hydrogen autoclave testing. There may also be differences for the instrumentation and data reduction procedures being different in air and autoclave testing. For instance, air testing with unloading compliance give a J_{Ic} (or J_Q) value that has 0.2mm of crack growth. d-c electric potential in autoclave testing however gives the very start of crack growth where the J_i value is less than ASTM J_{Ic} even in air at the same loading rate, but d-c EP data reduction is an art. Hydrogen testing standardization is needed, which is starting in an EPRG effort.	Some K_{IH} efforts are ongoing, more so in private JIPs. We are not aware of evaluations of the isochronous stress-strain curves (primary creep) dropping further with H+ than with air. Testing standardization for autoclave testing in hydrogen is needed, and just starting in an EPRG effort. Sandia has a IPC2024 paper that includes testing in nitrogen at slow rates for comparison to hydrogen testing at various amounts of hydrogen.	5

Table 16 Suggested 5-year program on the various topics for hydrogen pipeline integrity evaluations in order of their ranking, continued

Item #	Topic	Discussion and Needs	Any on-going work on this topic?	Priority rating
12	Repair sleeves	Repair sleeves exist in many pipeline that may be considered for hydrogen service (blended or 100% hydrogen). The Type B repair sleeve has a circumferential fillet weld. Some lines may have hundreds of these sleeves. The fillet weld has a natural crack/singularity at the root, and with the welding residual stresses that will be a location of high hydrogen concentration. Being a post-construction field weld done in the ditch, the quality of this type of weld may be less than seam welds or automated girth welds. Hence the hydrogen might be higher and there is a greater likelihood of weld flaws in such fillet welds too.	Emc^2 did evaluation of hydrogen at fillet weld, and examined the concept of applying an overlay on top of a fillet weld for a new type B sleeve being put on. EFI is interested in this topic for H_2 accumulation in annular area. A future DOT/PHMSA project may address this topic.	4
13	General Corrosion Integrity	This topic was brought up during the SME elicitation effort, and it is thought it might be less important than other service flaw types, but there are no data. Hydrogen may have an effect on the burst pressure due to the reduction of strain capacity. The importance depends if actual failure criterion (not codes and standards criteria) depends on a reaching a critical strain or the ultimate strength for a corrosion patch region. There is one publication that suggest that hydrogen might affect the reactivity of the steel to corrosion, but the pragmatic implication are not known.	Some EFI testing is planned. Emc^2 hydrogen concentration analysis showed the H+ concentration is not high in the corrosion patch (using a laser scan of irregular depth case), but if a crack is in the corrosion patch, the sensitivity may be higher. Some autoclave SEN(T) or notched round-bar testing might improve understanding.	4
14	Material properties for medium strength steels (~1970-2000 vintage)	This includes X65 to early X80 steels – from 1970 to 2000 construction; da/dn, S-N, stress-strain curve, and toughness data are needed.	European full-scale testing on their earlier steels falls in this category. Some C(T) data by Sandia exists, but one needs to do constraint corrections to apply to a pipeline surface flaw evaluation. Data reduction procedure should also be reviewed. (See Topic 1.)	4
15	Effect of hydrotesting prior to H_2 service	Some preliminary H+ concentration FE analyses were conducted for different flaw types in this program. The procedures still need to determine how that local level H+ concentration affects material properties. (This is being initially examined as part of separate DOT/PHMSA project at Emc^2.) Since repurposing of the pipeline for different service can require hydrotesting by DOT, this topic becomes more important.	We are not aware of any experimental efforts. Potentially, this topic could be evaluated by SEN(T) evaluations simulating the hydrotest overload prior to going into hydrogen service. The importance depends on how sensitive toughness is to different levels of hydrogen.	3
16	Hot taps/stopples	New hot taps versus hot taps on vintage lines for H_2 injection lines both consist of having saddle welds that would be concentration points of H+, but if there are no flaws the higher H+ would not be a problem. K_{IH}, residual stresses, and fracture toughness impact the significance of this topic. Stopples have similar issues, but are only used on smaller diameter pipelines.	Some new hot-tap full-scale testing is being done in Europe. A future DOT/PHMSA project may address this as part of examining repair procedures.	3
17	Material properties of high-strength steels (2000-present)	X80 to X100 from 2000 to current construction; da/dn, S-N, stress-strain curve, and toughness data are needed. New steels (even lower grade) have high Charpy energy values, so their hydrogen toughness reduction could be larger than vintage steels. However, if in the limit-load region, the toughness reduction may not be very significant on the burst pressure. This is relevant to new construction. (See Topic 1)	Sandia and EPRG have developed data, maybe some data is developed in private JIPs. These data need to have constraint corrections to them to be applied to pipeline surface flaw evaluations, and test data reduction procedures should be evaluated.	3
18	Fatigue crack growth rates	While data on base metal are being generated, there is a need for tests on weld HAZ and bond lines in ERW pipe. The FCGR expression in B31.12 data suggests that the partial pressure of hydrogen is not as important at low pressures (<3,000psi). Do sufficient data exist to establish this for vintage pipeline welds? Do external surface cracks also have hydrogen-accelerated fatigue crack growth rates?	Europeans are doing some full-scale pipe tests with cracks in welds, but those seam welds were mechanically expanded so the residual stresses are greatly reduced. Some Sandia data on small pipes suggests that the external surface crack is susceptible to the internal hydrogen gas.	3

Table 16 Suggested 5-year program on the various topics for hydrogen pipeline integrity evaluations in order of their ranking, continued

