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A new assessment framework for lean hydrogen/natural gas blends in transmission pipelines

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ABSTRACT

The energy sector in Australia is shifting towards a reliable supply of carbon neutral energy. A key component of that transition is expected to be hydrogen, a synthetic fuel that can be produced from renewable energy or decarbonised fossil fuels. In the short- and medium- term, hydrogen gas may be blended with natural gas in transmission and distribution pipelines to reduce the level of carbon in the gas network while using existing infrastructure. However, a known barrier to this application is hydrogen embrittlement— an effect that reduces the ability of steel to resist crack formation, fatigue crack growth, rupture and fracture arrest.

Hydrogen embrittlement in pipelines is caused by atomic hydrogen permeating into the steel. The amount of hydrogen in the steel relates to the pressure and concentration of the hydrogen gas, surface conditions, and other gas composition elements that can promote or inhibit the uptake of hydrogen. At low hydrogen concentrations, the amount of hydrogen in the steel is low, so the magnitude of hydrogen embrittlement is reduced (compared to pure hydrogen).

In 2020, AGIG and GPA Engineering investigated the impact of natural gas blends with low hydrogen concentration on pipeline performance. The analysis reviewed data from published literature about the mechanisms of embrittlement, and the impact on material performance. It was determined that a permissible operating window can be defined, within which hydrogen concentration is limited to mitigate the effect of hydrogen embrittlement, and pressure cycling is limited to mitigate fatigue crack growth.

This paper proposes a framework for retrospective approval of a pipeline to transmit low hydrogen concentration gas compositions, and a model for predicting the reduction in crack resistance properties of typical pipeline steels. It can be applied for hydrogen partial pressures up to 5 bar. A design review process is presented that can be followed for an asset designed to AS 2885.1. A significant novel element of the method is that consideration of fatigue crack growth, which can usually be neglected for natural gas pipelines, must be integrated into the consideration of fracture control.

The proposed framework was applied to a case study from AGIG's Dampier-Bunbury Pipeline system in Western Australia. For the pipeline considered, a modest MOP reduction could permit operation with hydrogen concentrations up to ten per cent (by volume).

This investigation has successfully demonstrated that many pipelines will be able to transport hydrogen at lean concentrations, requiring only reasonably practicable controls.

INTRODUCTION

Australia's energy sector is shifting towards a reliable supply of carbon-neutral energy. Hydrogen, a fuel that can be produced from renewable energy or decarbonised fossil fuels, is expected to play a key part in that transition. One application of hydrogen that may be significant (especially early in an energy transition when there are limited local and international hydrogen consumers) is to blend with, and eventually displace, natural gas in transmission and distribution pipelines.

One of the most significant barriers identified for the hydrogen transition of the transmission sector is the effect on material properties due to hydrogen embrittlement (GPA Engineering, 2019). Hydrogen embrittlement is caused by atomic hydrogen permeating into steel, and the effect is related to the concentration of hydrogen, the material, the existing defect population or potential for new defects, and the pressure and associated stress regime of the pipeline.

AGIG are investigating the feasibility of injecting hydrogen into the Dampier Bunbury Natural Gas Pipeline (DBNGP) system in Western Australia. GPA Engineering were contracted to determine the maximum level of hydrogen for which the resulting hydrogen embrittlement would not impact the safe operating envelope of the DBNGP.

This paper will explore the impact of lean hydrogen blends on relevant pipeline failure modes, and present the assessment methodology that was established. The assessment showed that hydrogen could be injected into pipelines at concentrations low enough that the significant effects of hydrogen embrittlement can be avoided or the effects are sufficiently low that safe operation can be maintained.

FRACTURE THEORY AND THE EFFECT OF HYDROGEN

Hydrogen embrittlement decreases a material's ability to resist cracking, which could lead to a loss of containment in gas pipelines. Leaks, ruptures, or in the worst case, large scale failures from rapid running fracture, are three failure modes that can result from crack-type defects in the pipe material. However, surface defects (which include dents, gouges or part-through-wall cracks) do not always result in loss of containment. It is only when a part-through-wall defect reaches a critical *depth* that it will break through the pipe wall and a leak will occur. If the defect also reaches a critical *length*, it will be sufficient to burst the pipeline and cause a "rupture".

The process of a defect becoming a crack, and then a leak or rupture, is explored in three stages:

1. Crack initiation
2. Fatigue crack growth
3. Fracture propagation and arrest

For pipelines transporting hydrogen, it has been shown that hydrogen will permeate into the steel when the molecular form (H_2) dissociates into its atomic form (H). Some of the atomic hydrogen becomes trapped within the metal, typically in defects within the crystal structure of the steel (regions of high stress and hence increased atomic spacing) which then provides pressure on the crack tip, reduces the ability of the material to plastically deform, and encourages the steel to crack, affecting all three potential failure modes identified above. This is referred to as *hydrogen embrittlement*.

