Decoding Requirements for Engineering Assessment of Repurposed Hydrogen and Blended Pipelines

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Abstract

The energy transition has gathered momentum stimulating the natural gas industry to swiftly adapt to the evolving energy ecosystem, driven by the need to reduce carbon footprint and seek alternative fuels like hydrogen. In the last five years, there has been a significant increase in industry focus and research within the natural gas and hydrogen pipeline sectors. Gaps have been identified in the current technical standards for repurposing of natural gas pipelines for hydrogen gas. Neither ASME B31.8 nor ASME B31.12 effectively address the issues faced by transmission and distribution pipeline operators seeking to integrate hydrogen gas into the existing natural gas infrastructure. In this regard, Consensus Engineering Requirements (CERs) have been elaborated to provide practices for H_2 and H_2 blend pipeline services, aiming to be the basis for new guidance within ASME B31.8 code. The intent of the approach is to provide a robust analytical method for users to qualify pipelines for safe operation in H_2 commensurate with the asset specificities, alongside operational envelope, rather than using prescriptive approaches. This paper will discuss the guidelines created for repurposing within the CERS, which are proposed for inclusion in the 2026 version of ASME B31.8.

1. Introduction

The energy transition will accelerate the shift towards cleaner energy by using existing infrastructure, in this regard the repurposing of natural gas pipelines can expedite the deployment of hydrogen networks and create a cost-effective scenario for hydrogen gas and hydrogen blend transmission pipelines.

Nowadays, hydrogen gas infrastructure is still nascent in United States with about 1,600 miles of hydrogen pipelines, as compared to more than 360,000 miles of natural gas transmission pipelines. The growing clean energy market is promoting a shift towards large-scale production and transportation of hydrogen and hydrogen blend by transmission and distribution pipelines, which has garnered the attention of the Pipeline and Hazardous Materials Safety Administration (PHMSA) to develop contemporary framework codes that serve as standard regulatory reference.

Repurposing guidance and conversion to hydrogen service requirements are currently presented within the ASME B31.12 code [1]. A significant amount of the content in ASME B31.12 is more appropriate to industrial gas applications than for repurposing of existing natural gas transmission pipelines. In an attempt to overcome current limitations found when applying a prescriptive method, consensus engineering requirements (CERs) have been created [2], that addresses repurposing from a performance-based approach, drawn from state-of-art knowledge, where engineering assessment is used to evaluate the feasibility of repurposing [3,4,5,6,7]. The recently released CER publication, which is under consideration to be included in ASME B31.8 code [8], was created based on collaboration between a significant cross section of industry, which helped develop recommendations throughout consensus best practice approach.

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To perform repurposing of natural gas pipeline to hydrogen and blend service, all the active threats need to be identified, when reviewing the integrity management plan in place. Therefore, an engineering assessment must account for all the existing threats impacted by the change in product, and in addition, evaluate the susceptibility to new threats which may not have been considered in natural gas service. An ongoing PRCI project is revisiting ASME B31.8S [9], with the aim of updating it for hydrogen and blend service. By 2026, the expectation is to have a new hydrogen chapter in ASME B31.8 [8], and an update to ASME B31.8S with specific guidance on the integrity management of hydrogen pipelines. Industry will be able to leverage both codes to design, construct and maintain safe hydrogen transmission assets.