Item #	Topic	Discussion and Needs	Any on-going work on this topic?	Priority rating
19	Selective seam weld corrosion (SSWC)	Does hydrogen affect SSWC? Is hydrogen concentrated in SSWC due to stress concentration, and therefore reduce tolerable flaw size? The SME elicitation responses were undecided on this question. This topic might be more problematic if there was a hook crack joining the SSWC. We suspect the SSWC corrosion rate may not change much, but the toughness could.	We are not aware of any studies being done to address SSWC behavior with hydrogen. This is a vintage ERW/EFW issue, so it is important for some of those vintage lines. Some work may be undertaken by PRCI in the future with soil/CP external hydrogen creation, which may be helpful.	3
20	SCC interaction (both NN pH and high pH)	May need to do this evaluation in pipe specimens since SCC has external environment, and H+ is flowing through the steel from the ID. Some believe that once the H+ escaped to the OD surface it will escape from the SCC environment, others are concerned that the passive layer might be affected. Hydrogen definitely affects the tolerable flaw size for the amount of SCC growth – see the topics on fracture toughness.) Another hypothesis is that if the K value during the SCC growth exceeds the matrial K_{ITH}, then there could be an additive effect of additinal hydrogen crck growth.	Being evaluated in PRCI/EFI full-scale effort.	3
21	Repair welds	Weld repairs can be in the base metal (sometime referred as a type of hardspot) or seam weld repairs. There could be girth weld repairs as well. There are always higher tensile residual stresses in repair welds, and hardness might be higher too.	We are not sure anyone is examining this topic at this time.	3
22	Wrinkle bends	Prior plastic strain will cause higher H+ concentration in the steel affecting fatigue performance, buckling strain, and fracture. This topic is relevant only for an older pipeline, and but not of all vintage pipelines. But if there is one wrinkle bend, there is probably >100 wrinkle bends in that line.	PRCI/EFI are doing some full-scale pipe tests with a wrinkle bend in fatigue testing in future. Longitudinal fatigue may be more important than just pressure cycling.	3
23	Should operating pressure be changed with H_2 addition?	This is a study to be conducted once many of the topics in this table are addressed sufficiently and probably updated with time as more is known. This type of evaluation would represent a primary mitigation strategy to address smaller critical flaw sizes, but there may also be some line specific integrity challenges that will change the results from line to line.	This study could be undertaken to explore the benefits of reduced pressure on crack-driving force to account for lower fracture toughness. The effect of hydrogen concentration on fracture toughness, though, is still an unknown factor becasue of constraint effects and data reduction uncertainities describe in Item 1, particularly in the low hydrogen concentration range.	2
24	Effectiveness of ILI tools	There are two concerns here: (a) Sizing accuracy, but also; (b) Will hydrogen affect the electromagnetic properties of the steel so that pre-service corrosion ILI reading would be different than post-start-up ILI readings? This evaluation might require some pipe loop testing with ILI inspection before and after H_2 filling and sufficient hold time for H+ ingress into the steel and intentional flaws.	Concern (a) Depends on toughness changes, but we suspect the critical size is still large enough for effective ILI detection of structural limiting cracks, except for the potential of having very low toughness in harder flaws (hard spots and hard ERW/EFW seam welds per the Sandia data (which still needs validation and QA). (b) We are not sure if electromagnetic properties changes with hydrogen have a sufficient effect on ILI calibrations for corrosion growth analyses. This topic is still important, so it was ranked slightly higher from that viewpoint.	2
25	Low-cycle fatigue	Is the S-N curve in the <30,000 cycles (~40-year life for typical transmission line) decreased below the normal design safety factors? Larger pressure cycles for green lines might be a concern for lower cycle fatigue. Cyclic pressure changes may occur for nuclear plant hydrogen generation from load/power balancing with normal electrical demand. Grey hydrogen delivered by SMR steam methane reformers) would probably be more constant in pressure, so there may be less fatigue concern. Some S-N data suggest a drop in endurance limit.	S-N data in the codes and standards sometimes use a safety factor (SF) of 2 on stress or 20 on cycles of actual test data. Data in the NG-18 report 151 was analyzed, and that the SF of 2 on stress covered hydrogen degradation on S-N curve up to 10,000 cycles with a large margin. The SF of 20 on cycles was not adequate to bound the hydrogen S-N data relative to the methane gas S-N data, and should not be used as a basis to account for hydrogen reduction in the S-N curve.	2
26	Seals and Gaskets	This topic is probably more of an issue with high H_2 partial pressures.	Ongoing DOE program exists with GTI. Most materials are probably OK, but they are still in the process of evaluation. Long-term concern.	2
27	Composite pipe and joints	This topic is probably more applicable to low to moderate pressure lines. Composite pipe might go up to intermediate pipe diameters in the future, i.e., 12-inches, which could be for branch lines to smaller regions from the main line.	There are on-going effort at EWI for DOT/PHMSA on this topic. This topic is lower rated since it is a future application, i.e., possibly beyond 5-years from now.	2
28	MIC	Are MIC crack growth rates increased due to H+ going to the MIC surface? The SME elicitation responses were split 50-50 on this being a concern. Probably H+ is not affecting the MIC growth rate, only the tolerable flaw size might change.	Not aware of any work in this area.	2
29	Arc strikes	Local cracking could be enhanced but may only cause more leaks. Might be addressable from hard-spot research.	Not sure anyone is examining this topic.	2

Table 16 Suggested 5-year program on the various topics for hydrogen pipeline integrity evaluations in order of their ranking, continued

Item #	Topic	Discussion and Needs	Any on-going work on this topic?	Priority rating
30	Laminations	(a) Will H+ be trapped as H_2 molecules at the lamination boundary and cause bulges or step-wise cracking (like in a sour service line)? (b) Will H+ convert to H_2 at laminations that are responsible for hook cracks and affect the failure pressure? There is a lot less charging for gaseous hydrogen compared to sour gas lines or electrolytic charging, so a lower ranking was given.	PRCI is planning on doing some pipe tests with laminations. There may not be any test plans for laminations by ERW seam welds that might be responsible for potential hook crack failures. Perhaps ID ERW hook cracks may be more important.	1
31	Flow meters	Listed as a concern item by more knowledgeable people. The seal and gasket longevity is the primary concern from leakage. Residential meters are frequently outdoors, so small leakages are not a residential safety problem. Flow meters inside a facility would be more problematic.	Ongoing DOE program with GTI and national labs indirectly looking at this – see the DOE H-MAT project.	1
32	Pressure and temperature sensors	This was listed as a concern item by more knowledgeable people during the elicitation efforts.	We are not aware of issues even in refinery plant applications with high H_2 concentration lines, so this concern can be overcome.	1
33	Plastic pipe and fusion butt welds	Integrity of butt welds as well as the diffusivity through the plastic pipe is the concern. Diffusivity could be more of a problem for inside home service?	On-going efforts at PNNL on plastic pipe. H+ not much of an effect on the integrity of the materials for distribution lines, so only diffusivity for residential service in homes may be a concern.	1

5.3 A Pragmatic RoadMap for the 5-Year Plan

In Table 16 there were 11 different topics within the highest priority. These were topics that were deemed to affect both repurposing and new pipeline construction/use as a whole. There are some topics that might be for certain vintage, or certain new pipeline applications, but we chose topics that should have the greatest aspect on the entire national pipeline transportation system. As such, some additional details of these topics are given below in their order of importance (even though some topics seemed to overlap or related to later topics). Some of these topics are related, as noted in the text below, so Figure 50 shows how they are related to each other as well.

