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PAPER TITLE: FATIGUE CRACK GROWTH MODELLING FOR SAFE AND EFFICIENT HYDROGEN PIPELINE DESIGN
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ABSTRACT

Fatigue crack growth in pipeline steels is accelerated in the presence of gaseous hydrogen. Consequently, fatigue life may be a critical consideration for pipelines containing hydrogen though it would have been neglected for an equivalent natural gas pipeline under similar cyclic operation.

The current fatigue life assessment methodologies for hydrogen pipelines are based on fracture mechanics where it is assumed that the pipeline has a crack, and that the crack grows under cyclic loading. The analysis to predict the number of cycles to failure requires rigorous cycle-by-cycle crack growth, fracture mechanics analysis and failure assessment. To simplify the fatigue life assessment, a large set of potential pipeline designs were analysed using API 579-1/ASME FFS-1 and three choices of fatigue crack growth rate equations presented in ASME B31.12, ASME BPVC Code Case 2938 and the Sandia model which includes the pressure/fugacity dependence omitted from ASME Code Case 2938 equation.

The lower bound results were used to develop a series of simple S-N curves that can be easily applied as screening or detailed design criteria for consideration of fatigue life in hydrogen service without the need for complex fracture mechanics analysis. Additionally, the effect of reduced fracture toughness due to Hydrogen Embrittlement was investigated, and relevant S-N curves were developed which can be used for ASME B31.12 Option A designs.

DISCLAIMER

1. INTRODUCTION

Historically, fatigue has safely been neglected for the majority of gas pipeline designs because of the substantially steady-state conditions and the fact that the compressibility of gas prevents high-frequency, high-amplitude pressure fluctuations. An S-N curve is provided in the European Standard IGE/TD/1—Steel pipelines for High pressure Gas Transmission [1] and it is duplicated in the Australian Standard AS/NZS 2885.1 [2]. It can be used as a design tool or screening criteria to consider pressure cycling fatigue in pipelines.

In pure hydrogen and blended-hydrogen service, this approach must be reviewed and may not be suitable due to two known detrimental effects of hydrogen on the material.

1. Hydrogen causes hydrogen-assisted fatigue crack growth (HA-FCG), an acceleration of the crack growth rate that especially applies to high amplitude load cycles. The effect has been observed even at low hydrogen fugacity (down to 1 bar) [3], [4], [5]. It must be accommodated even for pipelines carrying lean hydrogen/natural-gas blends.
2. Hydrogen causes a reduction in toughness in carbon steel and some stainless-steel materials. This leads to a decrease in the critical crack size that can be sustained prior to unstable fracture initiation.

A heuristic has been proposed that the fatigue life in hydrogen-service is reduced by an order of magnitude. Existing models may be used by applying a fatigue-life reduction factor of 10. For example, for Piping Flexibility Analysis, ASME B31.12 specifies that when hydrogen embrittlement is a possibility, the number of required cycles is to be multiplied by 10 [6]. However, because of the two abovementioned reasons, this cannot be directly inferred from published fatigue crack growth rate data. The combined effect of higher FCGR and smaller critical crack size can potentially lead to an overall fatigue life reduced to a 10^{th} of that in air or natural gas

This paper aims to support the assessment of fatigue in hydrogen pipeline design. In Section 2, a series of S-N curves is developed that may be used as a design tool or screening criteria for new and existing pipelines. The presented S-N curves and equations will simplify the fatigue analysis for pipelines, especially when they are subject to low-medium cyclic stress range.

The work in this paper is further development of a fatigue screening study presented previously [7]. The work was modified by including pressure-correction terms in the fatigue crack growth rate for one of the models applied and adding resolution to the derived curves by dividing the data into two pipe size categories.

2. DESIGN AND FATIGUE CRACK GROWTH PARAMETRIC STUDY

A series of S-N curves has been developed based on 216,000 crack growth simulations performed across a range of commercially available pipe diameters, pipe thickness, steel grades and operating pressures. Selection of these parameters primarily referenced the design requirements of the hydrogen pipeline design standard, ASME B31.12 [6] and Linepipe standard API 5L [8]. It is intended that if this design standard is followed, the screening curve can be applied in lieu of detailed fatigue assessment.