2. Design Philosophy for New Build and Repurposed Pipelines

2.1 New-build Pipelines Design

The foundations for the new design criteria presented in the CERs do not use of the material performance factor (H_f) included in ASME B31.12. The material performance factor, H_f, incorporated in B31.12, aims to account for the expected reduction in predicted burst pressure in pipes with defects, due to increasing pipe strength and hydrogen pressure. This factor, however, is considered arbitrary and is linked to pipe grade, based on limited technical data [10,11]. This data was derived from burst tests on NPS 4 pipe with internal notches ranging from 6 to 10 inches in length. Consequently, H_f addresses the impact of pipeline damage on the pressure containment capabilities of a hydrogen pipeline. When B31.12 was created, the impact of hydrogen on material properties was believed to be proportional to nominal grade, which is not entirely accurate [12]. Grade is not a reliable indicator of strength, as shown in Figure 1, which illustrates the acceptable yield strength ranges in API 5L PSL2 based on grade [13]. For example, pipe designated as X52 can have a higher strength than pipe designated as X60. This issue was more prevalent in the past when pipes did not have a maximum strength limit for a given grade, potentially resulting in much higher strengths than the grade indicated. According to this study, the yield strength and tensile strength of low to intermediate carbon and low alloy steels are generally unaffected by hydrogen [12].

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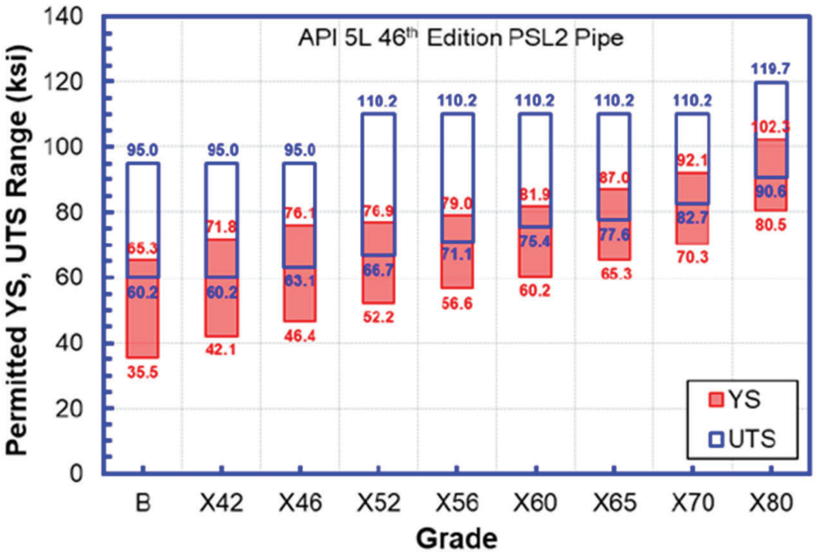

Figure 1. Yield strength (YS) and ultimate tensile strength (UTS) range values in API 5L PSL2 [13].

In vintage pipe materials there is a general trade-off between strength and toughness, whereas material strength increases, fracture toughness tends to decrease. This is correlated with the increase in carbon equivalent and change in microstructure, but it is not a linear relationship, and it does not hold for all pipe types. C-Mn steel pipes can achieve high strength and toughness by incorporating micro-alloying elements (Nb, Ti and V) and carefully designed thermomechanical controlled processing, which produce grain refinement in addition to the formation of fine precipitates within the microstructure, significantly enhancing the mechanical properties of the steel without compromising ductility. Figure 2 shows that acceptable fracture resistance can be achieved in high strength pipes at high partial pressure of hydrogen (210 bar) [14].

