Probabilistic Assessment of Crack-Like Seam Weld Anomalies in Hydrogen-Blended Natural Gas Pipelines

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Abstract

Many North American operators are currently evaluating options to blend hydrogen into their natural gas systems. The introduction of hydrogen may impact the long-term structural integrity of steel pipelines, with particular influence on crack-like anomalies due to embrittlement of the steel and increased fatigue crack growth rates. Crack-like anomalies such as those found in seam welds should be assessed for hydrogen-blended service with a crack assessment model capable of handling low toughness failures such as API 579 or the PRCI MAT-8 model (T. Anderson, 2017; Hanna et al., 2021), with proper adjustments to account for the effects of hydrogen.

This paper illustrates the limitations of conventional fatigue assessment methods when assessing integrity and risk of crack-like anomalies in blended hydrogen service and provides a technical review of factors influencing the assessment. This includes a summary of suitable assumptions regarding the variability in pipe strength and vintage seam weld toughness properties, the density, depths, and lengths of the population of defects expected on uninspected pipelines, and a review of historical mill test pressure requirements. A range of example analysis cases are presented to demonstrate the impact of embrittlement and accelerated fatigue crack growth rates due to hydrogen, and how this is affected by the operating conditions of the pipeline, such as the pressure loading history, current stress levels, and historical mill pressure tests.

Effect of hydrogen on crack-like seam weld anomalies

One of the primary impacts of hydrogen on the structural integrity of steel pipelines is hydrogen embrittlement, or a reduction in fracture toughness of the material. Current indications show fracture toughness reductions as high as 69% in the presence of hydrogen are possible (San Marchi & Somerday, 2012). However, the severity of the reduction in toughness will depend on the particular steel and hydrogen pressure and should be determined experimentally as prescribed in ASME B31.12 (ASME, 2023). As the burst pressure of a longitudinal seam-weld crack is largely dependent on the fracture toughness of the material (T. Anderson, 2015), a reduction in fracture toughness would result in shorter and shallower cracks failing at the same operating pressure. This can be illustrated using critical flaw curves, which indicate the combinations of the largest depths and lengths that crack-like anomalies can have at a given pressure (Kiefner, 2001). Figure 1 shows the critical flaw curves for a range of toughness reductions after the introduction of hydrogen.

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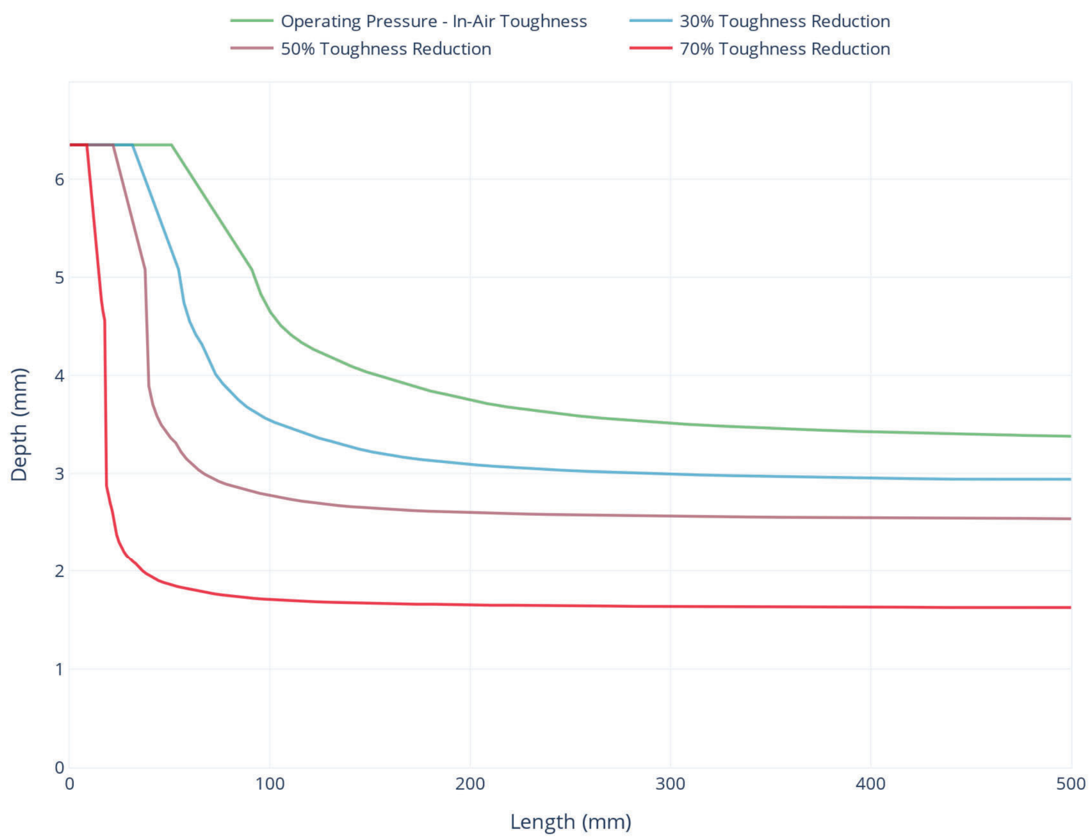

Figure 1. Critical flaw curves for a range of toughness reductions due to hydrogen.

Another primary impact of hydrogen on crack-like seam weld anomalies is the potential to accelerate the rate of growth due to pressure cycle fatigue. Many researchers have developed curves that describe the fatigue crack growth rates observed in hydrogen (Amaro et al., 2018; San Marchi et al., 2024). These curves all reflect that, above some critical value of stress intensity range, ΔK, the crack growth rate is greater than what would be expected without hydrogen (ASME, 2023). The curve developed by Amaro et al. (2018) and employed in ASME B31.12 (2023) was intended for use as an upper-bound of fatigue crack growth rates for pipeline steel. San Marchi et al. (2024) have developed an approach to reflect case-specific growth rates considering hydrogen partial pressure and the pressure cycle stress ratios (ratio of minimum over maximum stress). Figure 2 shows a histogram of stress intensity ranges due to pressure cycling on a hydrogen blended pipeline (blue bars) and the equivalent number of pressure cycles required in typical natural gas fatigue crack growth rates (FCGR) for the same amount of crack growth to occur (red bars). The Hydrogen FCGR curve is represented with a linearized version of the curve provided in ASME B31.12 (2023) in blue and a typical natural gas FCGR is shown with the red curve (T. L. Anderson *et al.*, 2022).