PARTIAL PRESSURE

The magnitude of hydrogen embrittlement is related to the level of hydrogen that accumulates in the steel, which is determined by the hydrogen concentration and the gas pressure. For hydrogen/natural gas blends, each gas individually expands to uniformly occupy the containing vessel. Each gas in the mixture has the same volume but exerts a different pressure, called its "partial pressure":

$$Partial\ pressure\ (Pa.a) = concentration\ (\%) \times absolute\ pressure\ (Pa.a)$$

Provided there are no interactions of other gas components to affect the uptake of hydrogen, it can be assumed that the effect of pure hydrogen at a certain pressure is equivalent to the effect of hydrogen in a mixture with the same partial pressure, because it would achieve equivalent concentration in the steel. (Note the stress in the material still relates to *total* pressure). Consequently, where stresses can be controlled, it is expected that at low hydrogen concentrations, the hydrogen effect is insignificant enough that the pipeline can be operated without modification.

CRACK INITIATION

Crack initiation (the conditions under which a defect will begin to grow rapidly) depends on the material toughness and strength, and the applied stress (internal pressure). Generally, the higher the toughness, the longer the crack the material can tolerate (to a flow-stress controlled limit). Material toughness is typically measured using Charpy V-Notch tests, which are impact tests on notched specimens. However, Charpy tests cannot be conducted in a hydrogen environment, hence all published data uses other toughness measures. In this paper, toughness is represented by the critical stress intensity factor, K_{IC}.

Hydrogen causes a reduction of K_{IC}, resulting in a reduction in critical defect dimensions, so that a pipeline with part-through-wall defects is more vulnerable to leak and through-wall defects are more likely to rupture. Defects that are growing due to fatigue or corrosion will fail sooner than they would have, so more frequent repairs will be required. However, as shown in Figure 1, data published by Sandia National Laboratories (USA) demonstrates a decreasing impact on toughness with low hydrogen pressures. This indicates that there is a level of hydrogen below which toughness effects may become negligible, and suggests that initiation conditions can be managed by keeping hydrogen concentration low.

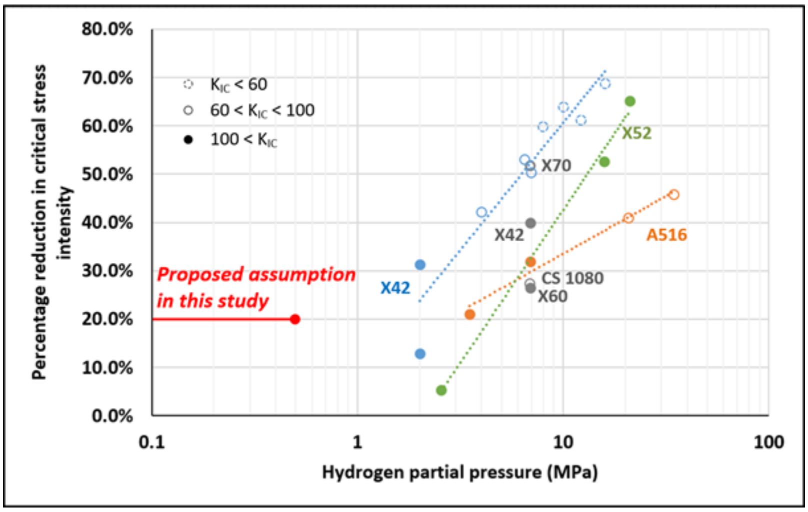

Figure 1: Logarithmic plot of toughness reduction (%reduction in K_{IC}) created from data from the Sandia technical databases for hydrogen compatibility of materials (San Marchi & Somerday, 2012) (Ronevich & San Marchi, 2021)

In the absence of actual toughness values for pipeline steels in hydrogen, which is difficult to obtain for an existing pipeline, a model is proposed which conservatively assumes from the above data that the stress intensity factor (K_{IC}) for typical pipelines steels does not reduce by more than 20%, for partial pressures up to 0.5 MPa. K_{IC} is also limited to 100 MPa $m^{0.5}$ so that it doesn't exceed the range of the underlying data.

$$K_{IC}(H_2) = \min(0.8K_{IC}\,,100)\ \ \mathrm{MPa.m^{0.5}}$$

Figure 2 demonstrates the model in graph format. Note that where K_{IC} is not known, but Charpy toughness in Joules is available, the Rolfe-Novak-Barsom conversion formula in API 579 may be used to convert Charpy test results into a stress intensity factor.

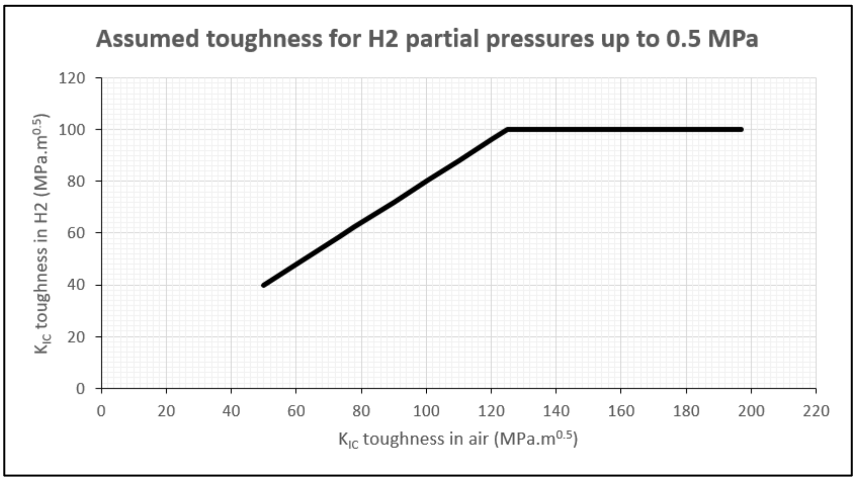

Figure 2: Conservative assumed toughness (K_{IC}) reduction for hydrogen partial pressures up to 0.5MPa

The well-established NG-18 equation can be applied to toughness values to determine the material's critical defect length (CDL). Though CDL is only through-wall (not for surface defects), it is considered a reasonable proxy for estimating the effect on critical crack conditions generally. Alternately, the methodology in this paper could also be applied by assessing part-through-wall defects, using the equations in AS/NZS 2885.1.