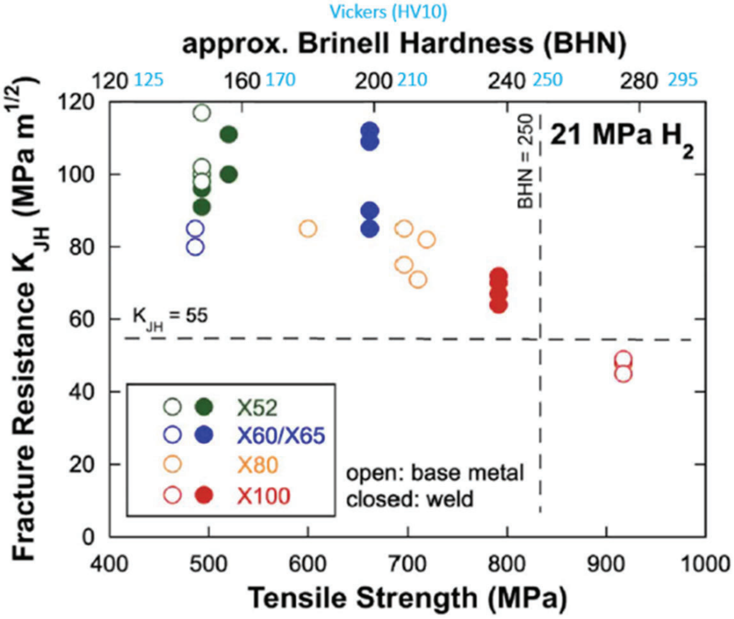

Figure 2. Pipeline material fracture resistance in hydrogen vs tensile strength and hardness [14].

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The inclusion of the H_f factor means that the design of pipelines with higher strength materials and increased hydrogen pressures are unduly penalized. The ASME B31.12 committee has acknowledged this issue, and it will be addressed in the 2026 revision of ASME B31.12 through code case 220 [15], and the removal of the H_f factor. However, the code case requires application of post weld heat treatment, production testing, and use seamless pipe, all of which will be challenging to include in transmission and distribution pipelines. The CERs have taken the route of removing the H_f factor, and using design based on the Engineering Assessment and an Engineering Critical Assessment (ECA), discussed in section 3. This design philosophy is named the ‘high stress’ option.

For new pipeline constructions, when stress levels are controlled to meet workmanship acceptance criteria, the CERs offer a 'low stress' option. This option eliminates the need for an engineering assessment or specific hydrogen testing. The limit for this approach is set at 52 ksi for the S parameter in equation 841.1.1 (a) of ASME B31.8, and a maximum design factors of 0.5 in all class locations. This broadly aligns with the Option A approach in ASME B31.12, which has been used safely for many years by maintaining the same absolute maximum stress / MAOP limitation, while eliminating the dependency on grade:

2.2 Repurposed Pipeline Design

For repurposing existing pipelines an engineering assessment is mandatory. The content is at its core the same as that for new build with a few key differences. The major difference in the design of repurposed lines is that the current condition and understanding of the pipeline history requires to be characterized and applied as an input into the engineering assessment. Factors that must be considered in the design include, but are not limited to:

- Year of manufacturing / construction
- Manufacturing and construction specifications
- Material records
- Welding and joining methods and procedures, qualification records and production logs.
- Pipeline repairs / replacements / alterations of system configuration
- Records of pipeline operational history
- Type of previous service history (liquid/gas)
- Design related to internal and external corrosion control methods (e.g., coatings and CP)
- Above ground surveys and performance reviews of external corrosion control methods
- Depth of cover
- Historic in-line pipeline inspections
- Failures, Leak records
- Historic engineering assessments or risk assessments
- Pipeline Integrity Management Plans

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Gaps in knowledge about the current condition of the pipeline must be closed. In-line inspection (ILI) will likely be required in most repurposing projects, including other technologies perhaps not previously considered, particularly those designed to detect hard spots and characterize the threat of cracking. Testing of the existing material is a fundamental requirement. Testing must be performed in hydrogen, unless the low stress option is used. For repurposed pipelines the principal stress is limited to 30% SMYS or 26 ksi, whichever is lower to establish a low risk of rupture [16,17,18]. The topic of what material properties are used in the ECA for repurposed lines is discussed in section 3.1.

A simple flow chart was created to reference the various design approaches included in the CERs, illustrated in Figure 3.