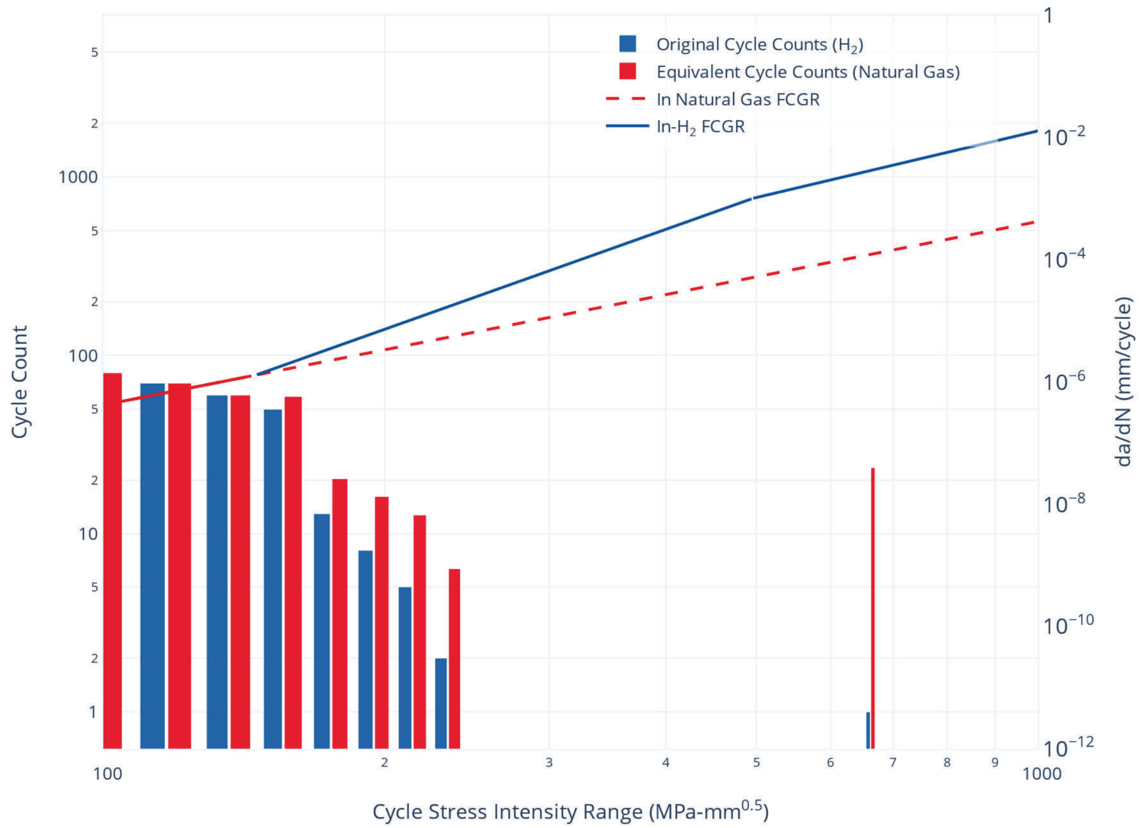

Figure 2. The counts of pressure cycles in natural gas expected to cause equivalent growth in hydrogen.

Deterministic fatigue assessment

The goal of a deterministic fatigue assessment is to assess the remaining life of any existing crack-like features present on a pipeline considering pipe-specific properties and the expected cycling severity of the system. However, the pipe strength and fracture properties required for this assessment may be unknown and assumptions must be made to best represent the system. Below is a summary of some of the key inputs to a deterministic fatigue assessment, and suitable references that may be used.

As outlined previously, the fracture toughness of the pipe will dictate the burst pressure of a crack-like seam weld anomaly. Bagnoli et al. conducted a comprehensive experimental program to measure the seam weld toughness of vintage electric resistance weld (ERW) (Bagnoli *et al.*, 2022) and fit the statistical distribution shown in Figure 3 to these measurements. For the assessments in this paper, the 10th percentile, 44.6 MPa-m$^{0.5}$ (40.5 ksi-in$^{0.5}$), of this distribution was taken as a conservative value for in-air fracture toughness (i.e. with no hydrogen effect).

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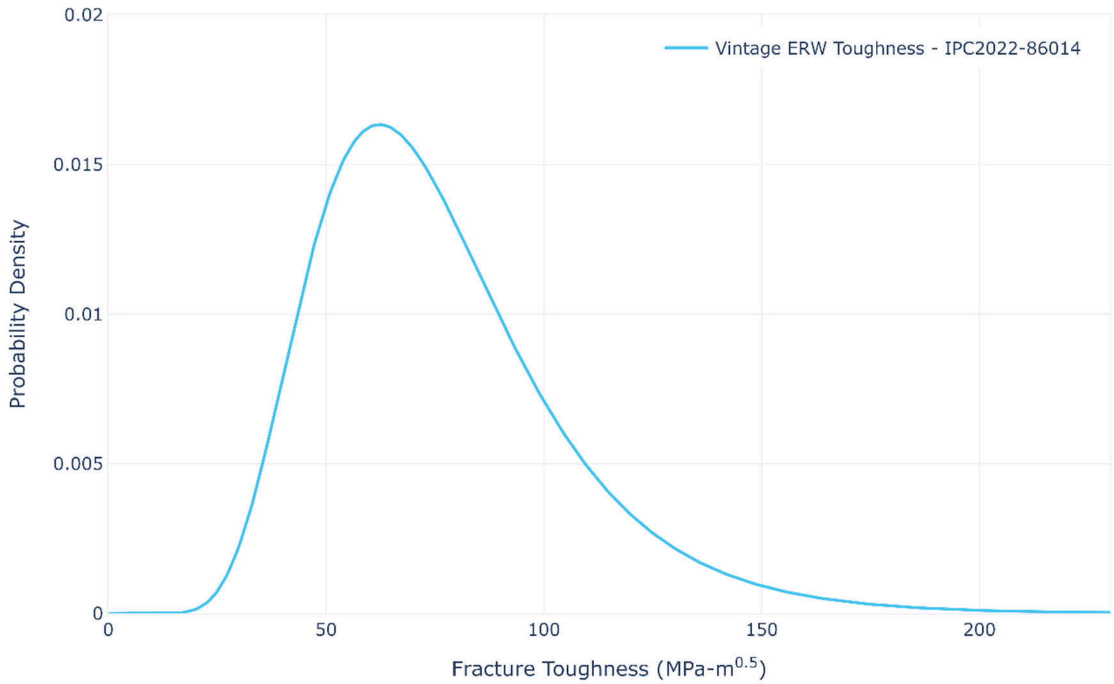

Figure 3. Vintage ERW fracture toughness distribution outlined in (Bagnoli et al., 2022).

Gas distribution piping systems typically operate below 20%-30% of the pipe's specified minimum yield strength (SMYS) depending on the regulatory jurisdiction (49 CFR Part 192, 2022; CSA, 2023) and are generally not inspected with in-line inspection (ILI) (Ersoy *et al.*, 2021, ASME, 2022). In the absence of a measured crack population, a conservative deterministic fatigue assessment assumes the worst-case crack sizes are present. Historic API standards have required hydrostatic pressure testing in the mill at the time of manufacture to detect anomalies in the pipe body and weld (INGAA, 2005). This mill test pressure can be used to establish the worst-possible crack-like anomalies critical flaw curve that could have survived the test and therefore be present at the time of pipe install. A commissioning pressure test can be used instead if records are available, and that pressure is higher. The remaining life of each feature on the mill test critical flaw curve can be assessed considering pressure cycle driven fatigue growth to find the minimum time to failure. The remaining life of a pipe segment is taken as the minimum time to failure of all the potential flaws on the critical flaw curve after the mill pressure test.