Since hydrogen is introduced to existing pipelines *after* the hydrotest, the margin of safety provided by the test is reduced or eliminated. To understand hydrogen's effect on the safety margin, the safety factor can be found using the calculated critical defect length in hydrogen:

$$SF = \frac{CDL_{operation}}{CDL_{hydrotest}}$$

A safety factor of greater than 1 indicates that the CDL of the pipeline in hydrogen remains greater than the CDL during hydrotesting conditions, so the pipeline hydrotest can still be considered a valid 'proof test' of the pipeline condition at time of testing.

FATIGUE CRACK GROWTH

Fatigue can cause new defects over long periods of time, but more often leads to growth of defects that already exist. It is a slow crack-growth mechanism caused by stress cycles in the pipeline. Under the right conditions, it can cause a crack to grow to the point that it reaches a critical size and fracture occurs.

Fatigue can be neglected for most natural gas pipelines due to the slow cycling rate compared to the fatigue life - the compressibility of the gas limits the rate at which the pressure in the pipe can change, and consequently limits the number of cycles that the pipeline can experience during its life. However, gas pipelines operated in "pack-and-deplete" regimes (e.g. supply to a peak loading power station) or with a high design factor, may see sufficient cycling to require fatigue assessment. Pipelines that have been completely blown down and re-pressurised several times may also be at risk of fatigue damage.

Fatigue crack growth rate testing has shown conclusively that, even at low concentrations, the effect of hydrogen on fatigue life can be significant due to hydrogen assisted fatigue crack growth (HA-FCG) (Slifka, et al., 2018) (Amaro, White, Looney, Drexler, & Slifka, 2018) (Meng, et al., 2017) – refer Figure 3. No low concentration (even down to 1 bar partial pressure) could be shown to mitigate the effect of HA-FCG. At low stress amplitudes (small pressure swings, on smaller cracks) the effect is negligible, but at large stress amplitudes (the transition varies, but typically above 5 MPa.m$^{0.5}$), the effect can result in an increase in crack growth rate by a factor of 10 to 100 times that in air or methane.

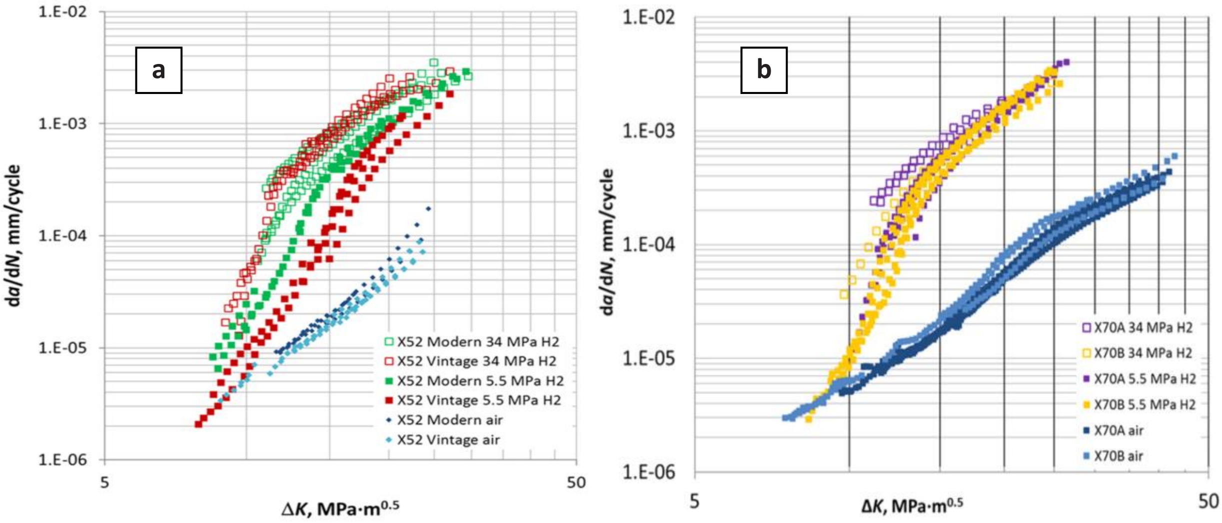

Figure 3: Fatigue crack growth rate of (a) X52 and (b) X70 steels at pressures of 34 MPa and 5.5 MPa (Slifka, et al., 2018)

In the absence of data, it was assumed that the fatigue crack growth rate in a hydrogen blend is the same as that for pure hydrogen, and consequently that high amplitude stress intensities must be avoided in hydrogen pipelines, regardless of the hydrogen concentration. In addition, gas pipelines for which fatigue could previously be neglected may require fatigue control/assessment once in hydrogen service.