The analyses including calculation of stress intensity factor, reference stress and failure assessment diagram (FAD) were performed to API 579/ASME FFS-1 [9] using a software developed for the project.

The analyses considered an internal semi-elliptical crack in the longitudinal direction of the pipeline. The stress intensity solutions provided in API 579 are not valid for cracks deeper than 80% of the pipe wall thickness. For those cracks, the stress intensity and reference stresses were calculated by interpolation between the crack with depth equal to 80% of the pipe thickness and a through wall crack.

The following parameters were considered in the parametric minimum required thickness calculation and fatigue crack growth study:

Diameter, D . Pipe diameters between 114.3mm (DN100) and 1066.8 mm (DN1050) were assessed as per Table 1.

DN100	DN150	DN200	DN250	DN300	DN350	DN400	DN450	DN500	DN550	DN600
DN650	DN700	DN750	DN800	DN850	DN900	DN950	DN1000	DN1050		

Table 1 Analysed pipe sizes.

Maximum pressure, P . Maximum pipeline pressures were evaluated at the maximum allowable pressure of the common ASME B16.5/MSS SP-44 flange ratings i.e., Class 150, 300, 400, 600 and 900 as shown in Table 2.

ASME Class	150	300	400	600	900
Pressure, MPa	1.96	5.11	6.81	10.21	15.32

Table 2 Maximum pressure vs. ASME Class.

Cycling pressure, ΔP . The analysis considered a set of pressure cycle ranges from 10% to 100% of the design pressure, in 10% increments. Where the stress ratio, R , was required as an input to the analysis, it was taken to be the worst-case possibility:

$$R = \frac{P - \Delta P}{P} \tag{1}$$

R is defined as the ratio of the minimum applied stress intensity factor to the maximum applied stress intensity factor.

Material specification. Pipe materials were based on API 5L and included materials from Grade B (L245) up to X70 (L485). The flow stress, σ_f, based on API 579, was taken to be the average of the specified minimum yield stress (SMYS) and the specified minimum tensile strength (SMTS) shown in Table 3.

API 5L Grade	B	X42	X46	X52	X56	X60	X65	X70
SMYS, MPa	245	290	320	360	390	415	450	485
SMTS, MPa	415	415	435	460	490	520	535	570
Flow Stress, MPa	230	352.5	377.5	410	440	467.5	492.5	527.5

Table 3 SMYS and SMTS for API 5L grades.

Thickness, t . The thickness was calculated using Barlow's equation for the pipe diameters (D), maximum pressure (P), SMYS and a range of design factors. For pipeline designs to ASME B31.12 Option A, the design factor was limited to 0.5 whilst the Design Factor for Option B was limited to 0.72. Furthermore, the selected pipe thicknesses were limited by the minimum and maximum permitted thickness as per API 5L Table 9 [8] and where the thickness calculations resulted in thickness larger than the permitted value, the maximum permitted thickness was selected, and the maximum pressure was reduced to maintain the designated design factor. Table 4 shows the design factors considered in the present study.

Methodology	Design Factor					
Option A	0.3	0.4	0.5	-	-	-
Option B	0.3	0.4	0.5	0.6	0.67	0.72

Table 4, Design Factor for ASME B31.12 Option A and Option B design methodology

Initial crack type. In accordance with ASME B31.12 PL-3.7.1 (b)(2) an internal semi-elliptical crack in longitudinal direction of the pipe was assumed.

Initial crack size. ASME B31.12 PL-3.7.1 (b)(2) states that the crack growth analysis and fatigue life assessment are to be performed to either ASME BPVC VIII Div. 3 KD-10 requirements [10] or alternatively, an initial crack with depth equal to one quarter of the pipe thickness and a length equal to 1.5 times the pipe thickness must be considered.