Several additional analysis assumptions are required:

- The hydrostatic test pressure requirements have varied over time as historic API standards have been updated (INGAA, 2005). The maximum test pressure prescribed in each API standard has typically increased over time in both the original API 5L and API 5LX before they were combined into one standard. Early versions of the API standards also prescribed specific test pressures for small diameter pipe that varied depending on the weld method.

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- Pipe strength properties published by API in Recommended Practice 1176 (2016) or those published by Hassanien *et al.* (2016) provide nominal values and distributions for yield and tensile strength by grade.
- Lack of fusion manufacturing flaws typical of ERW seams would generally not be sharp at the time of the mill test and therefore would have a reduced fracture demand. A representative fracture demand for these blunt features can be conservatively captured by a reduction of 2x (T. Anderson, 2023). These features may sharpen over time due to pressure cycling, so this adjustment should only be applied at the time of manufacture unless the time-to-sharpen can be estimated.
- If the expected cycling severity of the pipeline system is unknown, a range of common natural gas cycling severity levels are provided by Ma et al. (2018).
- Finally, the residual stress in the pipe should also be considered. Various references provide recommendations for residual stress that can be used in a fatigue assessment (Andrews & Slater, 2018; Anderson, 2017).

Once the key inputs to the analysis have been selected, a deterministic fatigue assessment can be completed for a range of potential toughness reductions. The timeline of crack growth used for the analysis is shown in Figure 4.

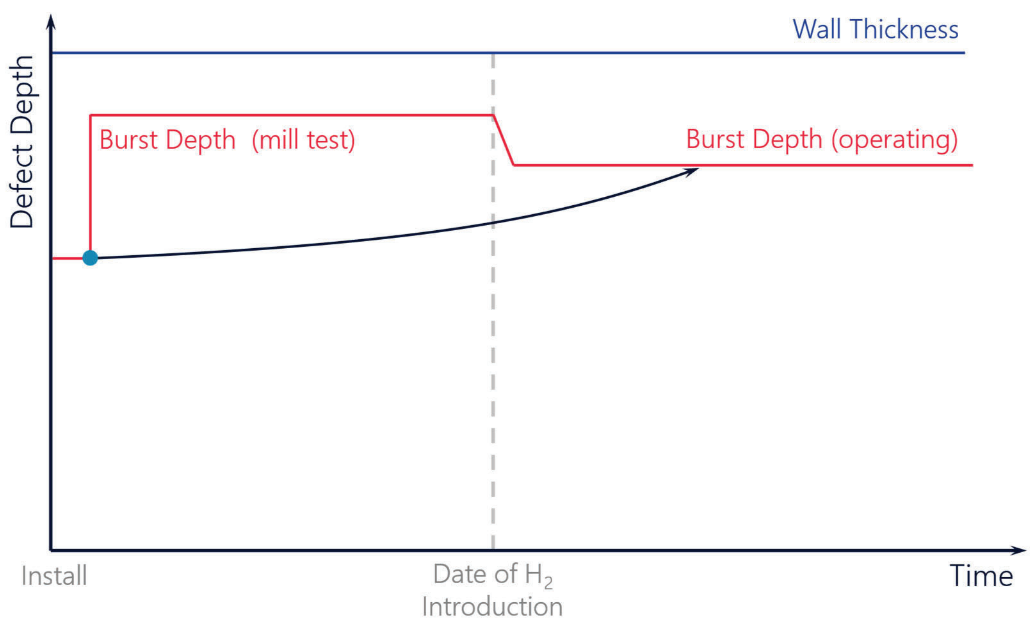

Figure 4. Crack growth timeline for conservative deterministic fatigue assessment. For illustrative purposes, only growth in the depth direction is shown, however feature length growth is also considered.

As shown in Figure 4, the depth at which a crack will fail changes over time between the date of installation, the date of hydrogen introduction, and into future operation. The maximum possible burst depth without failing is lowest at the time of install due to the higher mill test pressure. The influence of this loading is reduced when accounting for the reduced fracture demand of blunt features. From the time of installation to the date of hydrogen introduction, the depth at which a

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crack would fail is increased since the operating pressure is typically much lower than the mill test pressure. Finally, there is a reduction in burst depth at the time of hydrogen introduction due to the toughness reduction. In a deterministic assessment, crack sizes are conservatively assumed to be at the largest potential size after the mill pressure test and are grown to the time of hydrogen introduction. Given that a flaw survives the toughness reduction, it is then grown to failure using accelerated fatigue growth rates due to hydrogen.

Table 1 outlines the general inputs to the deterministic assessment example case shown in Figures5 and 6 and their respective source if applicable.

Table 1. Deterministic Assessment – General Inputs

Parameter	Value	Source
Pipe Diameter	NPS 16	
Wall Thickness	6.35 mm	
Residual to Yield Stress Ratio	10%	Andrews & Slater, 2018
Grade	X52	
Material Toughness	44.6 MPa-m$^{0.5}$	Bagnoli et al., 2022
Operating Stress	30% SMYS	
Mill Test Pressure	90% SMYS	INGAA, 2005
Surface	OD	
MOP Cycles	1 per year	Ma et al., 2018
Install Decade	1970	

Figure 5 shows the critical flaw curves for a pipe segment during the mill pressure test and at normal operating pressure for in-air fracture toughness and various toughness reductions. For higher toughness reductions, the remaining life between the mill test and reduced toughness critical curves is decreased. This is evident for the 50% toughness reduction, as there is very little difference between the two curves at some points.