For natural gas pipelines, the need to consider fatigue damage is decided using a screening criteria from AS 2885.1 Appendix J. The fatigue life in number of cycles, N, for a given stress amplitude, S, is given by:

$$N = \begin{cases} \dfrac{2.93 \times 10^{10}}{S^3} & 35 < S < 165\ MPa \\ \infty & S < 35\ MPa \end{cases}$$

As a preliminary analysis, the fatigue screening criteria from AS 2885.1 can be applied with an allowance for a 20-fold decrease in fatigue life to accommodate for the effect of hydrogen. This is consistent with, but more conservative than, a draft supplement to European pipeline standard IGEM/TD/1 Edition 6, which proposed the same philosophy, but with a factor of 10 applied. However, this screening method fails to account for the change in fatigue end-point (critical crack dimensions) and hence it is not supported if the fracture initiation safety factor has decreased.

A more in-depth analysis would use research data by NIST and Sandia laboratories, which has quantified the crack growth rate differences and therefore the reduction in fatigue life due to hydrogen. The fatigue models developed by those organisations have been implemented into ASME B31.12 and ASME Code Case 2938, respectively. Analysing pipelines using API 579 failure models with the ASME B31.12 fatigue growth formula will provide a fatigue life estimate; where that fatigue life is inadequate (i.e. less than the design life), reduction of MOP, hydrotesting at an increased pressure, or inspection for cracks may be used to manage it.

FRACTURE PROPAGATION

Once fracture has initiated in a pipeline, gas escapes through the tip of the crack, typically at supersonic velocities due to rapid expansion. Initially, the stress intensity around the crack increases, causing the crack to propagate, and the velocity of that propagation to increase. The material provides less resistance to a crack that is already growing than to a stationary one, further enabling crack growth.

The crack will continue growing until the crack “arrests”. Most commonly, arrest is a result of the gas decompression (the reduction of internal pressure, due to the gas escaping). This process is dynamic: as gas flows towards the rupture, a decompression wavefront travels down the pipeline, away from the rupture site, causing a pressure gradient that varies from operating pressure far down the pipeline, to a reduced pressure at the crack tip. The reduction in pressure causes a reduction in pipeline hoop stress, which causes a decrease in the fracture velocity. Once the stress drops below a critical level, the fracture propagation velocity drops to zero and the fracture is arrested.

Consequently, the conditions for fracture arrest require that the decompression wave must travel faster than the crack. If the crack out-paces the decompression wave, the crack can grow indefinitely. Sufficient material toughness in the pipe will reduce the fracture velocity, and be able to arrest the crack.

Fracture arrest can be predicted using the Battelle two-curve method, in which a curve representing the fracture velocity is overlaid on a curve representing the decompression velocity. Provided the two curves do not overlap, the fracture is expected to arrest. Because numerical methods are required, this method is typically applied using computer software, such as the Australian software developed by the Energy Pipelines CRC, called EPDECOM.

Data supporting an understanding of hydrogen’s effect on fracture propagation and arrest is scarce. This is due to the complexity of the experiments required to obtain such data. It would be expected that fracture velocity is increased in hydrogen service due to the more brittle fracture mode. However, the effect of hydrogen is weaker on dynamic fracture than static fracture. That is, hydrogen can have a strong effect on cracks that are being loaded or are growing slowly, but has less effect on rapid cracks. (This has been demonstrated by fatigue experiments that have changed the cycling frequency and found that low frequencies see greater effect from hydrogen than high frequencies.)(Aihara et al., 2008) (Davis, Liu, Michal, Godbole, & Lu, 2020).

Hydrogen also decompresses more rapidly than natural gas. Consequently, for pure hydrogen pipelines, the more rapid decompression of hydrogen is expected to compensate for the marginal increase in crack growth speed that may occur. For lean hydrogen blends (the focus of this paper), however, this will be insufficient to contribute meaningful benefit.

In general, a pipeline will only be vulnerable to fracture propagation in hydrogen service if it already has a low margin of safety from fracture propagation in natural gas (as calculated using the Battelle Two Curve Method). A reasonable basis for assessment would be to use the reduced static toughness (used in the CDL calculation) in the fracture arrest calculation. This is expected to provide a conservative result. This conclusion is further supported by ASME B31.12, which uses a *less* conservative formula for fracture propagation control than ASME B31.8 and AS 2885.1, hence not capturing any deleterious effects of hydrogen.

FRACTURE CONTROL FRAMEWORK

AS 2885 FRACTURE CONTROL PHILOSOPHY

AS 2885 outlines a fracture control philosophy for *natural gas* pipelines that includes the following considerations:

1. *Defect identification:* Hydrotest at 125% of the maximum allowable operating pressure to prove the initial pipe is free of critical defects
2. *Defect control:* Management of the pipeline condition during its life
3. *Crack initiation control:* Control of Critical Defect Length (CDL) to avoid rupture in the event of external interference; a safety factor of 1.5 is required in high consequence areas
4. *Brittle fracture control:* Prevention of brittle fracture propagation for all pipelines, or the conditions that could lead to brittle propagation, by only operating above the dynamic transition temperature (determined from Drop-Weight Tear Tests) in all conditions where there is sufficient stress to drive a brittle fracture (taken to be 85 MPa).
5. *Fatigue life control:* Screening study of fatigue life, and detailed fatigue analysis only if required by the screening study.
6. *Fracture arrest control:* Prevention of ductile fracture propagation for all pipelines, to keep the arrest length less than 5 pipe lengths, or 1 pipe length in high consequence areas

NG/HYDROGEN BLEND ASSESSMENT FRAMEWORK

A framework has been established based on the same fracture control philosophy as AS 2885, but which is intended for retrospectively approving an existing pipeline to transmit low hydrogen concentration gas compositions.