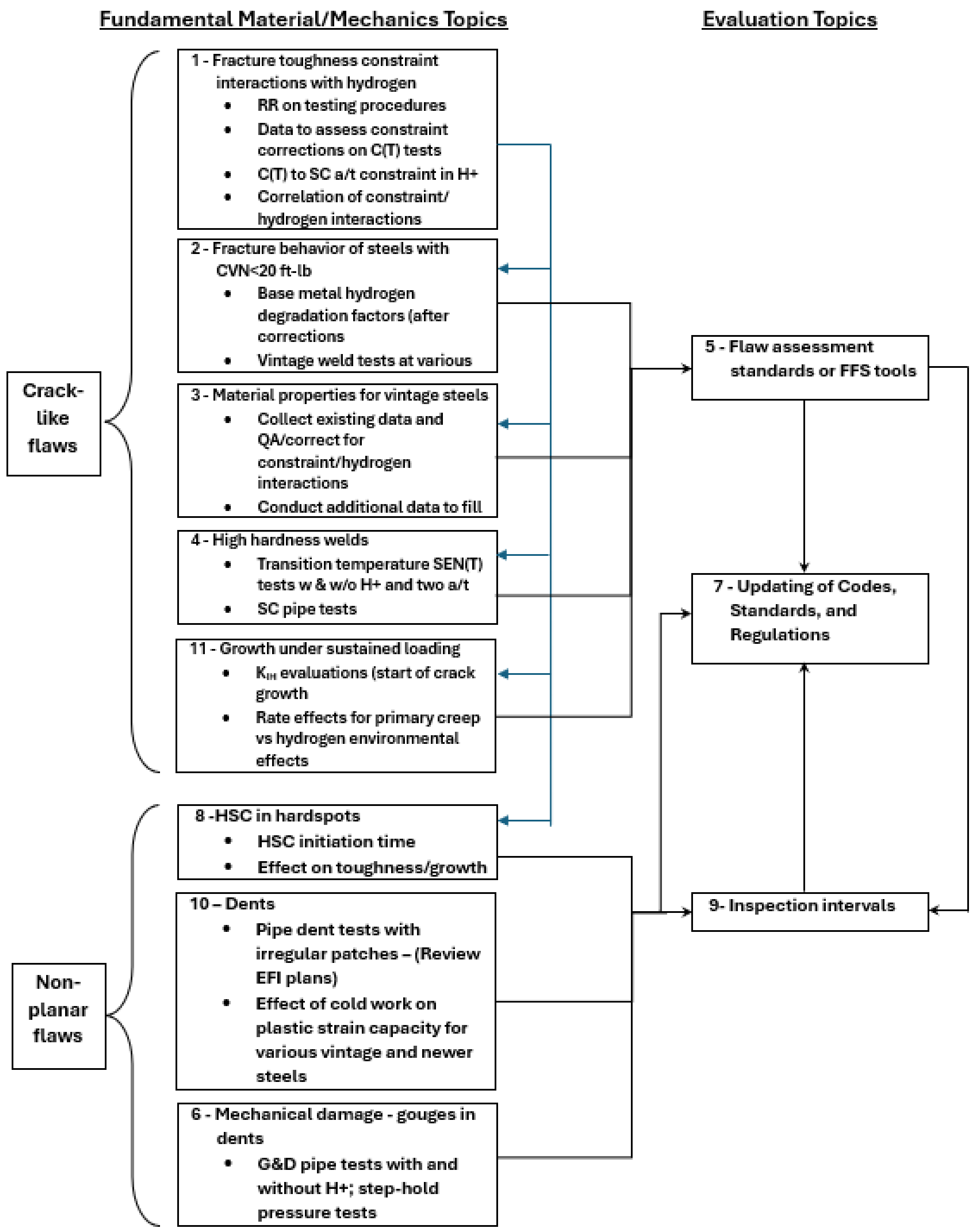


Figure 50 Schematic of a roadmap showing interactions of the 11 highest priority items

5.3.1 Topic 1 - Evaluation of Fracture Toughness Constraint Effect Interaction with Hydrogen Degradation

The objectives of this topic are to (1) get the laboratory testing community to recognize how to conduct tests in a consistent manner. This topic will also require establishing corrections to data developed to date, (2) assessing the potential toughness degradation in a consistent manner for all materials regardless of their thickness, grade or vintage, (3) conduct laboratory tests to assess material behavior on several specific important integrity challenges not being addressed to date, and (4) to establish how to take the typical gaseous hydrogen autoclave fracture toughness data and covert it with appropriate constraint/hydrogen interactions for surface-cracked-pipe integrity evaluations.

For the first sub-objective, part of that objective involves round-robin testing to establish gaseous hydrogen autoclave testing procedures. Effects like loading rate, environmental cleanliness, and specimen dimension standardization will be part of near-future round-robin efforts being undertaken by EPRG and PRCI. Ideally, there should be some ISO/ASTM standardization as well. There has been a significant body of data developed already, that should be reviewed from the viewpoint of do they meet consistent procedures, and if not, are there corrections that could be employed to adjust those past data to the new consistency standard. One aspect that is at the forefront is that C(T) tests are used, but the specimens' dimensions in past testing may be outside the ASTM E1820 range for fracture toughness determination. Even in ASTM E1820, they fail to give a warning to the user that if they are using the non-preferred specimen geometries for C(T) specimens (i.e., W/B=2 and a/W=0.5), those results may need some corrections on the toughness values to be comparable to the preferred/standard specimen geometry. The preferred/standard geometry is needed as a reference toughness to determine the toughness that surface cracks of different a/t values may have. The corrections are straightforward for inert environment testing [14], but if using a geometry that elevates the toughness, that higher toughness comes with increased plastic strain, which in turn is susceptible to higher hydrogen concentrations and degradation. The interaction of constraint and hydrogen is not clear at this time but should exist. This sub-topic affects any crack-related evaluation for repurposing or new pipeline flaw evaluations. Similarly, there may be a need to QA the data reduction procedure from hydrogen autoclave testing to ensure the consistency of data developed to date. There are indications that some fracture toughness values might change by a factor of 10 to 20 just from the data reduction procedures.

For the second evaluation of this topic, the sub-objective is reached partially from the first effort. Many of the existing data are on specimens tested close to the pipe thickness, but for convenience, the specimen planform dimensions (i.e., 1/2T C(T) dimension except thickness or a/W) were kept constant for different materials. The specimen width-to-thickness ratio (W/B) changes the fracture initiation toughness values (J_i and $CTOD_i$) from constraint effects, so it is difficult to see if there is a consistent toughness degradation between materials of different thicknesses. As an example of the difficulty involved, an operator might have a large Charpy database. The Charpy upper-shelf data can be used with existing correlations [14] to determine the material initiation toughness, which might be determined from standard C(T) testing in an inert environment. (Those correlations are for C(T) specimens having preferred dimensions, i.e., W/B=2 and a/W=0.5.) So, if there is a hydrogen autoclave test with a C(T) specimen having W/B=7, there is an unintentional increase in the toughness by a factor of about 250%. So, even with hydrogen degradation on that W/B=7 specimen, one might conclude that the flaw tolerance is better with hydrogen than with natural gas. This is an obvious erroneous condition that needs rectifying before such data is used in flaw evaluation efforts.

The third part of this topic is to conduct laboratory tests to assess material behavior on the important integrity challenges that have yet to be addressed. One of the biggest aspects is that the toughness from a C(T) specimen can be related to a surface crack in a pipe. The surface-cracked-pipe fracture initiation toughness increases with decreasing a/t of the surface crack [30]. This happens in SEN(T) specimens too. There are only recent relationships [14] established to make these toughness constraint adjustments, but assuming that standard size C(T) specimens are used (building on the 2nd point). However, with the toughness changing with a/t, the amount of hydrogen concentration changes, and the toughness may drop more with higher a/t values. At this time, there is no autoclave test data with gaseous hydrogen to show the difference in toughness with a/t. That needs to be done for a range of steels to have a confident correction factor developed for all the past data.

The fourth point is that a correlation for hydrogen/constraint interaction needs to be established from the third-point data development to take the more common standard C(T) hydrogen data (from the second point) and convert it to the toughness appropriate for a surface-cracked pipe for flaw evaluations in Topic 5. The SENT trend of higher hydrogen trapping sites with smaller a/W values (higher toughness and larger plastic straining) is consistent with the current observations that new steels with higher toughness in the C(T) specimen have a greater hydrogen toughness drop. The higher toughness steels have more plastic strain in C(T) tests, which attracts more hydrogen, which is all consistent behavior. This may lead to a general hydrogen/constraint procedure that might be relatable to the Charpy data taken in existing pipelines.

5.3.2 Topic 2 - Fracture Behavior of Steels with CVN<20 ft-lb

Most of the existing US pipeline transportation system exists of pre-1970 pipelines. It is cost-prohibitive to replace all of those pipelines for the transportation of hydrogen. Additionally, hydrogen has a lower BTU value than natural gas, so these vintage pipelines are the key starting point for a hydrogen economy, and even many new pipelines may be needed for a pure hydrogen system in the future.

This topic applies to some lower toughness vintage base metals or ERW/EFW seams where da/dn, S-N, stress-strain curve, and toughness data are needed. It is desirable to know how much reduction there is in upper-shelf toughness (J_i) with H_2 partial pressures (see discussion on Topic 11).

As part of this effort, it will also be necessary to determine if the brittle-fracture initiation transition temperature changes with hydrogen for vintage welds that have warmer transition temperatures. To our knowledge, there is no autoclave testing with gaseous hydrogen as a function of temperature to date, especially for cases with warmer transition temperature materials. We have not yet seen vintage ERW/EFW seam weld data other than an early Battelle NG-18 report #151 in the 1980s.