The ASME BPVC VIII Div. 3 approach would require assessment of cracks detectable by Non-Destructive Test (NDT) and given that the cracks/defects in the welded pipe are normally found in the weld or heat affected zone (HAZ), welding residual stresses must also be considered in the analysis. Additionally, pipe manufacturing process may result in some undesired geometrical features such as ovality, peaking, out-of-roundness, weld toe angle, misalignment, etc. Each of these features add to the overall driving force on the crack. Finally, the critical crack size and number of cycles are further reduced by accounting for safety margins.

In deterministic fracture mechanics and fatigue life assessments, the crack type and size are determined via NDT and the analysis is performed for a fixed configuration. For a parametric study in which the lower bound S-N curve being developed, the individual cases must be based on the largest geometry feature that API 5L permits, otherwise results cannot be assumed to be valid for every real scenario.

However, the linearly combined stresses, due to various geometrical features, may exceed the yield strength. In such cases, a non-linear Finite Element Analysis (FEA) can be performed to estimate a more realistic stress distribution. This is because, unlike an analytical solution where the stress distribution for a given geometry, loading and crack size can be easily calculated, non-linear FEA must be performed for all cases and for the incremental crack growth conditions. The elastic plastic FEA results are also only valid for the case analysed.

Therefore, the ASME BPVC VIII Div. 3 approach was not considered practical for a deterministic parametric study aimed at the development of S-N curves or screening criteria. An alternative to the applied deterministic approach would require a probabilistic study with billions of cases accounting for potential coincident geometric features and defects which is outside of the scope of the current study.

Therefore, an alternative initial crack size which is prescriptive and is a function of the pipe thickness was chosen for the current study.

Fatigue Crack Growth Rate (FCGR). Three different fatigue crack growth rate equations were explored in the current study, ASME B31.12 PL-3.7.1 Equation 1 [6], ASME Code Case 2938 [11] and the modified ASME Code Case 2938 with pressure/fugacity dependence, designated "CC2938_m" in this study. [12].

1- *ASME B31.12 PL-3.7.1 Equation 1*

The FCGR equation presented in ASME B31.12 is based on the paper by Amaro et al [13], and summarised as follows:

$$\frac{da}{dN} = a1\Delta K^{b1} + \left[\left(a2\Delta K^{b2}\right)^{-1} + \left(a3\Delta K^{b3}\right)^{-1}\right]^{-1} \quad (2)$$

Where $a1$, $a2$, $a3$, $b1$, $b2$ and $b3$ are constants, da/dN is the crack growth rate, and ΔK is the stress intensity factor range. According to ASME B31.12 this equation has an applicability range of R ratio <0.5.

2- ASME Boilers and Pressure Vessels, Code Case 2938

The second set of analysis applied the crack growth model developed by Sandia laboratories [12], and implemented in ASME BPVC Code Case 2938.

$$\frac{da}{dN} = C\left[\frac{1 + C_H R}{1 - R}\right]\Delta K^m \tag{3}$$

Where m and C_H are constants. The model has two regions, for "high" and a "low" stress intensity amplitude, which each have different constants.

3- Pressure modified ASME Boilers and pressure Vessels, Code Case 2938

The third set of analysis applied the crack growth model developed by Sandia National Laboratories [12]. This is the same model implemented in ASME BPVC Code Case 2938, but the low stress intensity formula is modified with a term that accounts for the reduced severity at lower hydrogen pressures.

$$\frac{da}{dN_{low}} = C\left[\frac{1 + C_H R}{1 - R}\right]\Delta K^m \left(\frac{f}{f_{ref}}\right)^{1/2} \tag{4}$$

The term f is the fugacity of hydrogen at the pressure of interest, which has been approximated as the maximum pressure of each case, P, and f_{ref} is the fugacity at a reference pressure.