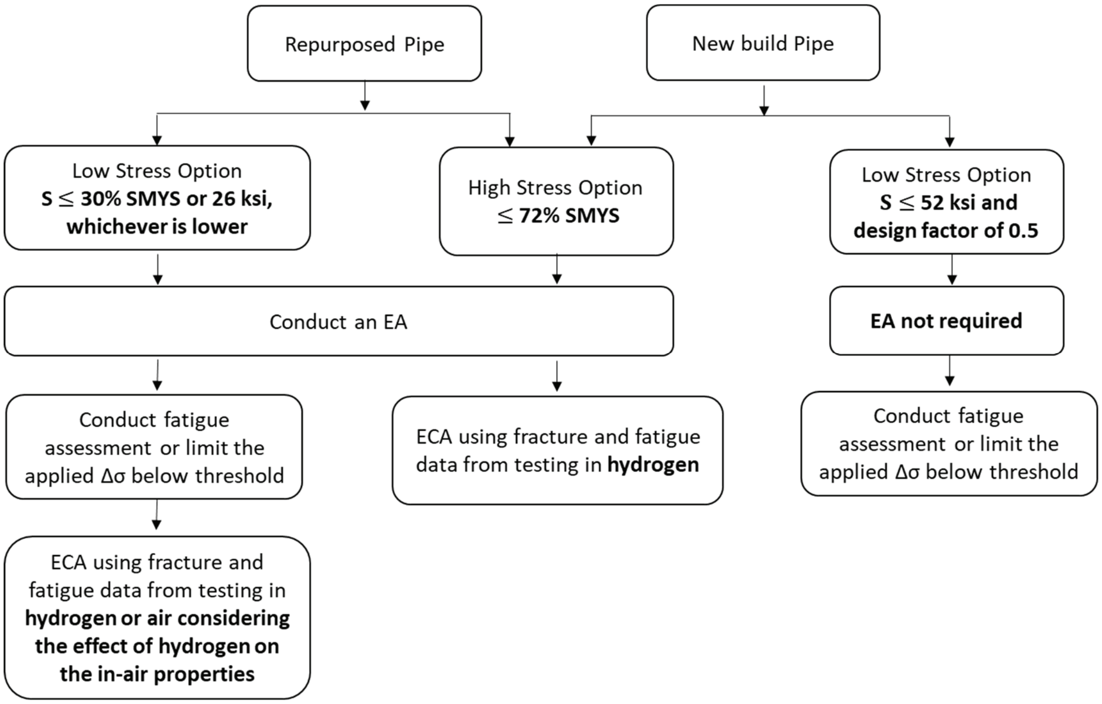

Figure 3. Design criteria for new build and repurposed hydrogen and blends pipelines.

3. Engineering Critical Assessment Requirements

The Engineering Critical Assessment (ECA) will be implemented in design as part of ASME B31.8, and in integrity management as part of ASME B31.8S. Conducting ECA for a pipeline intended for hydrogen or hydrogen blend service is a complex task that demands the expertise of highly skilled and experienced professionals. Although existing codes like API 579/ASME FFS-1 and BS 7910 provide guidelines for these assessments, their application can be challenging [19,20]. Most existing pipeline defect assessment models are based on properties in air, such as Charpy V-notch toughness, which might not be applicable for hydrogen service. All assessment models require detailed material property inputs and a comprehensive understanding of any potential anomalies in the pipeline, including existing repairs. Therefore, having a precise understanding of these inputs, especially the impact of hydrogen on material properties, is crucial for the successful completion of an ECA.

The intent of conducting an ECA on hydrogen and blends pipelines is to provide a sound analytical performance-based method to address some of the uncertainties and potential lack of conservatism in the current design Option B of ASME B31.12 PL-3.7.1 [1]. While it doesn't provide prescriptive rules for operating at higher stress levels, it offers guidance on the areas that need to be considered. The assessment methods for defects in hydrogen and blends pipelines are not yet standardized, so it is recommended that operators consult with experts on the latest advancements in assessment techniques. Industry organizations like PRCI, EPRG, and APGA are active in this area. PRCI project JEFI 04-06, Hydrogen Impact on Usage of Existing Integrity Assessment Models, is nearing conclusion and that will present a detailed discussion of how existing models may be used for hydrogen and the effects on model inputs [21].

Pertaining to repurposed pipelines, the following variables must be considered in the ECA:

- **Material suitability** and the effects of gaseous hydrogen on materials properties and performance: fracture toughness, crack under static load, fatigue crack growth and hardness.
- **Integrity threats and susceptibility**.
- **Existing anomalies** (e.g., planar, volumetric, geometric) and sizes arising from either manufacturing workmanship acceptance criteria, inspection, flaws arising during service or survivable flaws from hydrotest.