So, building on the first topic, some SEN(T) specimens of hard ERW/EFW seam welds should be tested in gaseous hydrogen over the range of operational temperatures, i.e., 50F and warmer. SEN(T) specimens are more desirable since constraint affects not only the upper-shelf toughness with a/t but the brittle-to-ductile transition temperature, which is closer to a surface-cracked pipe than C(T) specimens [62].

5.3.3 Topic 3 - Material Properties for Vintage Steels

This topic includes X42 to X60 vintage pipe with ERW/EFW/DSAW and girth welds – pre-1970 steels; da/dn, S-N, stress-strain curve, toughness data are needed. The topic overlaps with Topics 1 and 2. Sandia and SwRI have developed a small amount of such data, but there is not much public data to date. There are a number of private JIP projects that are developing such data.

What needs to be done here is, first and foremost, to collect and make appropriate constraint corrections to existing gaseous hydrogen data that have a variety of non-preferred specimen dimensions and perhaps data-reduction inconsistencies as well. Look at the variety of steels that operators already have in their databases for their MegaRule toughness compliance efforts [14] and then determine what additional steels may need to be tested in a constraint-compatible manner (per Item 1). From that, the effective toughness degradation to be applied to the vintage steels should be developed. This information would then be used in Topics 5, 7, and 9.

5.3.4 Topic 4 - High Hardness Welds (HBN>220)

This topic has input to the above topic (Topic 3). It includes a special category of older girth welds, higher hardness ERW/EFW, and hard spots where fracture toughness data is needed, which could also be considered part of the third topic. This topic was separated out during the SME elicitation efforts and is done here to be consistent with the SME opinions and ranking. The hard-spot topic is discussed as a later stand-alone item in Topic 8.

There are fracture toughness tests in the older Battelle/NG-18 Report 151 on simulated a hard spot, and the ERW fusion line is in natural gas with 60% hydrogen. There is also an IPC2024 paper by Sandia on the effect of gaseous hydrogen and hardness on toughness [25], although some of the values look so low that validation and QA are needed.

The higher hardness seam welds of interest here were made from 1948 to 1958 when the carbon and Mn content was higher in base metals, resulting in d-c/LF-ERW and flash welds having high-hardness autogenous seam welds. Figure 51 shows an interesting comparison of hard spots relative to the C and Mn content and also one hard seam weld failure [63]. Transition temperature SEN(T) testing was suggested in Topic 2 for hard seam welds, and surface-cracked-pipe tests should be done for burst pressure validations of various models – with and without hydrogen. The analyses of such tests are discussed in *Topic 5 - Flaw assessment standards or FFS tools.*

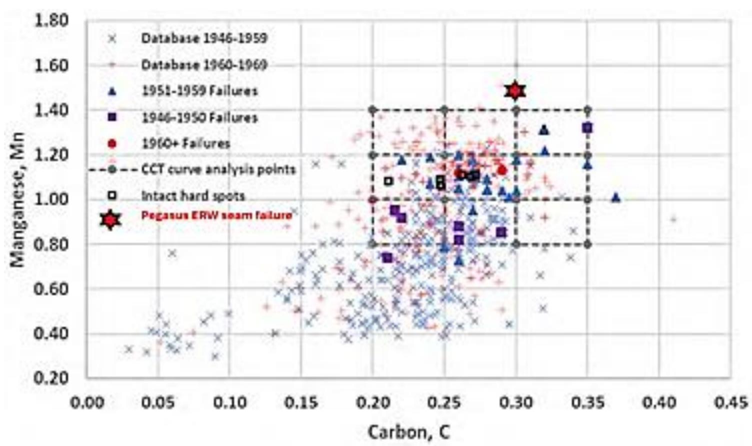


Figure 51 C and Mn content of hard sot failures, historical hard spot data, and a hard seam weld failure in the Pegasus pipeline

5.3.5 Topic 5 - Flaw Assessment Standards or FFS Tools

Guidelines on acceptable flaw sizes with hydrogen degradation are still needed. Many full-scale tests are just barely starting in the planning stage yet. Material testing is further along, but not yet, with the materials of higher concern for repurposing existing pipelines. For the burst pressure analyses, one thought is that a change to the inputs is needed rather than adjusting the analysis procedures themselves. However, as found in this program, the existing analyses do not calculate the crack-driving force well for cracks in welds that have higher strength than the base metal [11].

From the efforts in this program, we have seen from FE analyses that the crack-driving force is reduced if the higher strength of the weld metal is included in the burst-pressure analyses. Currently, none of the burst-pressure models account for that effect, so modifications are needed. In nuclear piping programs, the modification was developed by determining an effective stress-strain curve based on FE analyses with all base-metal lower strength, all weld-metal everywhere, and weld metal higher strength only in the ligament, [57] and [62]. With typical hook crack depths and lengths, the error in the crack-driving force might be a factor of five or a factor of two on burst pressure. Getting the crack-driving force correct will avoid confusion on the effect of hydrogen on the toughness from full-scale tests suggested in Topic 5.

Eventually, there is a need to relate hydrogen toughness changes to the database of air material toughness as an input. This relationship can feed an eventual probabilistic evaluation to assess if ILI is adequate for sharp flaw evaluations or if operating pressure should be changed with hydrogen additions (see Topic 9).

5.3.6 Topic 6 - Mechanical Damage - Gouges in Dents

Mechanical damage is one of the leading causes of NG and liquid pipeline failures. Plastic deformation and residual stresses in the damaged region can significantly affect the H+ concentration in the damaged region. The hydrogen concentration should affect the sustained load or delayed failure time, and the fatigue crack initiation and growth from the damaged region.

EFI is planning some mechanically damaged pipe fatigue tests, but this is a difficult problem since the hydrogen concentration may be much larger in this type of flaw from the local plastic straining; see discussion in Section 2.3.1.

The degradation of the burst pressure for a dent-and-gouged pipe is difficult to assess in laboratory specimen testing. It is likely that full-scale pipe tests are needed with identical dent-and-gouge defects with and without hydrogen. Numerical modeling of dent-and-gouge flaws has been done for past tests done in the air. The air tests are good for determining near-immediate failure conditions since hydrogen has not had time to be absorbed in the steel. So, the main integrity concern with hydrogen is that longer-term failures might occur with less severe damage or marginal damage might fail quicker. These tests can be done with step-hold pressurization and monitoring of the crack deformation and stability. These results will feed into Topics 7 and 9.

5.3.7 Topic 7 - Updating of Codes, Standards, and Regulations

Hydrogen pipeline standards are in the infantile stage at this time. The B31.12 pipeline aspects are to be moved to an annex in B31.8. Emc^2 staff are getting involved with that effort to communicate the results of this and a companion DOT/PHMSA project, although our companion project only has one additional year of duration over this project. The Codes and Standards efforts are usually long-term efforts, and the results of this project and future testing projects should be updated by the standards committee for their information. The updating of the Code and Standards naturally has an impact on Regulatory requirements.

EFI has a project to identify threats and then pare them down to be addressed with this new B31.8 hydrogen effort. That EFI effort will not be completed before the end of this project. There might also be hydrogen pipeline flaw evaluation efforts in API-1176 in the future. The Australians are in the process of updating their standards for hydrogen pipelines as well. The EFI project is to develop a threats list for the new B31.8 group to consider how the standards should account for those threats. Emc^2 is to contribute findings from this program to the B31.8 group as well. The next meeting in September 2024 is at the end of this project. Progress to date in the B31.8 group is that they will not include hydrogen effects in B31.8S in time to be in the 2026 Edition. Continued interaction and monitoring are needed for this activity.