As the target pipelines are already in operation, the initial hydrotest has already been performed, and the pipeline condition has been managed according to an existing integrity management plan. For pipelines that comply with the requirements of AS 2885.1, the issue of brittle fracture control does not need to be considered independently of the other fracture considerations.

The framework (Figure 4) is therefore based on the remaining three controls, targeting the main failure mechanisms identified above: crack initiation, fatigue and crack propagation. This framework can be applied to hydrogen concentrations up to a partial pressure of 0.5 MPa (5 bar). This partial pressure can be divided by the total pressure in the pipeline to determine the maximum mol% hydrogen concentration.

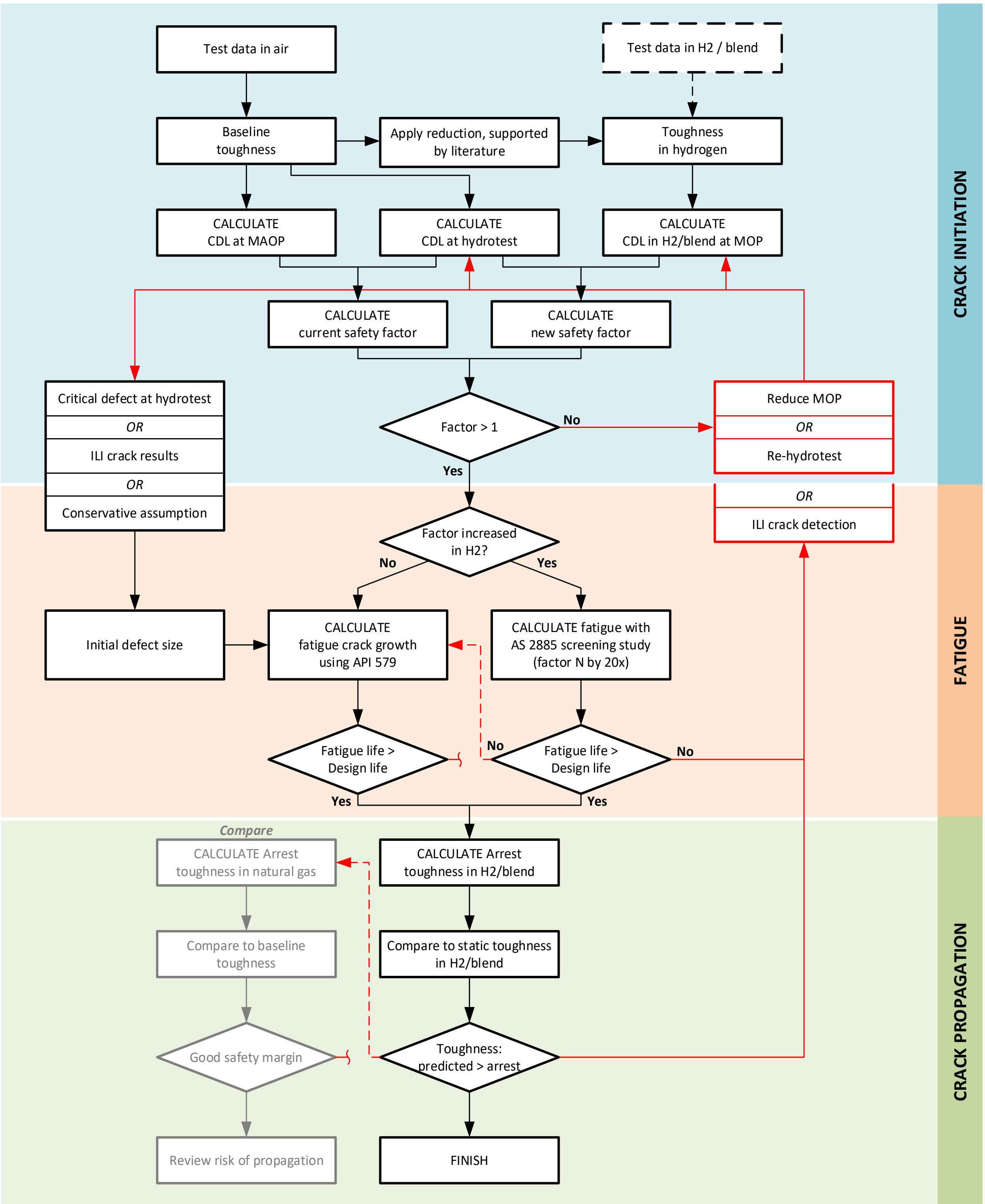

Figure 4: Assessment methodology for hydrogen blend conversion

CASE STUDY: DAMPIER-BUNBURY NATURAL GAS PIPELINE LATERAL

The Dampier-Bunbury Natural Gas Pipeline (DBNGP) transports natural gas approximately 1,600km from the Burrup Peninsula, starting near the township of Dampier in Western Australia, running parallel to the west coast of Western Australia and finishing at the Clifton Road Meter Station near Bunbury. The DBNGP has twelve looped sections and seventeen laterals along its length. Several of these sections were identified as good candidates for low concentration hydrogen blending.