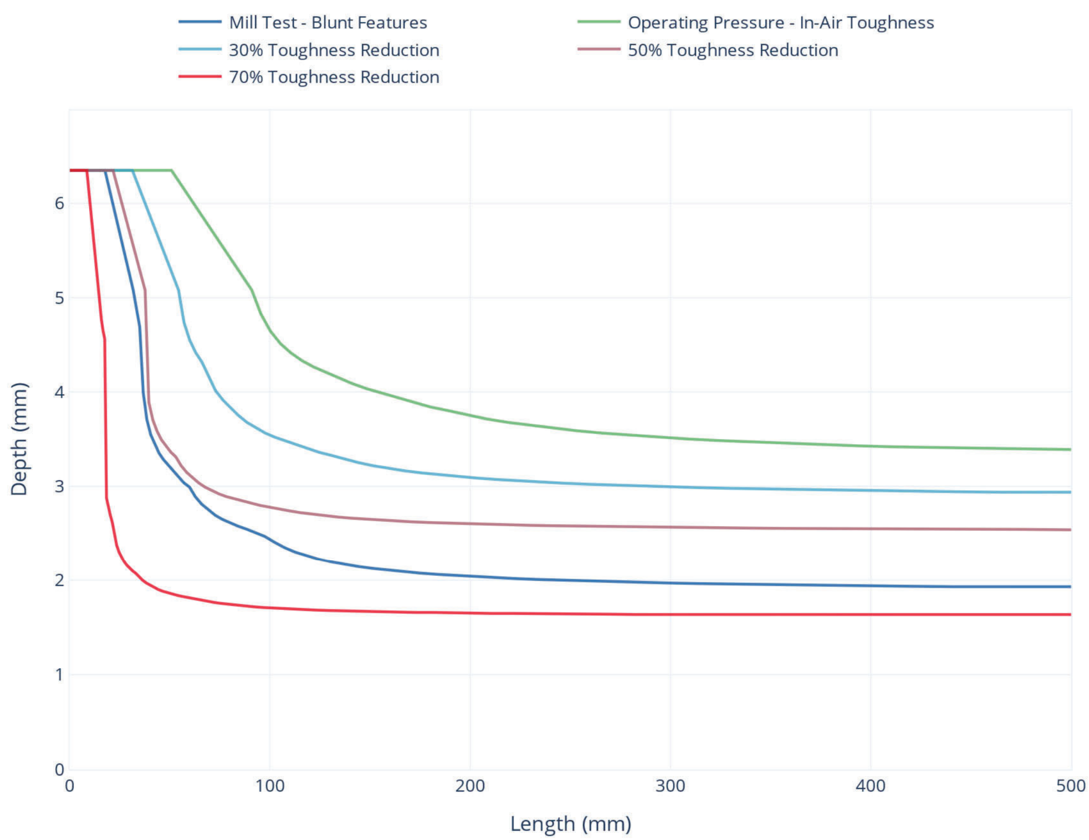

Figure 5. Critical flaw curves at mill test pressure and operating pressure for range of toughness reductions.

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Figure 6 shows the effect of toughness reduction on the deterministic remaining life of a pipe segment in hydrogen. As shown, the remaining life will decrease for higher toughness reductions to the point where remaining life decreases to zero. These cases of zero remaining life reflect that the critical feature on the segment would not survive the toughness reduction. The limitations of a conventional deterministic fatigue assessment are evident for the 70% toughness reduction curve because all points on the curve are below the mill test curve, meaning all the worst-case features would fail the toughness reduction. In truth, these worst-case flaws may be very unlikely to exist, and a probabilistic assessment is required to properly characterize the risk, as described in section the below.

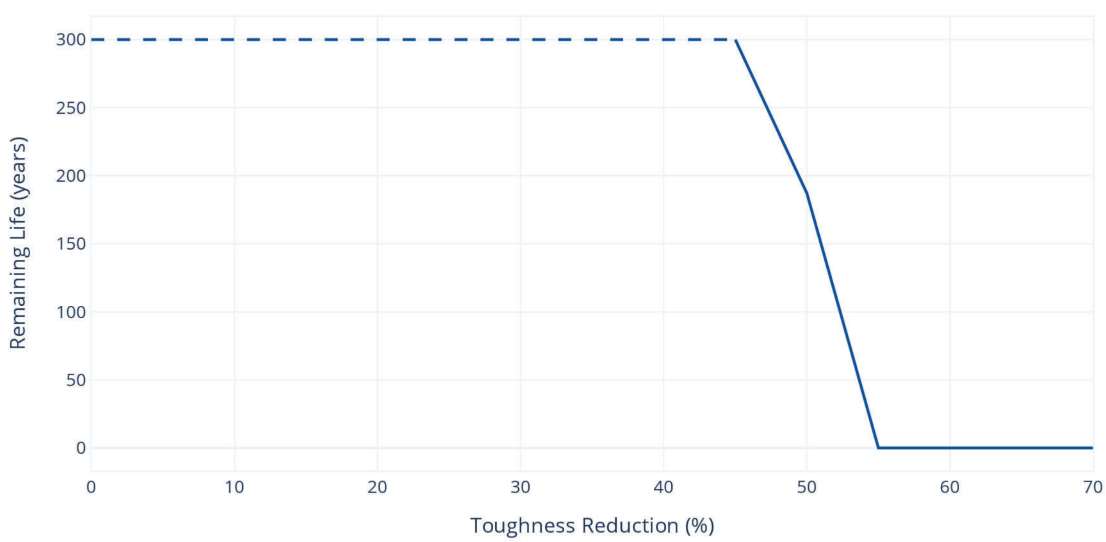

Figure 6. Remaining life in hydrogen by toughness reduction. Note that the remaining life has been capped at 300 years.

Probabilistic reliability assessment

Structural reliability methods can be used to assess the likelihood of failure for pipeline crack-like seam weld anomalies, where failure is defined as a loss of containment (CSA, 2023). A loss of containment may occur by two different failure modes – small leak or burst – where each failure mode is defined by a limit state function. An illustration of these two limit states as defined in CSA Annex O is shown below in Figure 7.

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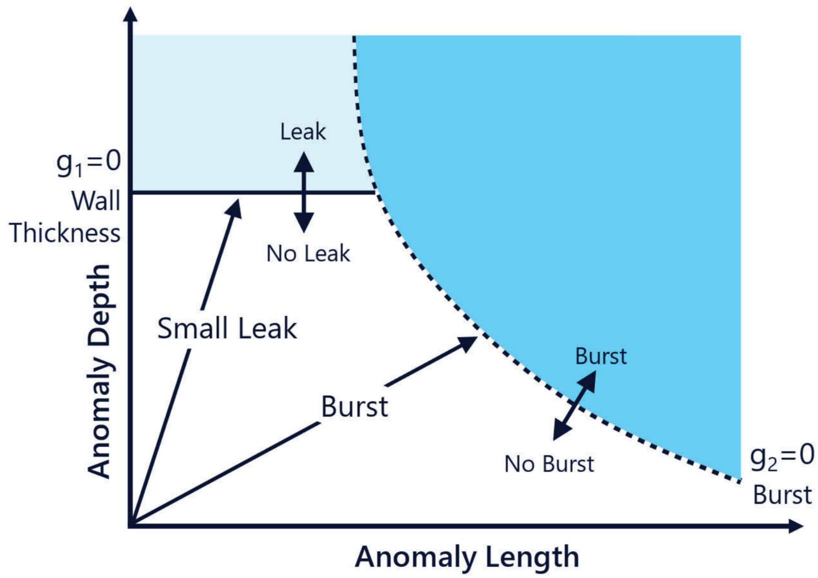

Figure 7. Limit states for failure modes associated with cracks.

Burst occurs when the pressure resistance of the flaw decreases over time and eventually reaches the internal pressure of the pipeline. The pressure resistance of a crack-like flaw is a function of crack driving force and fracture toughness. The limit state equation for a burst failure (g_2) of a crack-like defect is:

$$g_2 = r - P \tag{1}$$

Where r is the pressure resistance for burst of a crack-like flaw determined by a pipeline fracture model, and P is the internal pressure of the pipeline. Alternatively, a small leak (g_1) occurs if the maximum depth of the crack-like flaw exceeds the wall thickness, as shown in Figure 7, and the flaw is short enough to grow through-wall without violating the burst pressure criterion. The limit state equation for a small leak (g_1) of a crack-like flaw is:

$$g_1 = t - d \tag{2}$$

Where t is the wall thickness, and d is flaw depth.

The probability of failure of a pipeline segment can be calculated using a structural reliability implementation of a pipeline fracture model such as API 579 or the PRCI MAT-8 model, solved using Monte Carlo simulation. With this, results of the analysis provide an estimate of the probability of failure by leak and burst in each future year. Beginning at the date of the assessment, input dimensions of a crack-like anomaly are randomly sampled from statistical distributions for each Monte Carlo trial. This trial is only included if the randomly generated sampled attributes would not have burst at the time of the assessment at the local operating condition, and if it would not have failed the mill pressure test, considering the changes in the size of the feature over time due to fatigue growth.