Toughness in hydrogen, $\boldsymbol{K_{IH}}$. Several different scenarios were assessed for the toughness of the pipe in hydrogen. Data for pipeline materials measured in gaseous hydrogen is varied, and no predictive correlation is known. For ASME B31.12 Option B designs, it is assumed that testing in hydrogen establishes a toughness of at least 55 MPa(m)$^{0.5}$. For Option A designs, which have a maximum design factor of 0.5, three toughness cases are assessed, based on a full-size Charpy V-Notch toughness in air, high toughness with the toughness double the minimum API 5L PSL2 requirement (C_v = 54J), API 5L PSL2 compliant pipe (C_v = 27J) and low toughness pipe (C_v = 10J) which is considered a conservative estimation for typical untested material.

These toughness values in air were converted to stress intensities using the Rolfe-Novak-Barsom conversion [14] [15]. It was then assumed that the resulting stress intensity will halve in hydrogen service. The assumed toughness in air and corresponding critical stress intensity values, K_{IC}, are summarised in Table 5 below.

	Critical stress intensity factor, K_{IC} / K_{IH} (MPa.m$^{0.5}$) – air / hydrogen			
Steel Grade	ASME B31.12 Option B	ASME B31.12 Option A, High Toughness (CVN= 54 J)	ASME B31.12 Option A, API 5L PSL2 (CVN=27 J)	ASME B31.12 Option A, Low Toughness (CVN=10 J)
Grade B (245 MPa)	NA/55	89.9 / 45.0	62.0 / 31.0	34.4 / 17.2
X42 (290 MPa)		97.4 / 48.7	66.9 / 33.4	36.3 / 18.2
X46 (320 MPa)		102 / 51.0	69.8 / 34.9	37.3 / 18.7
X52 (360 MPa)		107.8 / 55.9	73.4 / 36.7	38.4 / 19.2
X52 (390 MPa)		111.8 / 55.9	75.9 / 38.0	39.0 / 19.5
X60 (415 MPa)		115.1 / 57.5	77.9 / 39.0	39.4 / 19.7
X65 (450 MPa)		119.4 / 59.7	80.5 / 40.2	39.8 / 19.2
X70 (485 MPa)		123.5 / 61.8	82.9 / 41.5	40.0 / 20.0

Table 5. Assumed toughness in air and hydrogen

3. RESULTS AND ANALYSIS

The results of parametric analyses are shown in Figure 1 (DN100-DN600) and Figure 2 (DN660-DN1050). The stress range, i.e., the fluctuating hoop stress, S, calculated from Barlow's formula $(\Delta P)D/2t$, is plotted against the number of cycles to failure, N, from the analysis.

ASME B31.12 Option A and Option B designs are fundamentally different. Therefore, in each figure, Option A designs are presented in (a) and Option B designs are presented in (b). Designs above DN600 show a high level of sensitivity to material toughness, whereas designs for DN600 and below do not. Therefore, the results are presented in two different pipe diameter ranges (DN100-DN600 and DN650-DN1050).

In order to investigate toughness sensitivity of the ASME B31.12 Option B designs and in addition to the above-mentioned cases, fatigue analysis was repeated with five additional toughness values (K_{IH}= 60, 65, 70, 82.5 and 110 MPa(m)$^{0.5}$).