3.1 Material Suitability

The effect of hydrogen on material properties continues to be the most challenging aspect of expanding the hydrogen pipeline infrastructure. Significant work was required to address several key issues relating to material properties and testing. Based on the presence of hydrogen, one hypothetical starting point for material suitability was to consider guidance used for sour service pipelines as a basis. There is however a key distinction between sour service and gaseous hydrogen, namely the concentration of hydrogen expected in the steel from each service environment and the mechanism of trapping of hydrogen into the steel lattice. As shown in Table 1, taken from PD CEN/TR 17797 [22], the concentration of atomic hydrogen absorbed into the steel from H_2 gas pipeline service is much lower than for any other hydrogen charging sources, including sour service.

Table 1. Estimated atomic hydrogen concentration in steel at 20 °C [22].

Source of hydrogen	Concentration H atoms (ppm)	Equivalent pressure (bar)
81 bar H_2	0.25	81
3 ml H_2/100g welding electrode	150	15,000
0.01 bar H_2S	14	7,100
Cathodic overprotection	56	11,000
1 bar H_2S	185	16,000
Cathodic H_2 charging	650	21,000

Numerous studies [23,24,25] have shown that the conditions defined in NACE MR 0175 [26] Region 3 sour service, which underpin many current sour service standards, are more severe than those encountered with high-pressure gaseous hydrogen. Fracture toughness test results across different environments, demonstrated that even at low partial pressures of H_2S, the fracture toughness is lower than that in high partial pressure gaseous H_2 environments, see Figure 4 [27]. Hydrogen embrittlement is a primary concern with hydrogen gas, leading to hydrogen induced cracking (HIC). After H_2 surface adsorption, it dissociates into atomic H, and diffuses into the material, where is trapped at metal lattices, causing steel to become brittle and prone to cracking. In sour service and in the presence of H_2S impurities, corrosion process is governed by the electrochemical hydrogen evolution reaction, causing HIC, coupled with the anodic dissolution of carbon steel metal pipeline. Instead, hydrogen gas in the absence of moisture and H_2S impurities, does not typically cause corrosion but can significantly reduce the ductility and toughness of materials, due to hydrogen embrittlement.

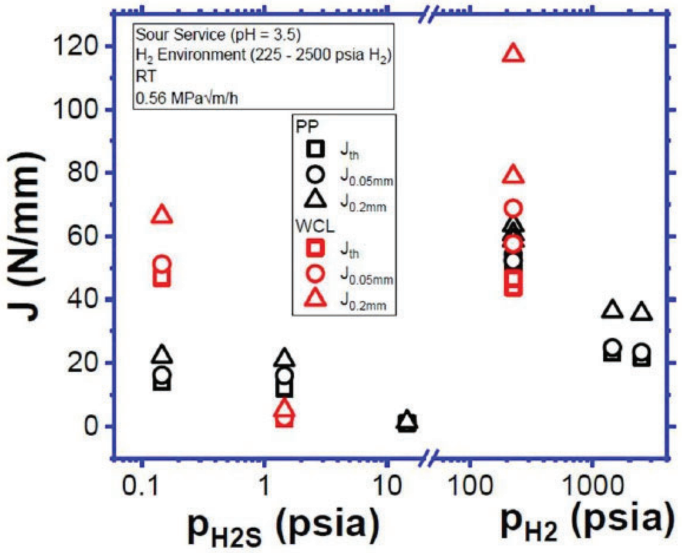

Figure 4. Influence of H_2 and H_2S partial pressures on crack initiation fracture toughness [23,24].

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For new pipeline construction, the initial step involves testing material properties in hydrogen as part of the line pipe Manufacturing Procedure Qualification (MPQ), as outlined in API 5L Annex B, and API 1104 for weld procedure qualification. The CERs reference testing according to ANSI CSA CHMC1 [28], and as part of the MPQ. Developed in 2012, ANSI CSA CHMC1 provides standardized test methods to evaluate material compatibility with compressed hydrogen applications.