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Unlike a deterministic assessment which assumes the worst-case crack sizes on the pipeline system, a probabilistic assessment considers the variability in the potential population of crack-like anomalies on each pipeline segment, including the range of feature depths, lengths, and the flaw density per mile. In work presented at the 2023 Clarion Pipeline Risk Management Forum, Dessein & Anderson (2023) described distributions that were fit to data from field measurements in the PRCI Project NDE 4E database (Skow et al., 2017) and new data provided by operators in the PRCI JCAS-01 Consortium project. Defect size distributions and densities were provided for use in probability of failure assessments for various severity categories based on operating history, line pressure, vintage, seam type, and manufacturer.

Figures 8 and 9 show one severity category from Dessein & Anderson (2023), *LF ERW & pre-1970 HF ERW – Flagged*, which represents expected flaw sizes on vintage (pre-1970) pipeline segments. These distributions represent the subset of low frequency electric resistance weld (LF-ERW) and pre-1970 high frequency electric resistance weld (HF-ERW) pipes from manufacturers that were flagged based on a higher frequency of historical incidents reported to the Pipeline and Hazardous Materials Safety Administration (PHMSA) and failures during hydrostatic pressure tests (PHMSA 2022, and GTI 2021). Figure 10 compares the average defect density per mile from this work to a distribution fit to the observed flaw densities in the ExxonMobil pipeline system described by Ma *et al.* (2022).

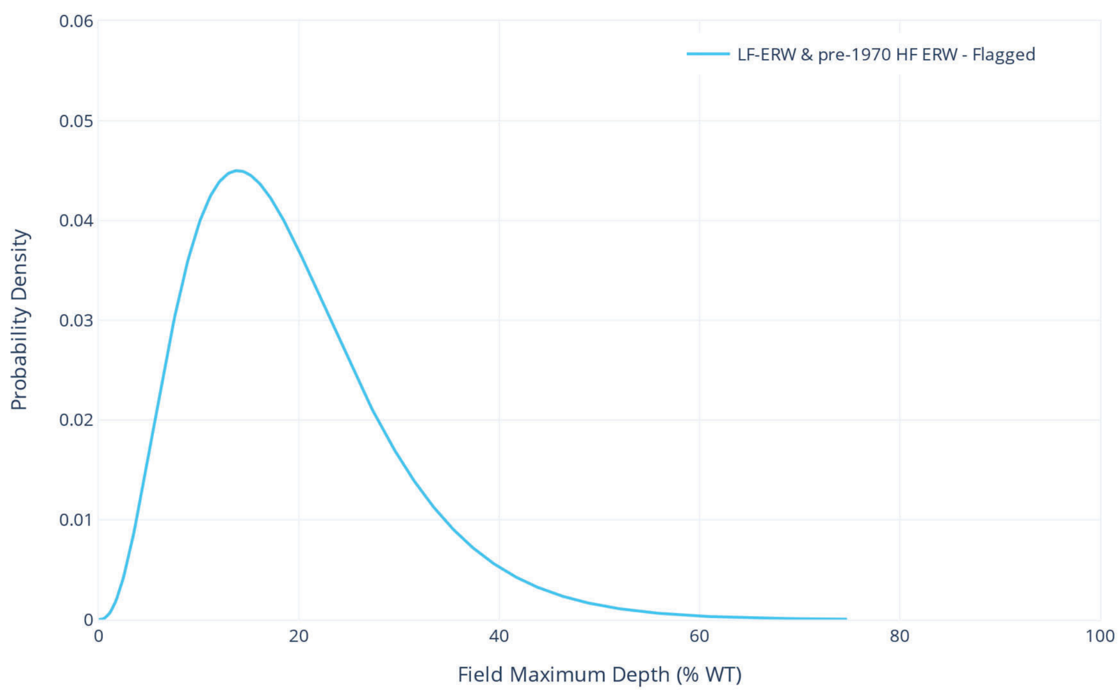

Figure 8. Defect depth (% wall thickness) distribution for vintage ERW pipe for flagged manufacturers from Dessein & Anderson (2023).

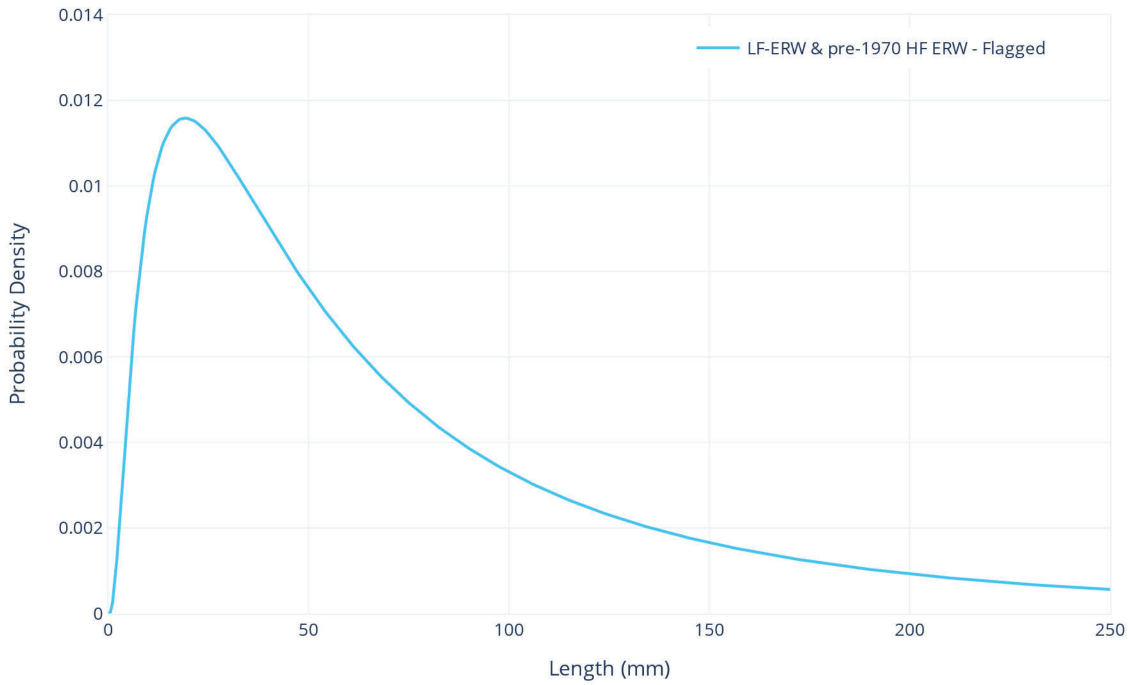

Figure 9. Defect length distribution for vintage ERW pipe for flagged manufacturers from Dessein & Anderson (2023).