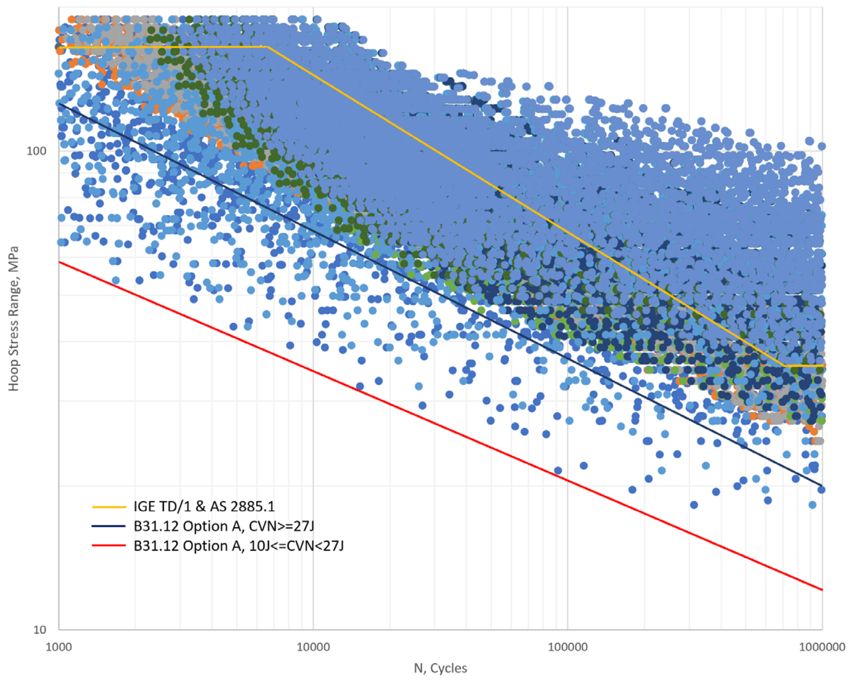
The results of the toughness sensitivity show that for the small diameter range (DN100-DN650), increasing the toughness above the minimum specified value of K_{IH} = 55 MPa(m)$^{0.5}$ does not affect the lower bound S-N curve. However, for the large diameter range (DN650-DN1050), and in order to achieve the toughness independent similar to the small diameter range, a toughness value of K_{IH}= 70 MPa(m)$^{0.5}$ would be required.

An additional observation is that, for pipes in the large diameter range, a material with will have the same lower bound S-N curve as that of pipes in the small diameter range with a toughness (see Figure 3).

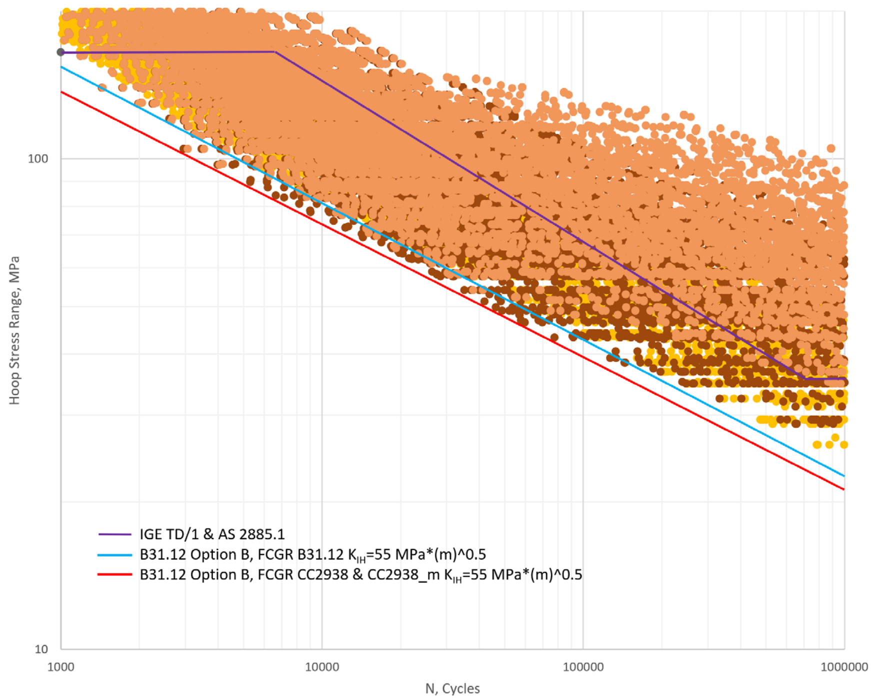
The results from the three Fatigue Crack Growth Rate (FCGR) equations show scattered results, and a single lower bound S-N curve leads to a conservative equation with limited usefulness in real applications.