For repurposed pipelines, the MPQ testing will have been performed in air. Therefore, the pipe and weld materials must be tested again in hydrogen to characterize the properties in hydrogen. This will require removing material from the pipeline and/or the use of existing data for equivalent materials in hydrogen. All pipelines contain a range of pipe and weld "populations", resulting from the use of different wall thickness and grades used during construction, maintenance and remediation. In general, the older the pipeline the more likely it is to contain many different populations of pipes and welds. Owing to the vintage of many US pipelines, with over 70% of lines constructed pre-1970 [29], a sizable portion of pipelines that could potentially undergo repurposing may lack the necessary documentation to confidently determine the populations and associated material properties. Populations can be distinguished by analyzing the existing documentation, such as material order records, construction documents, material delivery records, material testing records. If documentation is not available, ILI methods are available to help delineate populations based on multiple data sets. An example of the different pipe populations as a function of strength along an inspected pipeline is shown in Figure 5. This is a relatively simple pipeline, which contains seven populations. For any populations that do not have reliable material records, some level of testing would be required to close the gaps and identify if the pipeline is suitable for repurposing under the expected operating envelope.

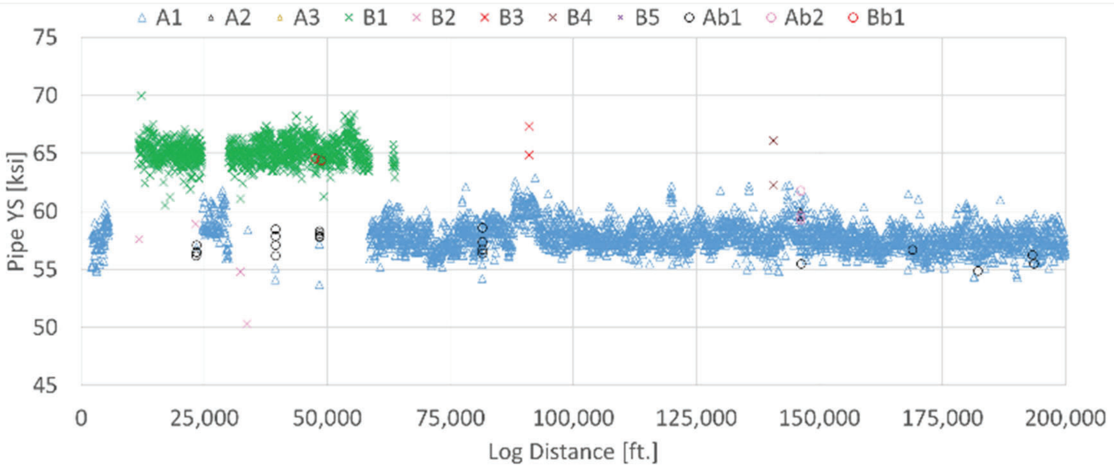

Figure 5. Pipeline population distribution.

Although characterization of material properties is addressed in ASME B31.12, the current guidance is not considered applicable to transmission pipelines. The guidance that was included in PL-3.21 does not address the need to characterize the different populations and define where testing is required and prescribes that random sampling should be used at a specific frequency of one test per mile. Taking such an approach would fail to characterize the risk profile of a pipeline. Assuming that no documentation was available for the pipeline shown in Figure 5, testing at 1 per mile would likely only capture some of the populations, and would therefore not accurately characterize the pipeline.

A sampling method is required that correctly captures the range of pipe types that exist. The revised guidance included in the CERs overcome this limitation by defining the populations of pipes and field butt welds that exist and then test those populations that are missing material documentation with a quantity of testing defined by the operator based on the relative risk profiles in each population to achieve the required level of confidence that the results are representative.