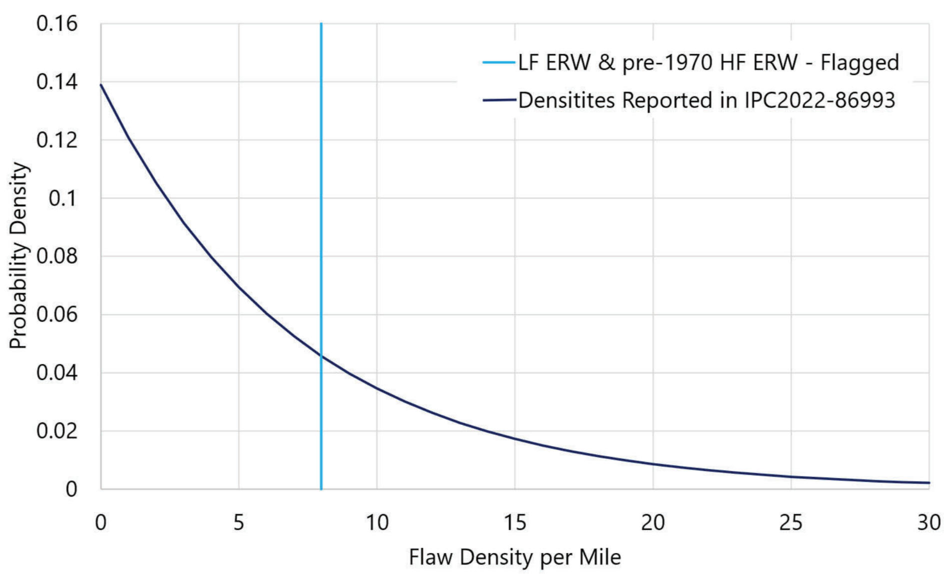

Figure 10. Defect density per mile for vintage segments from Dessein & Anderson (2023) and Ma et al. (2022).

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A probabilistic analysis allows the user to reflect the uncertainty of material properties of a pipeline segment such as pipe strength and fracture toughness using a probability distribution, unlike a deterministic analysis which requires the selection of a single deterministic value (PHMSA, 2020). Additionally, a probabilistic analysis can incorporate system-specific information such as the outcome of direct assessments and testing or field investigations such as NDE measurements.

Figure 11 shows the timeline of crack growth used in the probabilistic approach, including the two additional failure mechanisms driven by hydrogen effects on crack-like seam weld anomalies: failure by toughness reduction, and failure by hydrogen-accelerated FCGR. As outlined previously, each simulated Monte Carlo trial with randomly sampled crack depth and length, and pipe attributes is checked against the expected mill test pressure at the time of installation, and a portion of these sampled crack-like anomalies are eliminated from the simulations if they would have burst at the increased pressure. Each valid simulation is then grown to the date of hydrogen introduction, where it either bursts after the toughness reduction, or growth is continued at an accelerated rate due to hydrogen.

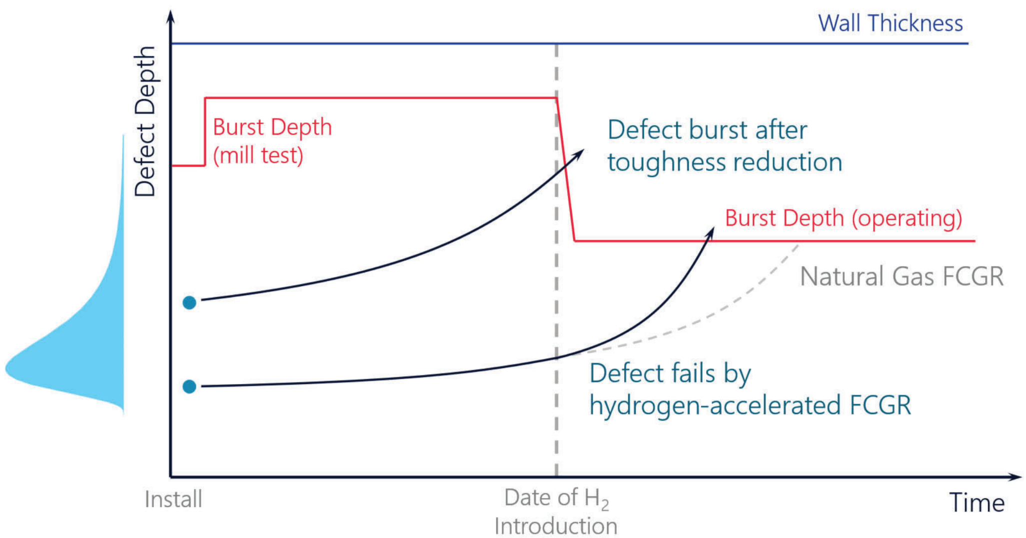

Figure 11. Crack growth timeline for probabilistic assessment. For illustrative purposes, only growth in depth direction is shown, however feature length growth is also considered.

Using the same example pipeline scenario shown previously (see Figure 5), the general input distributions and parameters used in the probabilistic assessment example cases are outlined in Table 2 with their respective source when applicable.

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Table 2. Probabilistic Assessment Analysis Inputs

Parameter	Selected Distribution	Mean, Standard Deviation	Source
Defect Depth	Gamma	1.22, 0.64 mm	Dessein & Anderson, 2023
Defect Length	Lognormal	97.8, 137 mm	Dessein & Anderson, 2023
Pipe Diameter	Constant	406.4 mm	
Residual to Yield Stress Ratio	Constant	10%	Andrews & Slater, 2018
Wall Thickness	Normal	6.41, 0.06 mm	CSA, 2023
Yield Strength	Normal	387.2, 22.1 MPa	Hassanien et al., 2016
Tensile to Yield Ratio	Lognormal	1.419, 0.088	Hassanien et al., 2016
Material Toughness	Lognormal	76.2, 28.9 MPa-$m^{0.5}$	Bagnoli et al., 2022
Operating Stress	Constant	30% SMYS	
Mill Test Pressure	Constant	90% SMYS	INGAA, 2005
Surface		OD	

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Figure 12 compares a subset of sampled crack sizes at the time of the mill test to the deterministic critical flaw curves. Any simulated crack that would have failed during the mill test (light blue points) is eliminated. Note that, for simplicity, this illustration ignores the effects that variability in pipe properties and loading conditions would have on the placement of the critical flaw curve.

