AUSTRALIA'S FIRST HYDROGEN PIPELINE CONVERSION PROJECT

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Abstract

APA Group is studying the feasibility of converting a section of the Parmelia natural gas pipeline in Western Australia to pure hydrogen service. This would be the first natural gas to hydrogen pipeline conversion in Australia, and one of the first in the world.

Hydrogen is a clean fuel and has potential to support an increase in the use of renewable or decarbonised energy in Australia's energy markets. Hydrogen may be economic if it can be stored and transported efficiently. A pipeline can simultaneously meet both these needs, and the use of existing pipeline infrastructure may be a particularly cost-effective solution.

There are, however, some uncertainties to using the existing pipelines with hydrogen at the high pressures typical in the transmission sector. When a steel pipeline is used to transport hydrogen, atomic hydrogen is absorbed into the steel and reduces the ductility, toughness, and fatigue life of the steel. This has potential to compromise the pipeline's design and change operating risks and consequences. Consequently, engineering, material testing, and applied research are all required to support the pipeline conversion.

For this project, the new H_2SAFE(TI) laboratory developed by the Future Fuels Cooperative Research Centre at the University of Wollongong will be used to measure material properties. This laboratory, the only one of its kind in Australia, is dedicated to the assessment of material performance in gaseous hydrogen environments, at pressures typical of transmission pipelines.

In conjunction with the modelling and the analysis conducted by Future Fuels CRC and GPA Engineering, the measured material properties will permit APA to maximise the operating envelope and hence the efficiency of its hydrogen pipeline. The results will also inform the operating and maintenance strategies for the rest of the pipeline life to ensure ongoing safe and reliable operation of the asset.

Through the application of risk assessment and management framework required by Australian Standard AS 2885.6, the project combines fundamental 'first-principles' engineering with precedents set by international standards, to execute an efficient conversion that will meet the high safety standards required of Australian pipelines.

1 Introduction

APA owns and operates the 416km Parmelia Gas Pipeline (PGP) that transports gas from the Perth Basin gas fields near Dongara (south of Geraldton), the Carnarvon Basin (via the Dampier to Bunbury Natural Gas Pipeline) and APA's Mondarra Gas Storage Facility, to customers in the Perth area and the southwest of Western Australia. The PGP also interconnects with the ATCO Gas distribution network in the Perth metropolitan area, providing future opportunities for injection into the distribution network.

A 43km section of the PGP, located south of Perth near the Kwinana Industrial Area (KIA), is being considered for conversion to pure hydrogen service. The section is made of vintage[1] X52 grade ERW 350 NB line pipes with a standard wall thickness of 5.56 mm, with some heavy walls with a nominal 7.92 mm wall thickness. Table 1 summarise the design of the section of PGP under consideration for hydrogen conversion.

Table 1 Basic pipeline design data

Material specification		API 5L
Material grade		X52
Diameter	D	355.6 mm
Wall thickness	t	5.56, 7.92 mm
Specified minimum yield strength	σ_y	360 MPa
Specified minimum tensile strength	σ_u	460 MPa
Allowances		0 mm
Length		42.3 km
Start and end KPs		364.6 to 406.9
Location classes (AS 2885.6)		T1, T2 and R2
Design temperature range	T	-7 to 65°C
Closing temperature (at time of burial)	T_c	Assumed 25 °C
Year of construction		Circa 1970
Original design code		ANSI B31.8 (probably 1968 edition)

A number of potential hydrogen offtakes are located in this area, including industrial processing, export and hydrogen transport (mobility). The WA Government's recent announcement supporting a high-tech manufacturing hub in the region further supports growth of the hydrogen industry. APA's converted pipeline could facilitate the transmission of hydrogen from point of generation to point of use and/or export. This would be the first hydrogen transmission pipeline conversion in Australia, and one of the first in the world.

The current barrier to using existing high-pressure pipelines for hydrogen storage and transportation is material compatibility. When a steel pipeline is used to transport hydrogen, atomic hydrogen is absorbed into the steel and affects the material properties [1]. In particular, the ductility, toughness and fatigue life of the steel is deteriorated. This has potential to compromise the pipeline's integrity and service performance, known as hydrogen embrittlement.

[1] Construction of the PGP commenced in 1970.

Australia's high-pressure pipeline standard AS/NZS 2885 does not currently provide requirements for hydrogen service. It does not consider the different design and material limitations or the associated conditions to safely accommodate hydrogen as a fluid. One prominent international standard exists, ASME B31.12 [2], but some of its requirements can't be applied retrospectively.

APA has partnered with Future Fuels Cooperative Research Centre (Future Fuels CRC), GPA Engineering and the University of Wollongong (UoW) around a multi-phase project to support the engineering, material testing, and applied research required to support the pipeline conversion.

Gas pipeline operators across the world are grappling with quantifying the impact of, and how to mitigate, hydrogen embrittlement issues when repurposing or requalifying operational gas pipelines to transport blended or hydrogen [3] [4] [5] [6]. This work is at the forefront of global research and will provide a significant contribution to the hydrogen body of knowledge in both Australia and internationally.