3.1.1 Fracture Toughness

Certain limitations have been identified in the application of the current ASME B31.12 code. In particular, using the crack resistance assessments using the pass/fail K_{IH} constant load or constant displacement test as per ASTM E1681 [30]. This test uses a pre-cracked specimen at a specific Stress Intensity Factor (SIF), deeming the material 'suitable' if crack growth does not exceed 0.01 inch (0.25 mm) at an SIF of at least 50 ksi√in (55 MPa√m) over a set period (1,000 hours for carbon steels). ASTM E1681 offers only a binary pass/fail outcome (either the crack extends, or it does not), making it unsuitable for assessing defect tolerance in an engineering assessment. The CERs incorporate testing following ASTM E1820 [31] in hydrogen environments per ANSI CSA-CHMC1. This is a rising load test yielding a fracture toughness value, K_{JH} [32], that can be used as a direct input to ECA. The loading rate is crucial, and the CERs provide guidance to ensure hydrogen's effects are accurately reflected in the test results.

3.1.2 Crack growth under static load

A significant challenge currently being addressed is crack growth under static load, which is still not fully understood. Observations have been made under specific laboratory conditions for older microstructures, but no cases have been reported for hydrogen pipelines currently in operation [33]. The crack growth under static load differs from fracture toughness, and necessitates specific testing methods. The ASTM E1681 test covers the determination of the environmentally assisted cracking (EAC) threshold stress intensity factor parameters used to determine if crack growth would occur under static load. However, constant displacement testing per ASTM E1681 is not deemed suitable for pipelines, as it is based on linear elastic fracture mechanics (LEFM). The CERs advise against using constant displacement tests and recommend constant load testing instead. In this regard, an alternative to ASTM E1681 is the constant load test described in [33], which is a variation of the ASTM F1624 test [34], utilizing a fatigue pre-cracked specimen exposed to hydrogen environment.

3.1.3 Fatigue crack growth

Fatigue crack growth must be considered for all pipelines, including those within the previously defined ASME B31.12 Option A design criteria. The reason for this is that fatigue crack growth is driven by the stress intensity range, ΔK. Pipelines operating at low stress levels may be at risk, particularly since the existing anomaly size might be larger compared to pipelines operating at higher

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pressures due to the proportionally lower pressure test stress. In addition, the effect of hydrogen to increase the fatigue crack growth rate, necessitates a detailed analysis of the threat of fatigue. It might be possible to identify a ΔK value below which crack growth does not occur, which could be used in the engineering assessment. An S/N curve approach, utilizing industry-recognized codes and representative materials data, may not always be feasible. The method outlined in ASME B31.12 code case 220, based on work presented in [35], is included in the CERs. Alternatively, testing can be conducted in accordance with ASTM E647 [36]., or other industry accepted approaches can be leveraged. In the ECA, the initial defect size is determined based on non-destructive testing (NDT) acceptance criteria applied during manufacturing and construction, in-line inspection (ILI) results, or the maximum survivable flaw size after a hydrotest (pipe mill, initial construction, or in-service).

3.1.4 Hardness

ASME B31.12 code sets a hardness limit of 235 HV for piping and pipelines and 237 BHN for production welds made to P-1 materials using SAW and FCAW processes. Discussions with the ASME B31.12 committee revealed that this hardness value stems from industry experience and prevailing guidelines in the refinery and piping sectors. The 235 HV value seems to have been chosen based on the minimum specified values found in various standards, especially API RP 934 [37], for Cr-Mo pressure vessels. However, this criterion does not directly apply to C-Mn steel pipes. To mitigate against the risk of hydrogen-assisted fracture, ASME B31.12 defines a 235 HV limit as a proxy for toughness, based on previous research studies [38,39]. Although there is a correlation between hardness and toughness, it may not apply to all types of pipe or welds.