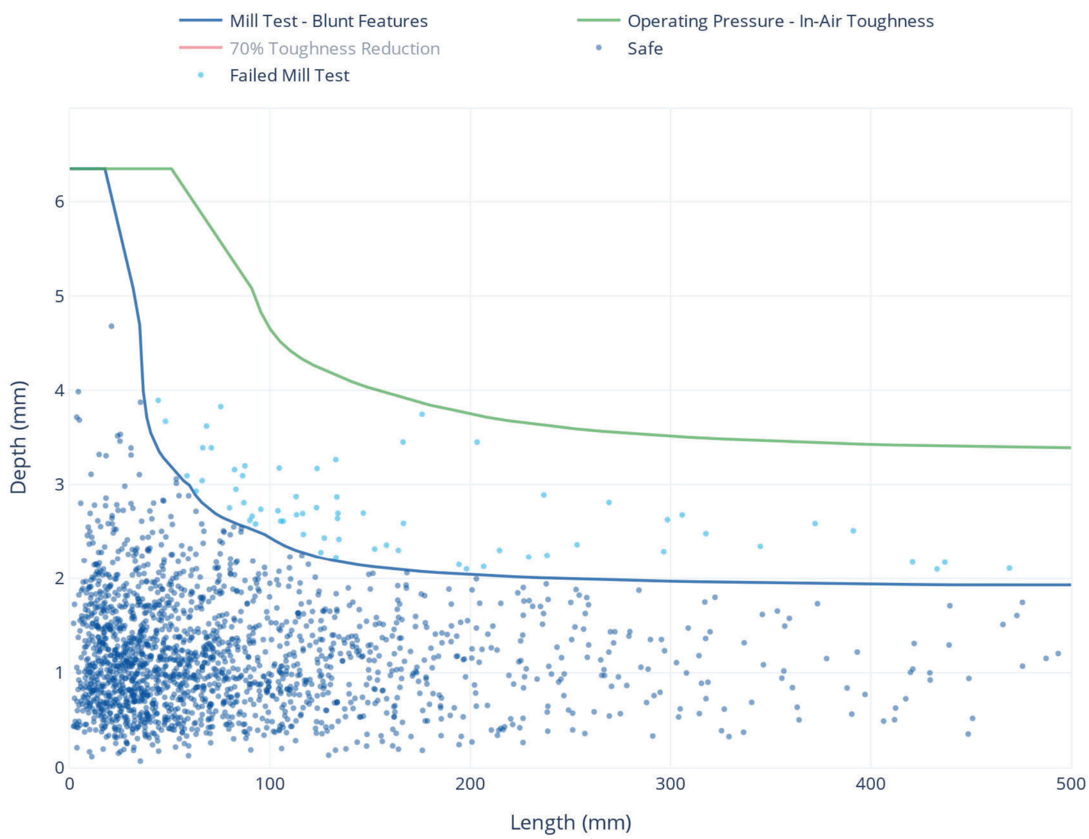

Figure 12. Simulated cracks at the time of mill test compared to critical flaw curve for mill test and operating pressure.

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Figure 13 shows the same subset of valid sampled cracks at the time of hydrogen introduction. At this point, fracture toughness is reduced, and any sampled crack that fails (red points) is recorded as a failure due to toughness reduction. Unlike the deterministic case where the entirety of the mill test critical flaw curve was eliminated and it was impossible to determine a remaining life, a set of cracks that survive the toughness reduction remain (dark blue points).

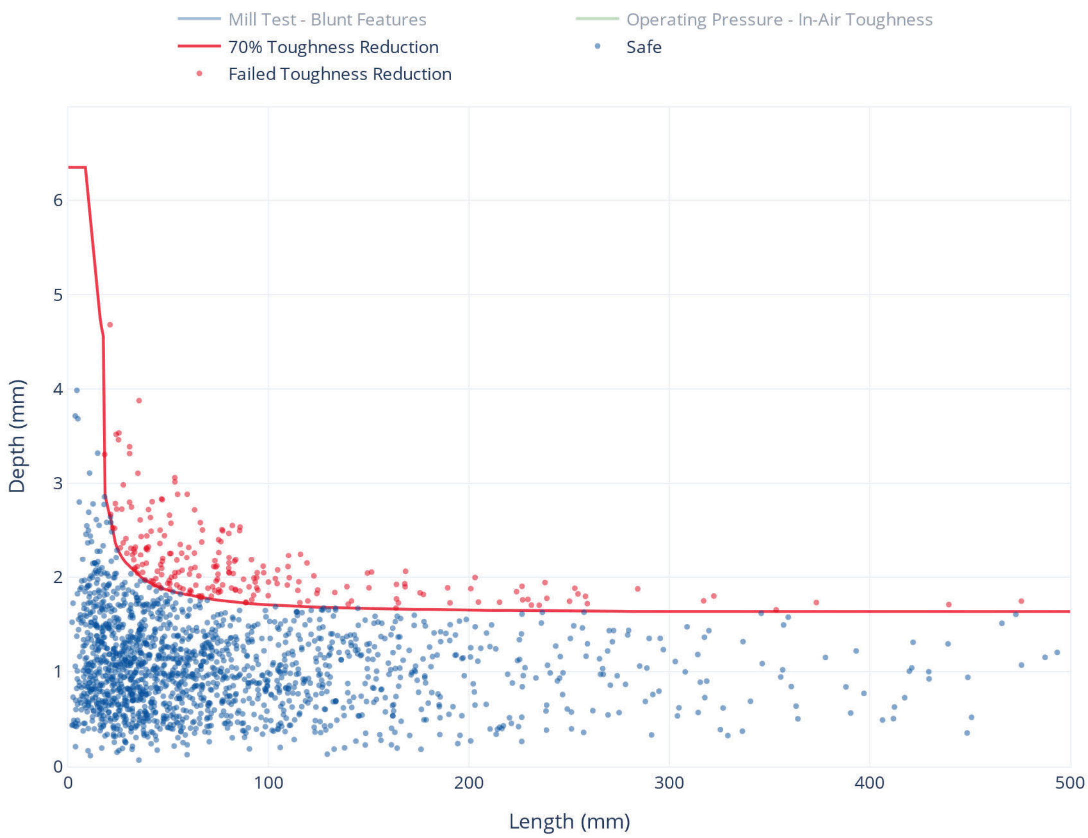

Figure 13. Simulated cracks at time of toughness reduction compared to critical flaw curve for reduced toughness.

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Figure 14 shows the same subset of cracks that survived the toughness reduction grown for 20 years with hydrogen-accelerated fatigue crack growth rates. Any crack that is grown to failure by fatigue is recorded as a hydrogen-accelerated fatigue crack growth rate (HA-FCGR) failure in that year. In this example, only 2 reach this limit in 20 years.