The cost of decarbonising gas infrastructure networks in Australia compared to an all-electric scenario is considered between two-thirds to half of the overall transition costs [7]. European studies specifically focussing on the benefits of using new and repurposed hydrogen pipeline infrastructure versus electrical transmission report cost benefits of pipelines between 12-25% (new built) to up 10 times cheaper for repurposed pipelines [8] [9].

Starting with an overview of the objectives, the scope of work and the methodology framing the PGP conversion feasibility study, the remainder of this paper highlights the testing and engineering design work undertaken to date (Phase 1) and provides an outlook for planned work associated with the second phase.

2 Objectives and scope of work

The PGP conversion project aims to demonstrate the pipeline can meet the intent of AS/NZS 2885.1 with regards to risk management [10]. The underlying objective is to provide the engineering data for a safe and efficient conversion to pure hydrogen service. The project supports the definition of the operating envelope within which the capacity of the pipeline will be maximised. The study follows the AS 2885.6 Safety Management Process to thoroughly review the risks posed by hydrogen [11].

To reach these primary objectives, activities were planned over the two phases of the project to understand and quantify the effect of hydrogen on the pipeline material(s) so that the safety of the pipeline can be assessed with due diligence. A suite of material tests is being undertaken in air and then in hydrogen. The results feed into the engineering calculations, the pipeline failure mode analyses, the pipeline conversion plan, and the Safety Management Study (SMS). In the absence of clear direction from mature standards, responsible engineering means demonstration of safety from first principles.

In parallel to the work being undertaken to understand the impact of hydrogen embrittlement on the infrastructure, a conversion plan is being developed to identify the activities required to be completed prior to the conversion. These include activities such as community engagement, inspections and assessments, hydrotests, etc.

‘Phase 1’ was executed in the first half of 2021. Its objective was to review the PGP suitability for hydrogen service. This phase collated and reviewed the pipeline data relative to the line pipe steel properties and its current conditions after nearly 50 years of services. A suite of tests were completed in air, at atmospheric pressure, to gain a good understanding of the material properties. The change in properties that results from hydrogen service was conservatively estimated from published results on similar materials to establish a baseline for the engineering calculations.

Building upon estimates of material behaviour changes, actual testing of the pipeline material in a gaseous hydrogen environment enables a design process that reduces conservatism and hence reduces cost. ‘Phase 2’, currently underway, builds on this strong accumulating knowledge-base to provide this logical next step for pipeline conversions in Australia. The project uses facilities at the University of Wollongong to test the hydrogen-charged steel and compare the material performance against that measured in air [12].

The study informs and benefits from several research projects that are being undertaken in parallel by the Future Fuels CRC, including several studies focusing on hydrogen embrittlement of line pipe steels. These projects include:

- The Future Fuels CRC literature review into hydrogen impacts on pipelines, which included an international study tour of hydrogen test facilities in Europe and USA [1];
- The COAG National hydrogen strategy report, which identified gaps in AS 2885 standard [3];
- Several Future Fuels CRC projects commenced to establish hydrogen embrittlement test facilities at University of Wollongong, Deakin University and University of Queensland [12] [13] [14];
- The participation in Standards Australia ME-093 committee and subcommittees for hydrogen in pipelines;
- The 2019 report for an anonymous pipeline company which applied the outcomes of the literature review. This project established a method for ranking pipelines by toughness demand, and identified that an analogy can be made between hydrogen embrittlement and pressure increase.
- The 2020 report for another pipeline company. This analysis focused on lean hydrogen mixtures. It used published literature for estimation of toughness decrease in pipeline materials, and developed an analysis methodology (flowchart) for pipeline conversion reviews.

Additionally, the team has engaged with an international review panel of world-leading hydrogen pipeline and hydrogen embrittlement experts, using contacts made over the course of the projects listed above.

3 Methodology

The overall approach to the pipeline conversion is to follow the Safety Management Study methodology of AS/NZS 2885.6 to critically assess the gaps between the requirements of AS/NZS 2885.1 and the expected performance of the pipeline. The process demonstrates that the pipeline meets the intent of AS/NZS 2885 and that all threats from hydrogen are managed to reduce risk to as low as reasonably practicable (ALARP).

Because AS/NZS 2885.1 is silent on the specific topic of hydrogen embrittlement from hydrogen fluid service, the study appeals to the American standard ASME B31.12, international experience and to available research.

The high-level assessment methodology is as follows:

- Identify the requirements of AS 2885.1, ASME B31.12, and other available guidance material including IGEM [15] and EIGA [16];
- Complete a gap analysis of the pipeline design against standard requirements, including the development of a full compliance matrix;
- Quantify expected material behaviour and hence the consequence of pipeline failure modes;
- Identify/update threats to the pipeline;
- Subject each 'gap' (identified above) to risk assessment using the SMS method;
- Define safe operating window and activities required to manage safety; and
- Prepare the pipeline conversion design basis.