5.3.8 Topic 8 - HSC in Hardspots

An integrity challenge of interest is whether H+ concentration in a hard spot from hydrogen gas transmission is less detrimental than externally generated H+ from CP/soil and coating loss. We suspect the soil/CP-inducted hydrogen effects are more detrimental. The hardspot aspect is interesting since hardspots are more traditionally on the OD surface, so the atomic hydrogen would have to get trapped there. Existing NG pipeline hard-spot failures have been due to coating damage with wet soil, and CP-induced hydrogen can be quite high.

For a hydrogen pipeline, the internal hydrogen might give a smaller hydrogen concentration at the external hardspot (an aspect that should be explored by numerical hydrogen transport analyses [11]), but all hard spots with good coating may be susceptible to some level of hydrogen adsorption from gaseous transportation. In a hardspot, there are also residual stresses from the plate quenching, where data to date (see earlier discussions) suggest there is a through-thickness bending stress with tension on the OD surface. There can also be a flatter region in the pipe by the hardspot spot (from the plate-to-pipe forming; remember, the hard spot is created in the plate form, so the softer steel around it deforms easier to make a pipe cylinder). For the flatter region, pressure can cause an additional through-thickness bending with tension on the OD. These two aspects (residual stresses and rounding of flatter regions) will give higher tension stress on the OD surface, where the hydrogen will want to have a higher density. The integrity question is if the magnitude of the hydrogen can cause hydrogen stress cracking (HSC) sometime later when the pipeline is transporting hydrogen. Some wet soil/CP hydrogen-induced cracking tests at different stress levels and hardness values are underway by PRCI, and similar evaluations with gaseous hydrogen on the ID surface of the hard spot seem prudent. Ideally, this could be done in a clever laboratory setting prior to any full-scale pipe testing. Fracture toughness testing in hard spots with different hydrogen partial pressures (ideally one-sided hydrogen exposure) and over the range of operating temperatures should be included. In the 1987 Battelle NG-18 Report #151 [26], the one simulated hard-spot material with BHN=350 showed ductile tearing in C(T) tests during room temperature autoclave testing, while higher hardness hardspot failures in service exhibited brittle behavior. The recent Sandia hardness evaluation testing showed similar ductile fracture behavior in their highest hardness condition in their room temperature C(T) tests [25]. So, the temperature effect on the toughness of the hard-spot material seems important to determine as well.

The above lab testing data could be used to conduct a well-designed full-scale test on hard spots with internal hydrogen. There can be two objectives in such a full-scale hard-spot test. The first is to determine the time to HSC with internal hydrogen. This may require accelerated tests (e.g., using higher stress levels) with extrapolation back to current operating conditions. The second is to assess critical flaw sizes and time from initiation to provide insights into ILI frequency of inspections. Obviously, understanding the residual stresses and stresses from rounding out flatter regions with pressure is essential in knowing the applied stress in the pipe's hard spot for comparisons to lab specimen data.

5.3.9 Topic 9 - Inspection Intervals

The SME group felt that there might be a need for shorter-duration inspections with lines more sensitive to pressure cycling (green hydrogen, service to gas turbines, nuclear power electrolysis during off-peak electrical survival demands, etc.) or other more time-sensitive threats. The time intervals between the ILI more than likely needs probabilistic evaluations with update of integrity management plans (inputs from Topics 1-5, 6-8, 10, and 11). Hence, the work before Item 5 on crack-like flaws and non-crack-like flaws, such as mechanical damage, dents, gouges, dents, etc., needs some enhancements before this evaluation should be taken seriously. The setting up of the procedure could be started, but the deterministic model and variable material property inputs will have to be established as results from those Topic areas are completed.

5.3.10 Topic 10 - Dents

Dents occur in most pipelines, so this is a high-priority item due to that logic. What needs to be determined is if guidelines for dent dimensions (percent of diameter and sharpness of dent) change due to plastic deformation attracting a higher hydrogen concentration. It is suspected that the higher H+ concentration from the plastic strain and the associated residual stresses in the dented region will affect the dent fatigue performance.

PRCI/EFI is doing a few full-scale dented-pipe fatigue tests in the future. This aspect is difficult to assess in lab testing, although specimen testing with different amounts of cold working and notched-round-bar testing is needed for the modeling that will be helpful for assessing the large variety of line-pipe steels rather than doing a large number of full-scale dented-pipe tests.

5.3.11 Topic 11 - Growth Under Sustained Loading

There are two aspects to this topic for pipe-integrity evaluations. The first is for subcritical crack growth; the second is the effect on the burst pressure and ductile tearing toughness.

One question to be addressed on a technical basis regarding either of the above aspects is, "Does the isochronous stress-strain curve change with hydrogen?" K_{IH} from autoclave testing is important, and it is different from sustained loading reductions of burst pressure. Some efforts on looking at K_{IH} are ongoing, but we are not sure how that might affect long-duration hold-pressure burst test margins, i.e., sustained loads drop the burst pressure by about 15% in inert environments due to primary creep (seen in the isochronous tensile tests), but the trend in H+ environment is unknown. This evaluation may require some step-hold pressure test comparisons using both lab specimens and surface-cracked pipes.

A somewhat related aspect involves comparing air test data to low levels of hydrogen conditions. Some engineers have said that "the first molecules of hydrogen might do more damage." We are not so sure about that statement. From a lab specimen testing viewpoint, the typical autoclave testing in hydrogen gas is at very slow rates to allow for hydrogen transport to the crack tip, while fracture toughness tests in air are done at higher loading rates. This loading rate difference contributes to the difference in J_{Ic} in air versus having a small amount of hydrogen. We suspect that much of the difference currently reported between air and small amounts of hydrogen is from the primary creep that is occurring in the hydrogen autoclave testing but not in the faster-rate air testing. There may also be differences in the instrumentation and data reduction procedures being different in air and autoclave testing (also see Topic 1). For instance, air testing with unloading compliance gives a J_{Ic} (or J_Q) value that has 0.2 mm of crack growth. d-c electric potential in autoclave testing, however, gives the very start of crack growth where the J_i (or J_{0mm}) value is less than ASTM J_{Ic} even in air at the same loading rate, and the interpretation of crack initiation in d-c EP data is an art.

Hydrogen testing standardization is needed, which is starting in an EPRG/EFI effort (see Topic 1). Some K_{IH} efforts are ongoing, more so in private JIPs. We are not aware of evaluations of the isochronous stress-strain curves (primary creep) dropping further with H+ than with air, other than what is shown in Figure 4. Sandia has a 2024 IPC paper that includes testing in nitrogen at slow rates for comparison to hydrogen testing at slow rates with various amounts of hydrogen, and more of that type of testing should be done to separate out primary creep from hydrogen effects on integrity.

It would also be helpful if the hydrogen testing evaluations included standard data like Charpy upper-shelf energy since much of the material toughness databases for satisfying the DOT/PHMSA MegaRule consisted of Charpy data.

The results of this topic will assist efforts in Topics 5, 6, 7, and 9.

6 Summary and Conclusions

This report summarizes a two-year effort to assess threat changes associated with the transport of hydrogen in existing and new pipelines. There are many ongoing and rapidly changing results and future directions on the various topics covering the effect of hydrogen on pipeline integrity. There were six tasks in this project, which are summarized below.