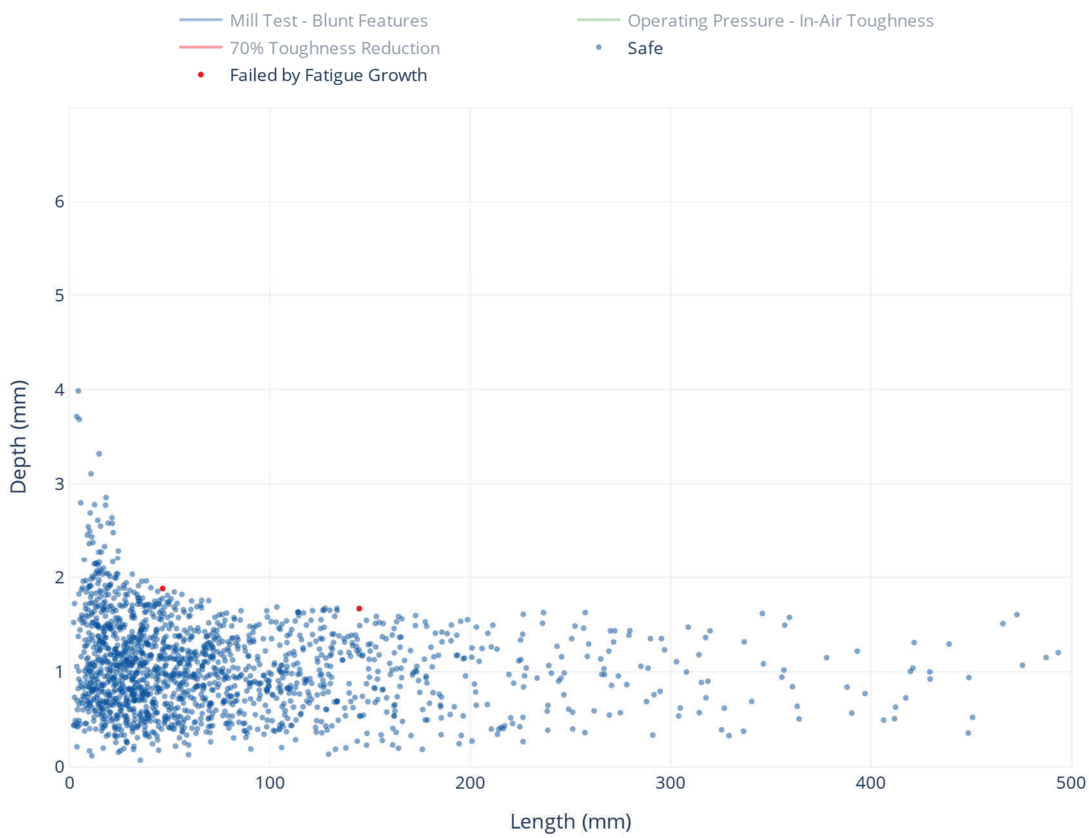

Figure 14. Simulated cracks after hydrogen-accelerated fatigue growth.

Figure 15 shows the probabilistic results for this pipeline scenario calculated using 10 million Monte Carlo simulations per segment for each toughness reduction. As the rate of burst due to toughness reduction approaches the resolution limit of 10 million simulations at low toughness reductions, rates have been extrapolated in cases where simulations have returned no failures (dark blue dashed line). The results are compared to an approximate historical rate of burst due to manufacturing defects on natural gas transmission pipelines. This historical rate was estimated using failure incident data from 2010-2023 published by the US Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) for pre-1970 ERW gas transmission pipelines with no pressure test or a pressure test to less than 1.1x Maximum Allowable Operating Pressure (MAOP) (U.S. Pipeline and Hazardous Materials Safety Administration, 2024).

The probability of failure results from the Monte Carlo simulations, which are shown in Figure 15 include uncertainty on all relevant pipeline attributes, such as the strength properties, fracture toughness, and crack growth rates. At 10 million simulations, there are no predicted failures due to toughness reduction below a 35% reduction. The probability of a burst due to toughness reduction occurring increases from 4.1×10^{-6} per mile-year at a 35% toughness reduction to 4.3×10^{-1} per mile-year at a 70% toughness reduction. Similarly, at 10 million simulations there are no predicted failures for HA-FCGR until a toughness reduction of 50%. The 10-year average annual HA-FCGR burst rate increases from 6.5×10^{-6} per mile-year at a 50% toughness reduction to 5.0×10^{-5} per mile-year at a 70% toughness reduction. The HA-FCGR rates have been extrapolated in cases where simulations have returned no failures (red dashed line). These results suggest that at a typical natural gas system distribution stress level of 30% SMYS, the probability of a burst occurring may reach or exceed the historical rate of bursts at transmission stress levels at high enough toughness reductions. This is evident in Figure 15 as the historical rate is already exceeded at a toughness reduction of 40%. This result can be combined with a consequence assessment to determine the change in individual and societal risk of introducing hydrogen to a pipeline system and to evaluate whether this risk level is acceptable.

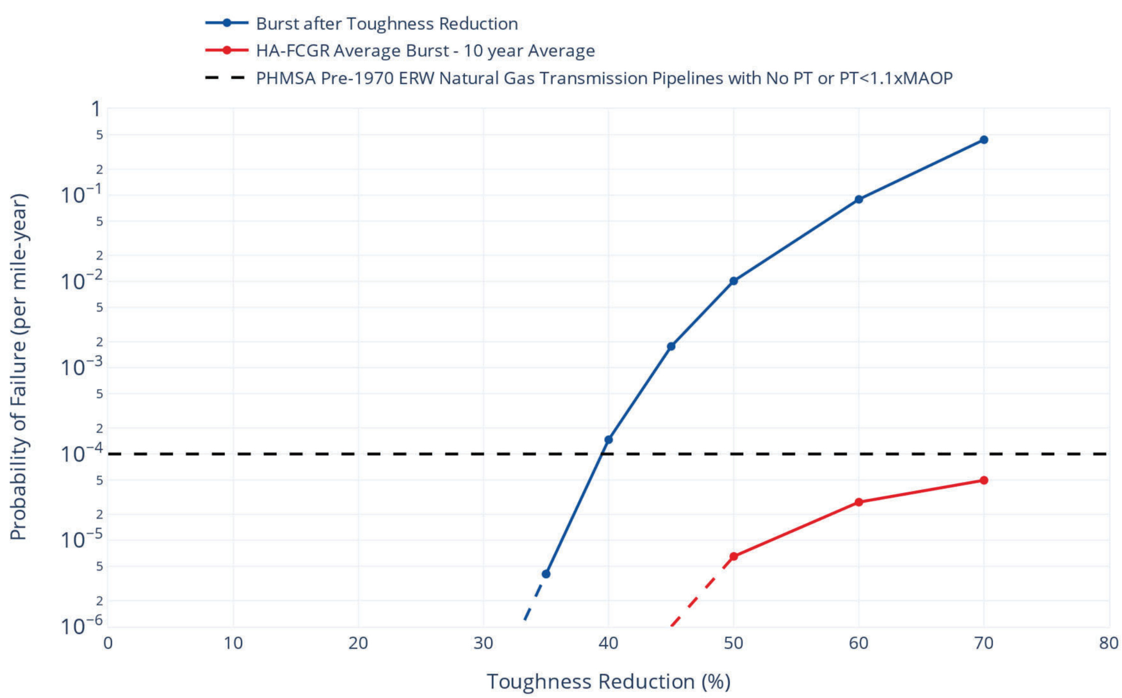

Figure 15. Toughness reduction and hydrogen-accelerated fatigue burst rates for 10 million simulations.

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Conclusion

The use of conservative deterministic fatigue assessment methods when assessing remaining life of a pipeline segment in hydrogen are limited by the fact that they assume that the worst-case crack sizes exist. At high enough toughness reduction due to the introduction of hydrogen, it is impossible to determine a remaining life if critical flaws after the mill pressure test would be expected to fail due to the reduction in toughness alone. A probabilistic structural reliability approach is better suited as it considers a full probabilistic range of outcomes, including these worst-case crack sizes, but weights these outcomes by how likely they are to actually be present on the pipeline. With probabilistic methods, one can obtain the likelihood of both a burst after toughness reduction due to the introduction of hydrogen, and the likelihood of future failures due to hydrogen-accelerated fatigue crack growth rates. These probability of failure results can be combined with a consequence assessment in a Quantitative Risk Assessment (QRA) to evaluate whether the change in risk of introducing hydrogen to a pipeline system is acceptable.

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