Some comments are in order:

- Although there are some differences between individual results of three different FCGR equations, the overall trend is similar, and the lower bound S-N curve is not influenced by the choice of FCGR equation.
- The low toughness S-N curve (C_v ≥ 10J) is the worst-case scenario as the material becomes toughness dependent where the failure mode is brittle fracture.
- High toughness materials (C_v ≥ 54J) with a 50% reduction in toughness due to Hydrogen Embrittlement have a similar lower bound S-N curve to Option B complaint material that has been tested in Hydrogen. This allows the designer to confidently apply the developed equations for Option A designs with modern high toughness steels.
- In the small diameter range (DN100-DN600), an API 5L PSL2 compliant pipe, where the minimum C_v is 27J, results in a lower bound S-N curve close to Option B qualified material.
- In the large diameter range (DN650-DN1050), the lower bound S-N curve is more sensitive to material toughness than for the small diameter range.
- The S-N curve for high toughness material (C_v ≥ 54J) in the large diameter range (DN650-DN1050) results in shorter life than API 5L PSL2 compliant pipe with minimum C_v = 27J.

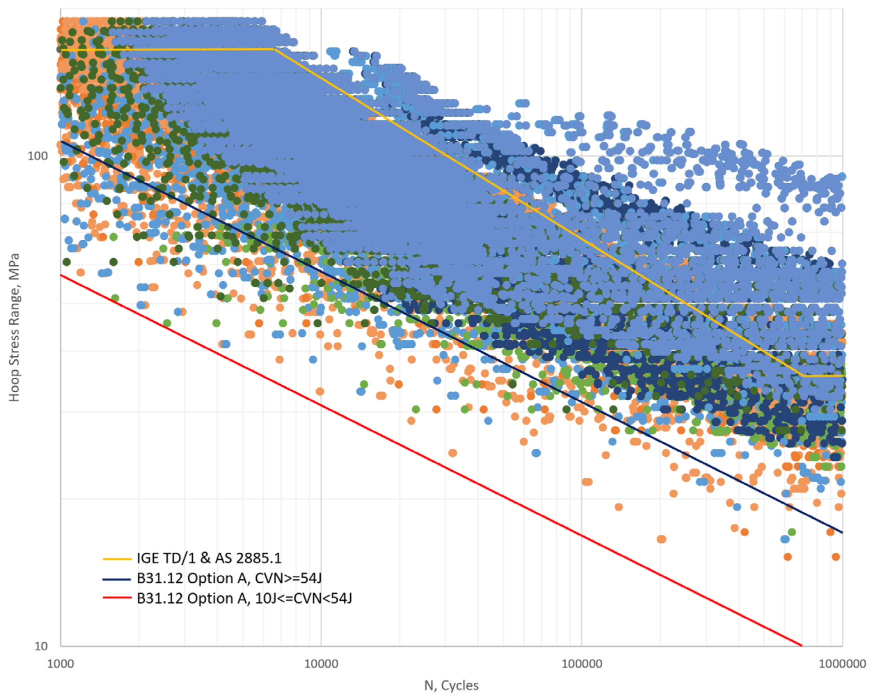


(a)



(b)

Figure 1. Results for the DN100-DN600 cases with ASME B31.12 (a) Option A and (b) Option B



(a)

(b)

Figure 2. Results for the DN650-DN1050 cases with ASME B31.12 (a) Option A and (b) Option B