- Task 1 was a literature survey of existing data and the state of current knowledge relevant to assess the mechanical integrity of pipelines in hydrogen service. This work has been used along with additional data gained in other tasks to assist in the assessment of threat level changes addressed and was separately published [4].
- Task 2 included developing a team of subject-matter experts (SMEs) to assist in this assessment. This elicitation effort was accomplished early in the program to guide the work and provide valuable input. The SME Team participants' evaluations of 64 different questions are provided in APPENDIX I.
- Task 3 focused on the threat changes associated with transporting hydrogen. This was approached through the collection of existing experience, relevant data from industry and government laboratories, and efforts outside the U.S. The SME team opinions assembled in Task 2 were then queried extensively to develop a consensus on the overall impact of hydrogen on mechanical integrity and possible mitigation strategies. Even after the SME meeting, there was individual communication with the Technical Advisory Group members who had keener knowledge of the topic.
- In Task 4, data collected from Task 1 was briefly summarized to provide an evaluation of the effects of hydrogen/natural gas mixtures on the integrity of existing pipelines. The quality of the data was examined in detail in many cases. As the existing natural gas (NG) infrastructure in the U.S. comprises a large fraction of so-called "vintage" pipelines (pre-1970), the impact of hydrogen on these steels is of primary importance. Root causes identified in B31.8S that are expected to be affected by hydrogen were discussed, and mitigation tasks were summarized.
- Task 5 identified a qualitative threat algorithm for ranking current or future threats. This work addressed questions about proper in-line inspection tools, repair criteria, and acceptance limits. As mentioned earlier, the companion study on repurposing existing pipelines (RA 697JK322RA001) describes in more detail the assessment approaches and specifics on fitness-for-service-assessment of threats, some of which are in a 2024 IPC paper [11]. This report covered these concerns in a general sense by providing the relative ranking of threats, identifying the criteria for acceptance, and comparing those results with existing approaches. This effort included a summary of existing methods for evaluating damage to pipelines, reviewing current regulatory requirements, and summarizing changes or gaps to existing procedures.
- Finally, Task 6 provided a five-year plan with prioritized efforts per our current understanding of the threats, SME elicitation opinions, and efforts ongoing elsewhere. This is more than just "field testing efforts" since it needs to include analyses to identify material susceptibility in the large variety of materials and different integrity challenges in existing and new pipelines. Not all of the identified threat categories could (or should) be explored, so a roadmap of what can be done reasonably in a five-year duration for the more challenging overall aspects was provided. This includes laboratory testing to develop the necessary material property data, development of analytical approaches for the engineering critical assessment (ECA) of damage, full-scale tests to

validate ECA analyses, and operating experience needed to improve integrity management plans. Repair evaluations (initially a higher consideration) were given a lower priority since there is a near-future DOT/PHMSA effort on that topic.

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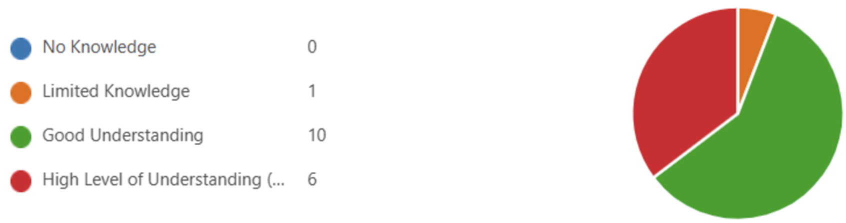
APPENDIX A – SME Elicitation Responses

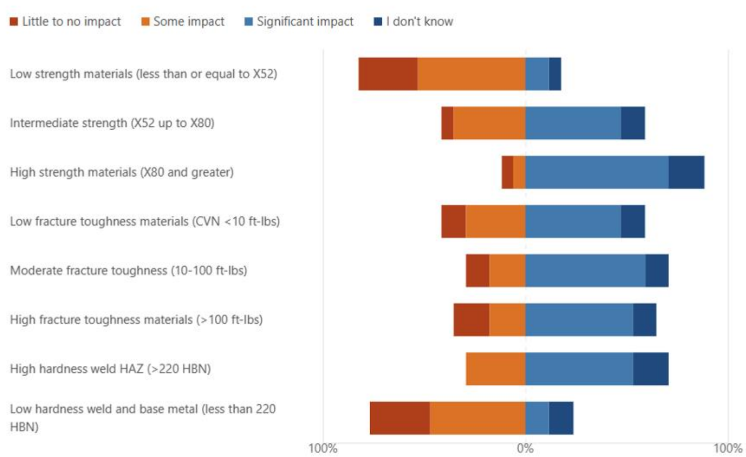
Expertise of Respondents

- ***Obtained responses from 17 out of 25 requests***
- ***16/17 reported having either "good" or "high" level of understanding of effects of hydrogen on steels***



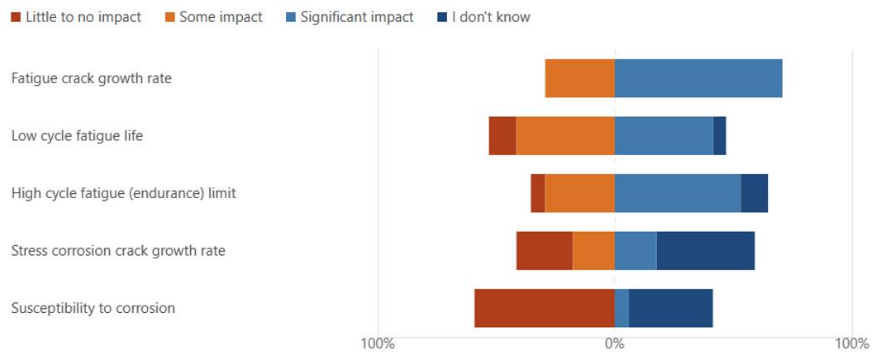
Topic 1 – Material properties

2. What impact would a 5% to 20% hydrogen blend have on the following **material properties** compared to 100% natural gas pipeline transport?



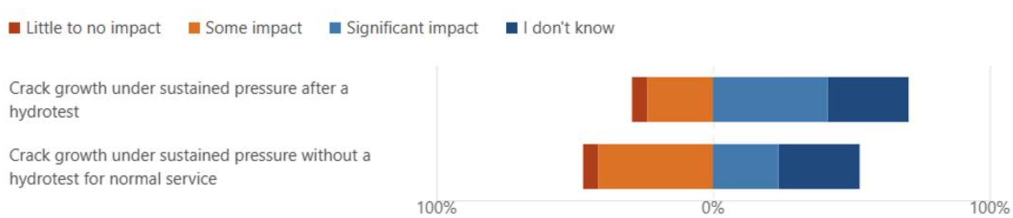
Topic 2 – Cracking Growth

5. What impact would a 5% to 20% hydrogen blend have on the following **susceptibility and crack-related parameters** compared to 100% natural gas pipeline transport?



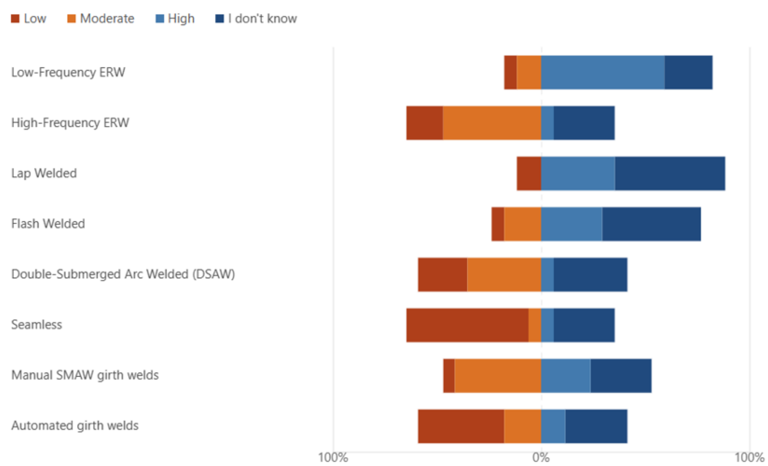
Topic 3 – Crack Initiation

8. What impact would a 5% to 20% hydrogen blend have on **crack growth (K1H/primary creep) under sustained pressure** (e.g., after a hydrotest or without a hydrotest for normal service)?