Hardness can indicate susceptibility to hydrogen embrittlement but is not a reliable measure for estimating fracture toughness in engineering integrity assessments. Consequently, the CERs have separated the requirements for hardness and toughness, where toughness must be evaluated separately from hardness. A literature survey and review of historical failure data of hard spots was performed in PRCI MAT-7-2 [40]. It confirms that hard spots on vintage pipelines (1950s-1960s) with a hardness of around 340 HV represent the 5th percentile for hard spot failures due to hydrogen-induced cracking from cathodic protection (CP). By extrapolation, a hardness limit of 275 HV would result in a much lower probability of cracking in gaseous hydrogen, considering that hydrogen charging from active CP is more severe than high partial pressures of gaseous hydrogen. Taking the available industry data and guidance into consideration, a hardness limit of 275 HV was defined in the CERs.

3.2 Integrity threats and susceptibility

Integrity threats and susceptibility are key considerations for EA on repurposed pipelines. Operators of natural gas pipeline in the US will have developed the threat assessment approach based on ASME B31.8S [9]. This includes prescriptive and performance requirements for natural gas and CO_2, but not hydrogen. An update for hydrogen is being created through content developed by PRCI in project JEFI 04-11A [41]. Work is also ongoing in a set of DOT projects [42,43], and the results will be considered as the content in B31.8S is created. Owing to the significant effect of hydrogen on the fracture toughness, ductility and fatigue crack growth rate, the current content in ASME B31.8S needs updating. Prescriptive requirements are included in ASME B31.8S as basic option, when minimal data is available, and a conservative approach can be utilized. This prescriptive approach alone is not considered appropriate for hydrogen at this stage, and the performance approach must be taken. A full set of data and information is required to manage the safety of hydrogen pipelines. Additional threats will have to be considered for hydrogen including hydrogen cracking, fatigue, crack extension under constant load and hard spots, which have all be discussed in this paper. More information will be presented as the projects evolve, and the reader should aware that changes in ASME B31.8S are being proposed.

3.3 Assessing existing anomalies

Anomalies that exist in repurposed pipelines in almost all case will be assessed using ILI, providing the pipeline is piggable. Once this information has been collected using the range of ILI technologies, each anomaly type must be analyzed to determine fitness-for-service using the ECA. The material property inputs have been discussed in previous sections. Material properties, information about existing anomalies and the operating stress are all fed into models to analyze the anomaly and decide if remediation is required. Several projects have been completed and some are still ongoing looking at the models used for hydrogen [2,21,41]. One project, JEFI 04-06 [21], is currently in progress that addresses the topic with the aim of creating guidance on how to implement the models and analysis techniques that are currently used for natural gas in hydrogen. In addition, there are a number of industry projects being progressed that include full-scale testing of pipes containing anomalies in hydrogen JEFI 04-08 and SafeH2Pipe [44,45], which will help define how the models are able to safely analyses the behavior of anomalies in representative conditions. This ongoing work will help operators form a cohesive approach to fitness for service analysis in hydrogen pipelines.

4. Conclusions

This paper summarizes the Consensus Engineering Requirements (CERs) for pipelines in hydrogen and blend service prepared by PRCI EFI. The CERs guidance document has been published by the EFI with free access. Operators, service providers, and regulatory bodies alike can adopt and use the CERs report as a reference as the industry continues to transition to emerging fuels. The CERs contain complete guidance for conducting an engineering critical assessment (ECA) to both new build repurposed hydrogen and hydrogen blend pipelines, thus providing a sound analytical performance-based method to address some of the uncertainties and potential lack of conservatism in the industry.

The CERs have been presented to the ASME committee for consideration and approval for inclusion in the 2026 version of ASME B31.8, as the international standard for hydrogen and blend service transmission and distribution pipelines. In parallel to that effort, the EFI team is also working on an update to ASME B31.8S, with guidelines for integrity management of hydrogen and blends pipelines.

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The work was built on significant collaboration among stakeholders. The project stands as a flagship of how the industry can come together to share experience, expertise, and vision to reach "Consensus" on a broader global scenario. The authors would like to acknowledge funding support from the Emerging Fuels Institute of Pipeline Research International Council Inc. (EFI-PRCI) of project JEFI 04-11 contract number PR337-23115. The authors also express their immense gratitude to all individuals involved, for all their contribution, effort, and energy which made possible to successfully complete this project.

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