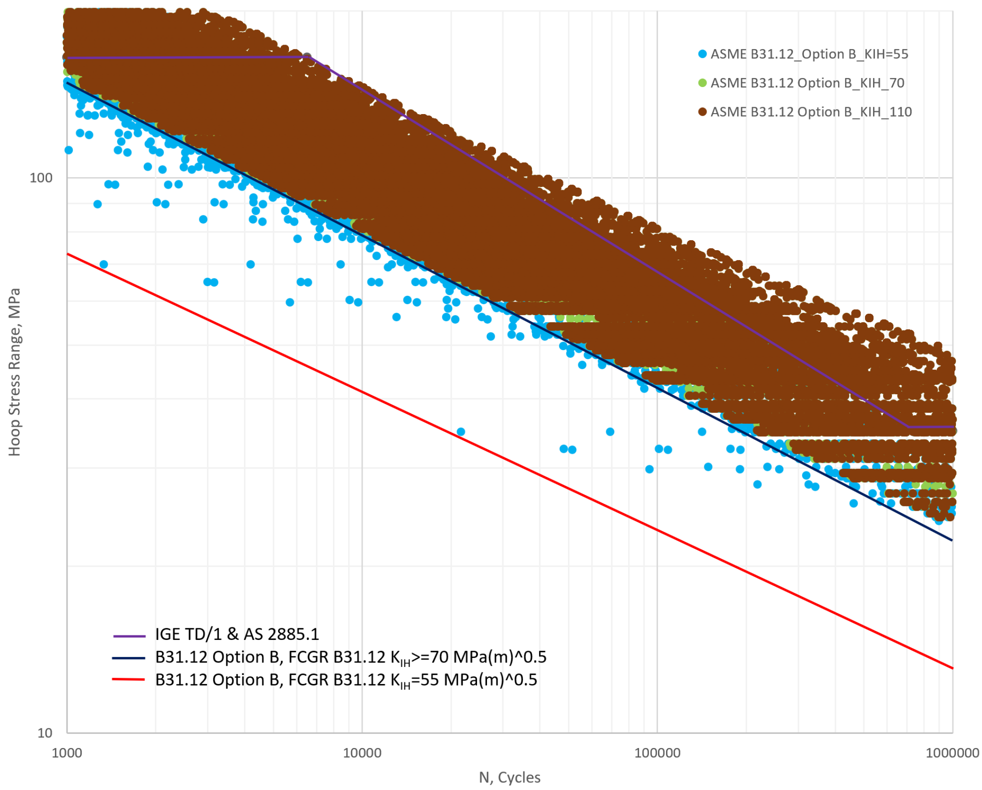


Figure 3, B31.12 Option B, DN100-DN1050, K_{IH} =70MPa(m)$^{0.5}$ and 110 MPa(m)$^{0.5}$

In the next step, the curves shown in Figure 1 and Figure 2 were fitted to a simple equation of. The fitting parameters are shown in Table 6.