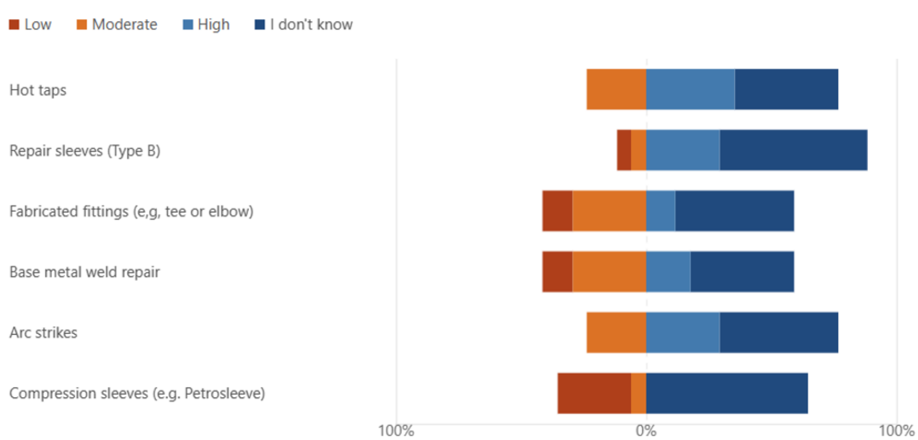
Topic 4 – Fabrication Type

11. Rank the susceptibility to hydrogen damage of the following **pre-1980 pipeline manufacturing and construction practices** as Low, Moderate, or High.



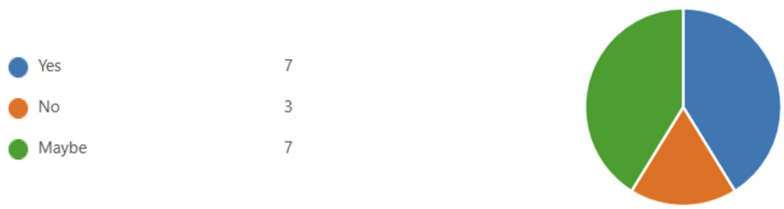
Topic 5 - Construction

14. Rank the susceptibility to hydrogen damage of the following **pre-1980 pipeline repair and construction practices** as Low, Moderate, or High.



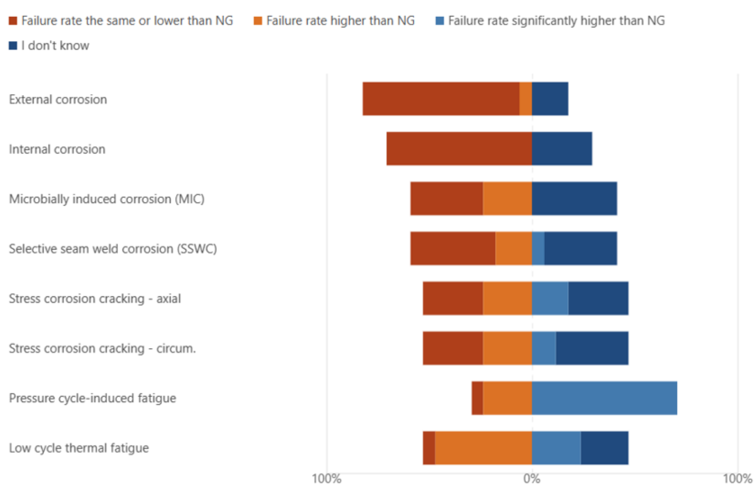
Topic 6 – Fatigue Demand

17. Would you anticipate a change in fatigue cycling severity after the addition of hydrogen?



Topic 7 – Time Dependent Threats

23. For **time dependent threats that impact pipeline integrity**, what impact would 5% to 20% hydrogen blend transport have on the likelihood of failure compared to 100% natural gas transport?



Topic 8 – Hydrogen Concentration

29. At what % hydrogen do you have concerns for a decrease in pipeline integrity (select all that apply)?

0% to 5%	13
5% to 20%	12
20% to 50%	14
50% to 75%	14
greater than 75%	14

Topic 9 – Stress Corrosion Cracking

31. Do you think hydrogen will affect near-neutral pH SCC cracking and growth rate?

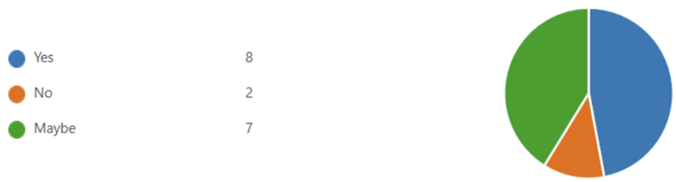
Increased rates	8
No effect	9
Decreased rates	0

32. Do you think hydrogen will affect high pH SCC cracking and growth rate?

Increased rates	7
No effect	10
Decreased rates	0

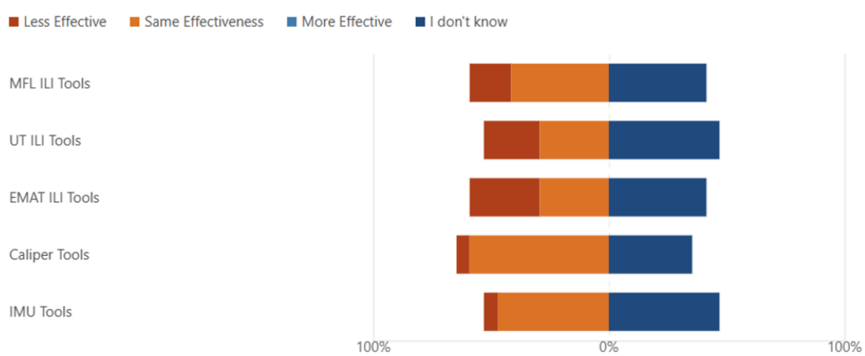
Topic 10 - Consequences

34. Do you consider the failure consequences to be increased with natural gas blended with hydrogen?



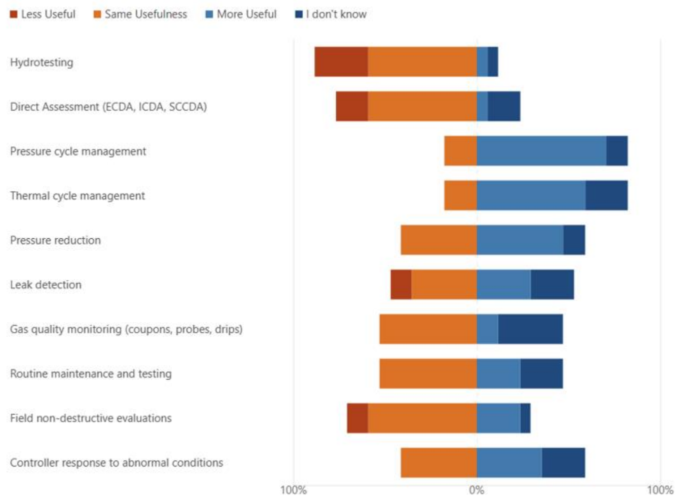
Topic 11 - ILI

36. For **inline inspection (ILI) tools**, what impact would 5% to 20% hydrogen blend transport have on their **effectiveness** compared to 100% natural gas transport (ability to detect smaller flaw sizes or effects of hydrogen on electromagnetic properties of steel)?