One of the DBNGP laterals was used as a case study to demonstrate the proposed framework. The parameters in Table 1 have been used for the analysis:

Table 1: Properties used for case-study calculations

Variable	DBNGP Lateral
Diameter	DN300
Wall thickness	9.53 mm
Grade	API 5L X46
Toughness	MIN: 184 J at -15°C
DWTT	100% at -15°C
MAOP	8.48 MPag
MOP (proposed)	5 MPag
Hydrotest pressure	10.6 MPag

STAGE 1: CRACK INITIATION

CHARPY / INITIATION TOUGHNESS CONDITIONS

The first step of the assessment is to determine the pipeline toughness – the baseline toughness in air, and the reduced toughness in hydrogen. Without actual values for material toughness in hydrogen, the Rolfe-Novak-Barsom correlation was used to calculate initiation toughness from measured Charpy results (Table 2). The toughness reduction model from Figure 2 was then applied to estimate the reduced value in lean hydrogen (also in Table 2). The reduced toughness estimate is likely to be quite conservative for the DBNGP Lateral, but as the data in the literature review applied to lower initial toughness values, it was considered suitable.

Table 2: Conversion of Charpy toughness to stress intensification factor

Variable	DBNGP Lateral
Initial	
Charpy toughness	184 J
Critical stress intensity	192 MPa.m$^{0.5}$
With lean hydrogen (estimated reduction in K_{IC})	
Charpy equivalent	52 J
Critical stress intensity	100 MPa.m$^{0.5}$

CDL AND SAFETY FACTOR

The toughness values were used in the NG-18 equation to determine CDL in operating and hydrotest conditions as shown in Table 3. The CDL was then used to understand the change in safety factor.

Table 3: Estimated CDL reduction due to hydrogen and pressure reduction

Variable	DBNGP Lateral
CDL – hydrotest	136 mm
CDL – operating at *MAOP*	181 mm
Safety factor	**1.33**
CDL – operating with lean hydrogen at *MAOP (8.48 MPa)*	178 mm
Reduced safety factor (in hydrogen)	**1.31**
CDL – operating with lean hydrogen at *MOP (5 MPa)*	319 mm
Revised safety factor (in hydrogen at MOP)	**2.34**

For the DBNGP Lateral, the safety factor in lean hydrogen at MAOP is greater than 1, so the pipeline hydrotest can be considered a valid 'proof test' of pipeline condition. Note, however, that hydrotesting only checks condition *at the time of testing.* Pipeline condition can deteriorate over time due to effects such as corrosion or fatigue. Therefore, when feasible (such as in this case), a reduced MOP is recommended, in order to restore the safety factor above the safety factor in natural gas. Where the safety factor is reduced in hydrogen and cannot be restored, the integrity management of a pipeline must be reviewed, specifically the condition of the line, how defects are being managed, and the assumptions that are currently being made regarding the time to failure.

STAGE 2: FATIGUE CRACK GROWTH

In order to assess fatigue risk to the DBNGP, the likely pressure cycling was estimated from historical operation, referencing hourly pressure readings for each pipeline section over a 2-year period. *Rainflow analysis* was used on each series of pressure cycles to create a 'typical' representative histogram (refer Table 4). The minimum amplitude reading for any cycle in the analysis is 50 kPa, though many cycles are <10 kPa; these low amplitude cycles are not a concern to overall fatigue life. The historical data did not include any full depressurisation cycles but it is assumed that pipelines are blown down periodically and this would represent the worst case pressure cycle, so 10-yearly *full* pressurisation cycles were added.

Table 4: DBNGP Lateral pressure cycling model

Amplitude (kPa)	Cycles per year	Average R value[1]
50	1150	~1
100	230	0.98
150	120	0.97
300	60	0.95
600	8	0.9
900	1	0.8
2000	1	0.65
4000	0.5	0.4
8480 (FULL)	0.1	0

[1] R-value is the "stress ratio", the ratio between the minimum and maximum pressures in a cycle. Low-pressure cycles correspond to a high R-value, whereas high pressure cycles correspond to a low R-value.

FATIGUE CRACK GROWTH – AS 2885 SCREENING STUDY

Fatigue life is impacted by two effects: the reduction in growth rate, and the reduction in critical crack dimensions. Consequently, the AS2885.1 screening study can only be applied if the MOP is reduced such that the hydrotest safety factor is restored. Otherwise, more detailed crack modelling, which considers the initial and final defect size, is required. In this case, the DBNGP Lateral shows an increased CDL safety factor at the reduced MOP, so the AS 2885.1 fatigue screening criterion can be applied with a safety factor of 20. The cumulative damage method (AS 2885.1 Appendix J) produced the results in Table 5.