$$N.S^{a} = b.(10)^{10} \tag{5}$$

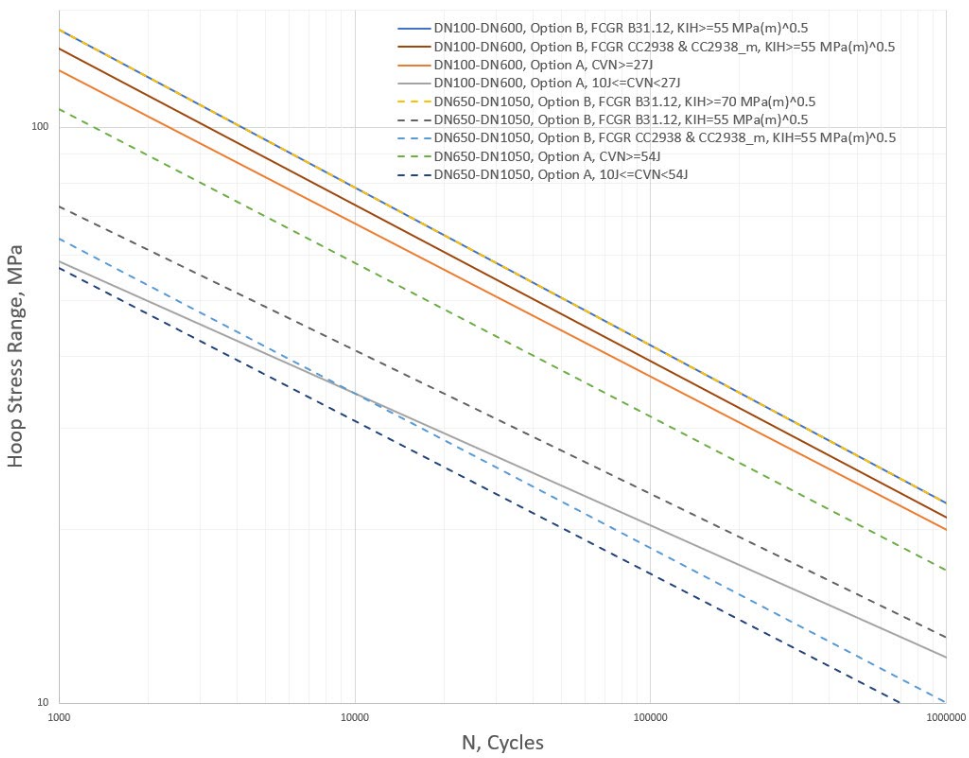


Figure 4. Proposed S-N curves for ASME B31.12 Option A and Option B design

Diameter range	Design and assessment basis	a	b
DN100-DN600	Option A, $C_v \geq 27$ J	3.761	7.825
	Option A, $C_v \geq 10$ J	4.361	5.080
	Option B, FCGR B31.12, $K_{IH} \geq 55$ MPa(m)$^{0.5}$	3.641	7.985
	Option B, FCGR CC2938 & CC2938_m, $K_{IH} \geq 55$ MPa(m)$^{0.5}$	3.683	7.414
DN650-DN1050	Option A, $C_v \geq 54$ J	3.746	4.061
	Option A, $C_v \geq 10$ J	3.764	0.407
	Option B, FCGR B31.12, $K_{IH} \geq 70$ MPa(m)$^{0.5}$	3.641	7.985
	Option B, FCGR B31.12, $K_{IH} \geq 55$ MPa(m)$^{0.5}$	4.003	2.880
	Option B, FCGR CC2938 & CC2938_m, $K_{IH} \geq 55$ MPa(m)$^{0.5}$	3.721	0.526

Table 6. Proposed fitted S-N curve equations for ASME B31.12 Option A and Option B design with different FCGR equations

4. CONCLUSION

A number of simple fatigue S-N curves have been developed to determine the fatigue life of hydrogen pipelines in lieu of detailed fatigue analysis. The difference between these curves and the curve used for natural gas from IGE/TD/1 demonstrates that some pipelines that were previously considered to be sufficiently steady state such that fatigue was not an issue, will no longer meet that criterion when hydrogen is introduced.

A lower bound curve to cover all pipe diameters (DN100-DN1050) leads to a conservative S-N curve, but if the diameter range is split into two ranges i.e., DN100-DN600 and DN650-DN1050, unnecessary conservatism for the small diameter range can be avoided.

The scatter in the results also suggests that for many cases that do not meet the screening criteria, a detailed assessment of the specific design might be warranted. A detailed assessment may demonstrate that the design has sufficient fatigue resistance for successful operation.

In the small diameter range (DN100-DN600), for pipe designed to ASME B31.12 Option A, the fatigue life is less sensitive to material toughness than the large diameter range (DN650-DN1050). Additionally, an API 5L PSL2 compliant pipe in small diameter range has a similar lower bound S-N curve than a pipe designed to ASME B31.12 option B with the same Design Factor.

For ASME B31.12 Option B designs in the small diameter range (DN100-DN600), the minimum specified K_{IH} = 55 MPa(m)$^{0.5}$ guarantees to meet a toughness-independent lower bound S-N curve. In other words, increasing the toughness will not affect the lower bound S-N curve. However, in order to achieve the same toughness independence for the large diameter range (DN650-DN1050), the material toughness in Hydrogen needs to be increased to K_{IH} = 70 MPa(m)$^{0.5}$.

The assumed 50% reduction in toughness due to Hydrogen Embrittlement in most cases is a conservative assumption, especially for modern steel with fine microstructures. For vintage steels with inferior microstructure, it is recommended to use the low toughness S-N curves.

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