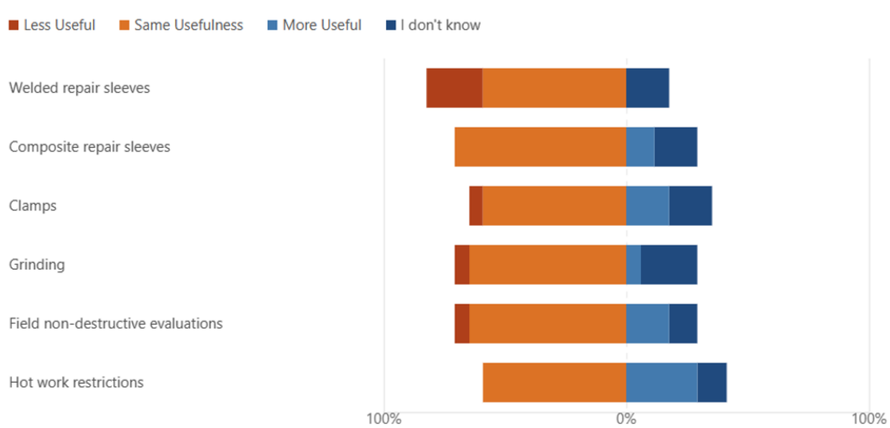
Topic 12 – Threat Mitigation

42. For **threat assessment (other than ILI) and preventive & mitigative measures** what impact would 5% to 20% hydrogen blend transport have on their **usefulness** compared to 100% natural gas transport?



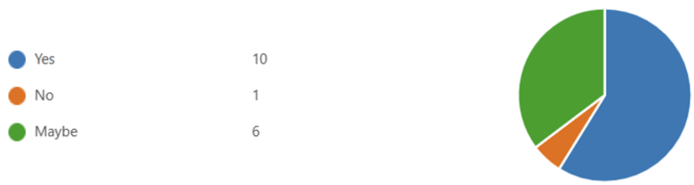
Topic 13 – Repair Procedures

45. For **field evaluations and repair procedures**, what impact would 5% to 20% hydrogen blend transport have on their **usefulness** compared to 100% natural gas transport?



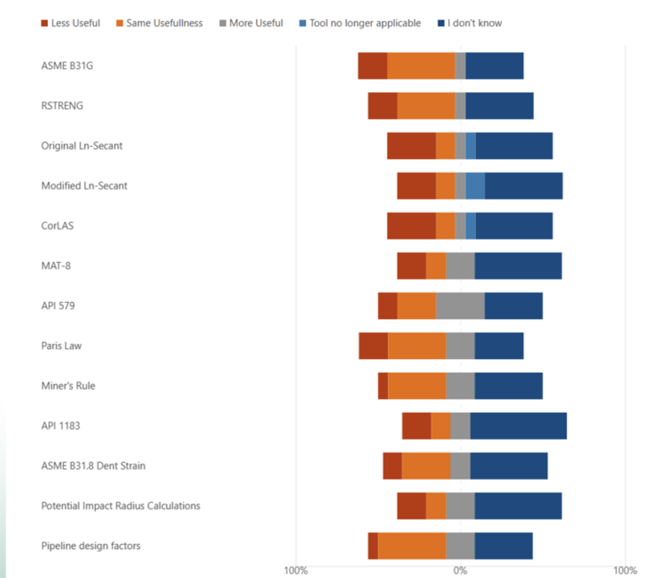
Topic 14 – Integrity Assessment

48. Do you anticipate an increase in integrity assessment frequency (inline inspection, hydrotesting, other) after the addition of hydrogen?



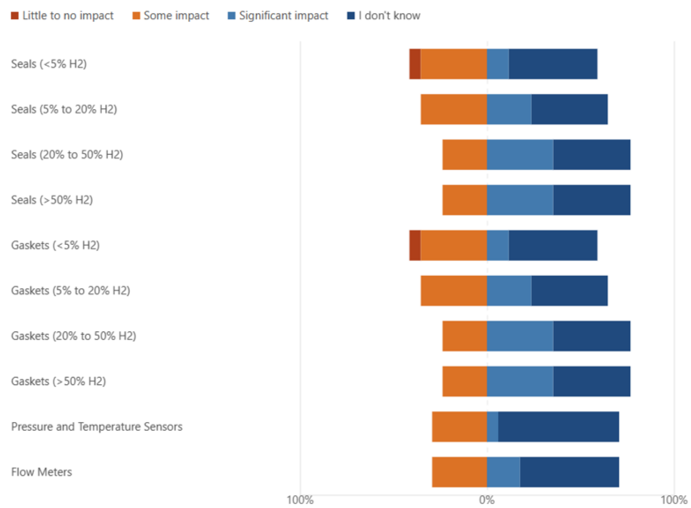
Topic 15 – Flaw Assessment

51. For **fitness for service tools**, what impact would 5% to 20% hydrogen blend transport have on their **usefulness** compared to 100% natural gas transport?



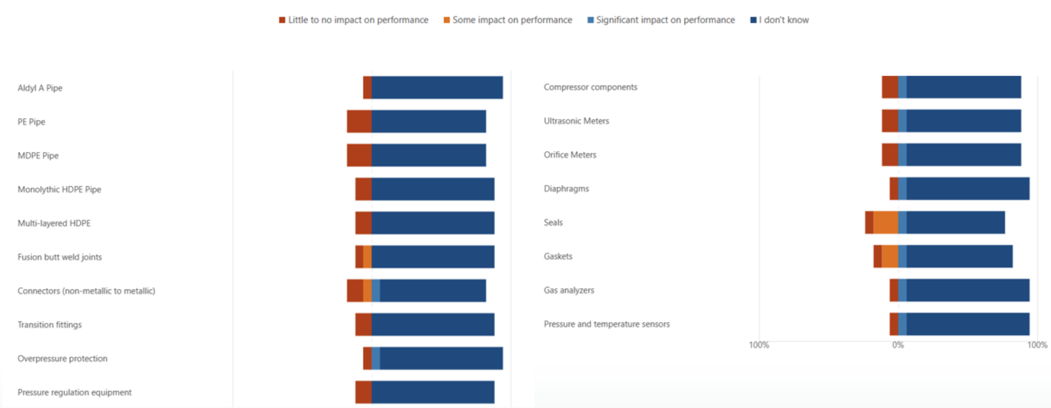
Topic 16 – Non-Metallics

54. What impact would hydrogen transport have on the following **non-metallic components in <u>transmission pipelines</u>** compared to 100% natural gas pipeline transport?



Non-Metallic Components

59. What impact would a 5% to 20% hydrogen blend have on the **<u>performance</u>** of the following **non-metallic components in <u>distribution pipelines</u>** compared to 100% natural gas pipeline transport?



Topic 17 – Leak Consequences

62. How are the consequences of a leak or release at a facility impacted by blended hydrogen service?

No impact	2
Less of an impact	0
More of an impact	14

Topic 18 – Codes and Standards

63. Do you think current codes and standards adequately address the effects that 5% to 20% hydrogen blends will have on pipeline integrity when using the existing natural gas pipeline infrastructure?

Yes	2
No	15