Table 5: DBNGP Lateral Fatigue damage estimation

Amplitude (kPa)	Hoop stress (MPa)	Cycles per year, n	N / 20	n / (N/20)
50	0.85	1150	2E9	4.8E-7
100	1.7	230	3E8	7.7E-7
150	2.6	120	9E7	1.35E-6
300	5.1	60	1E7	5.43E-6
600	10.2	8	1E6	5.79E-6
900	15.3	1	409,492	2.44E-6
2,000	34	1	37,315	2.68E-5
4,000	68	0.5	4,664	0.0001
8,480 (FULL)	147	0.1	489	0.0002
SUM				**0.00035**

The AS 2885.1 screening method indicates that, at these operating conditions, with only 0.035% of fatigue life being consumed each year, the fatigue life is predicted to be 2,820 years (*after* reducing the fatigue life by a factor of 20). This clearly demonstrates that it is not uncommon for a gas pipeline to have a safety factor much greater than 20 times for fatigue failure. In addition, 90% of all damage was done by the 4,000 and 8,480 kPa cycles, which illustrates how discrete large amplitude cycles contribute much more damage than distributed small amplitude cycles.

FATIGUE CRACK GROWTH – MODELLING

At the full MAOP the CDL safety factor marginally reduced, so, according to the framework, detailed fatigue growth modelling would be recommended (if the MOP were not reduced). Modelling of the growth rate of actual cracks can be conducted using the conservative Amaro fatigue growth rate model, which was incorporated into ASME B31.12, and the fracture mechanics formulae and failure criterion of API 579.

Fatigue crack growth modelling is complicated and a detailed overview is not provided in this paper. Significant inputs into fatigue crack growth simulation are the start- and end-points of the simulation; that is, the initial and final defect sizes. ASME B31.12 recommends a semi-elliptical crack of depth 0.25t and length 1.5t, though this is consistent with a common basis for weld defects in station piping and would not generally be used for pipelines. Another basis, where crack inspection tools are used, is the largest detected crack or the smallest *detectable* crack if none are found: 3mm x 50mm is a common approximation. The most conservative assumption is to consider the largest crack that could survive hydrotest—this is often non-credible, especially for high-toughness materials.

A simplified analysis was completed for the case study, to demonstrate the analysis. This specific analysis is simplified and conservative, but it is effective to illustrate the sensitivity of the assessment to start- and end-point.

This analysis assumed a crack that is infinitely long, and therefore grows in one dimension only. In this case, the initial depth was based on the most conservative assumption: the deepest crack that could survive hydrotest, and the end-point was determined using the reduced toughness calculated in Stage 1. The calculation predicted a life for the DBNGP Lateral of 2,100 years in natural gas service, reduced to *just 17 years* in hydrogen service, as shown in Figure 5:

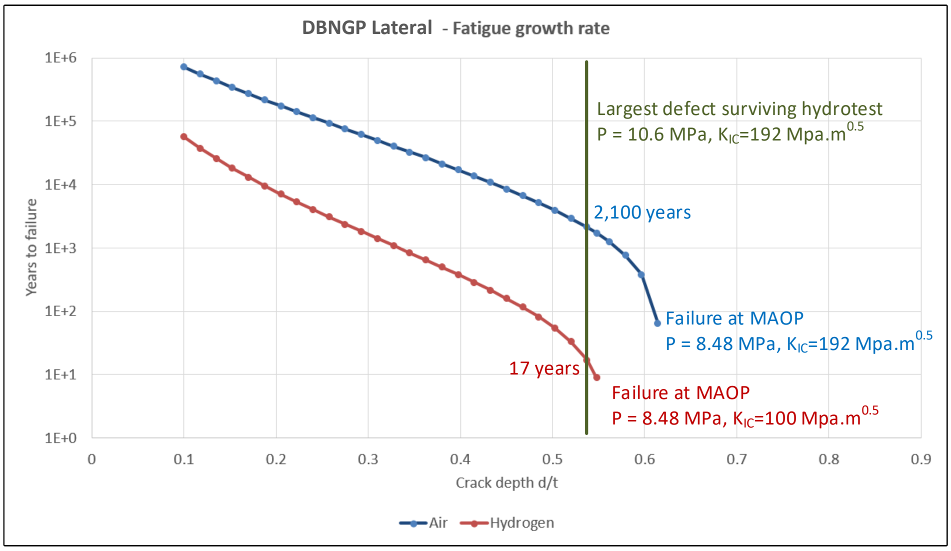

Figure 5: Fatigue life for infinite length crack of depth d in DBNGP Lateral at MAOP

At the MOP of 5 MPa, the results were significantly improved: an MOP of 5 MPa would increase the fatigue life in natural gas service to about 6,420 years, and in hydrogen, up to 145 years, refer Figure 6:

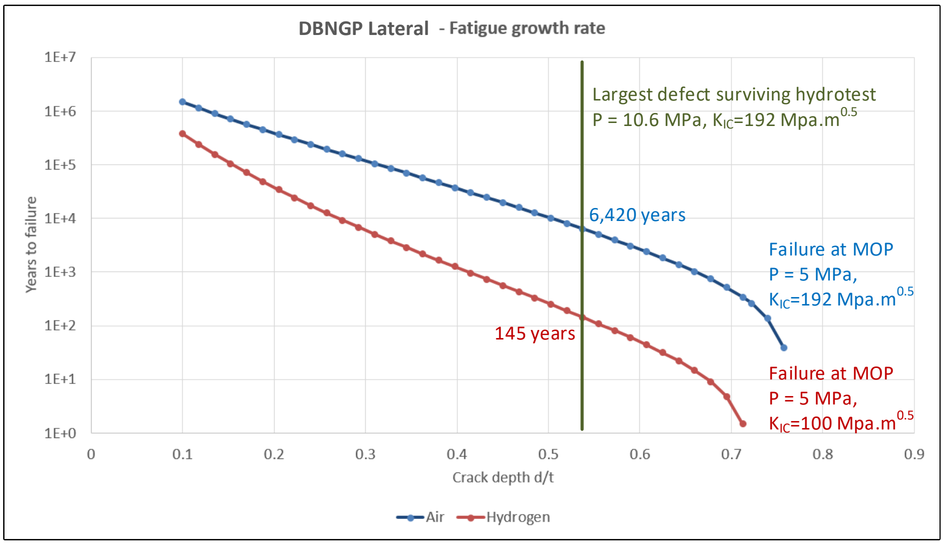

Figure 6: Fatigue life for infinite length crack of depth d at MOP of 5 MPa

For the case study DBNGP Lateral, an acceptable fatigue life was able to be achieved using conservative estimates and a reduced MOP. Most importantly, it was shown that the fatigue effect can be managed if the pressure cycling of the pipeline is limited. Typical operating conditions of transmission pipelines are substantially steady-state. A small number of large cycles contribute the largest proportion of damage and these should be carefully controlled and avoided – especially full emptying and filling operations.

STAGE 3: FRACTURE ARREST

The third step is to analyse fracture arrest using the Australian software package EPDECOM[2]. The average gas compositions for the pipeline were used, with an assumption of the same composition ratio with higher levels of hydrogen. The results of the analysis for the DBNGP Lateral are shown in Table 6.

Table 6: DBNGP Lateral arrest toughness results

Pressure	Arrest toughness at 15°C				
	0% H2	1% H2	5% H2	10%H2	100% H2
5 MPa.g	5.3 J	5.3 J	5.2 J	5.0 J	2 J
8.48 MPa.g	10.4 J	10.3 J	10.0 J	(9.7 J)	4.2 J

The results show that the higher the amount of hydrogen, the lower the arrest toughness required, and also that for lean compositions the change is not significant.

The margin between the calculated arrest toughness and the estimate of reduced static toughness determined from Stage 1 (52 J) is considerable. Given the conservatism of several assumptions that were made, arrest toughness is not considered to be a concern. It is therefore expected that hydrogen embrittlement will not compromise this design criteria for this pipeline.

CONCLUSION

This paper provides a framework for approving existing pipelines for transmission of low hydrogen concentrations. It involves assessing all the relevant failure modes and requires specific review of the pipeline’s condition, properties, and operating parameters.

A case study of a pipeline lateral from the Dampier-Bunbury Pipeline network supports that injection of a lean concentration of hydrogen (<0.5 MPa partial pressure) into a transmission pipeline can be managed using only reasonably practicable controls such as reduced MOP and a controlled stress-cycling regime.

An important outcome of the analysis was a demonstration that almost all fatigue damage would be caused by a small number of large pressure cycles. The results suggest that a pipeline can be operated in such a way that HA-FCG can be safely managed, but operation will have to be cautious of large amplitude cycles, especially those that result from total fill/empty operations.

The framework will improve in accuracy as data for pipeline material performance in a hydrogen environment is obtained. The Future Fuels Cooperative Research Centre is developing laboratory facilities to conduct testing in pressurised gaseous environments which may support this in the future.

[2] Note that EPDECOM can include hydrogen in the gas input composition, using the GERG equations of state. The FFCRC are currently undertaking work to validate the accuracy of these equations of state for hydrogen mixtures.

References

Amaro, R. L., White, R. M., Looney, C. P., Drexler, E. S., & Slifka, A. J. (2018). Development of a Model for Hydrogen-Assisted Fatigue Crack Growth of Pipeline Steel. *Journal of Pressure Vessel Technology, 140*.

Davis, B. J., Liu, X., Michal, G., Godbole, A., & Lu, C. (2020). *RP3.1-01 Final Report on the Knowledge Gap Analysis for Fracture Control of Future Fuels Pipelines and Recommendations for Future Work.* Australia: Future Fuels CRC.

GPA Engineering, . (2019). *Hydrogen in the Gas Distribution Networks.* COAG Energy Council.

Meng, B., Gu, C., Zhang, L., Zhou, C., Li, X., Zhao, Y., . . . Han, Y. (2017). Hydrogen effects on X80 pipeline steel in high-pressure natural gas/hydrogen mixtures. *International Journal of Hydrogen Energy, 42*, 7404-7412.

Ronevich, J. A., & San Marchi, C. (2021). Materials Compatibility Concerns for Hydrogen Blended into National Gas. *Pressure Vessels & Piping Conference PVP20201.* Virtual Online.

San Marchi, C., & Ronevich, J. (2018). Federal Research on Emerging Fuels - The Integrity Impact of Transporting Hydrogen via Existing Pipeline Systems. *Pipeline Research Council International (PRCI)*. Sandia National Laboratories.

San Marchi, C., & Somerday, B. (2012). *Technical Reference on Hydrogen Compatibility of Materials - Plain Carbon Ferritic Steels: C-Mn Alloys (code 1100).* Livermore CA: Sandia National Laboratories.

Slifka, A. J., Drexler, E. S., Amara, R. L., Hayden, L. E., Stalheim, D. G., Lauria, D. S., & Hrabe, N. W. (2018). Fatigue Measurement of Pipeline Steels for the Application of Transporting Gaseous Hydrogen. *Journal of Pressure Vessel Technology, 140*(February).