In line with this methodology, the test program and engineering calculations proposed across phases 1 and 2 have the following activities:

DATA GATHERING

- Measure, and when available, confirm the material properties in air against the company's records;
- Measure the material properties in gaseous hydrogen;
- Extend the acquisition of data beyond standard practices to cater for future assessment tools and new compliance requirements. For instance, complete stress-strain curves are recorded for future defect assessments by numerical methods while material is available for this study.

ENGINEERING CALCULATIONS

- Quantify the impact of hydrogen on pipeline performance; including pipeline failure modes and failure consequence for safety management:
    - Fatigue crack growth calculation, fracture initiation, critical defect length assessment;
    - Assessment of design compliance with published Standards.

PIPELINE OPERATING WINDOW

- Select design options and operating strategy for the pipeline remaining life; and
- Extend the operating limits within satisfactory margins of safety.
- Develop the conversion design basis; including the fracture control plan and the pipeline integrity management plan.

4 Test program and results – Phase 1

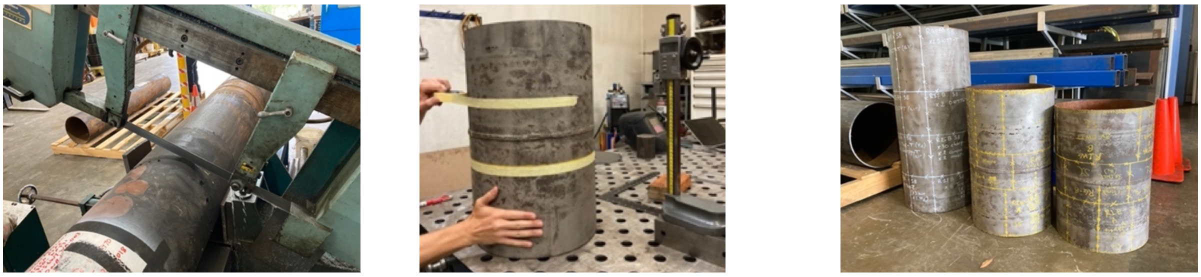
This section summarises the results of the laboratory tests conducted in air, at atmospheric pressure. The execution of the test program, from the preparation of the specimens to the processing of the data, was conducted by the H_2Safe(TI) laboratory at UoW.

Eight reclaimed pipe sections from the PGP were delivered to UoW. Three sections were selected for the test program, namely S1, S3 and S8. S8 is made of thin-wall pipes, predominantly used in the PGP. Each section includes a girth weld and, therefore, two pipes. The pipes were referred to by their section of origin (e.g. S1) and their arbitrary East/West location relative to the girth weld. The geometry of the selected sections is summarised in Table 2. Figure 1 presents on overview of the preparation of the sections prior to extraction of the test specimens.

Table 2 Pipe sections selected for the test program.

Section reference [#]	Section length [mm]	West[1] pipe length [mm]	East[1] pipe length [mm]	OD[2] [mm]	wt[2] [mm]	Pipe type [-]	Width girth weld cap [mm]	Years of service [YYYY-YYYY]
S1	510	245	250	355.6	7.92	X52 ERW	15	1971-2016
S5	570	260	290	355.6	7.92	X52 ERW	15	1971-2016
S8	4755	2140	2615	355.6	5.56	X52 ERW	15	1971-2018

[1] The East/West identification is arbitrary, [2] Nominal



(a) (b) (c)

Figure 1 Preparation of the sections for sampling. (a) Ring cut out of S8 using a band saw. (b) Marking and measuring of the rings to locate the plates to be cut by water-jetting. (c) Completed marking from S1, S5 and S8.

Table 3 Test program for Phase 1

Task group	Task reference	Task detail	# tests	Test material								
				Section S8			Section S1			Section S5		
				R1W to R4W	RG	R1E	R1W	RG	R1E	R1W	RG	R1E
MATERIAL	COMP/B	Base metal steel composition. OES	12	2	-	2	2	-	2	2	-	2
	MICR/B	Base metal optical micrograph	12	2	-	2	2	-	2	2	-	2
	HARD/SW	Seam weld hardness map	4	2	-	2	-	-	-	-	-	-
	HARD/GW	Girth weld hardness map	4	-	2	-	-	2	-	-	-	-
TENSILE	TENS-T/B	Base metal circumferential tensile	18	3	-	3	3	-	3	3	-	3
	TENS-L/B	Base metal longitudinal tensile	3	3	-	-	-	-	-	-	-	-
	TENS-T/SW	Seam weld circumferential tensile	18	3	-	3	3	-	3	3	-	3
	TENS-L/GW	Girth weld longitudinal tensile	9	-	3	-	-	3	-	-	3	-
STATIC FRACTURE	SFRA-T/B	Base metal circumferential static fracture (CT)	3	3	-	-	-	-	-	-	-	-
	SFRA-L/B	Base metal longitudinal static fracture (CT)	3	3	-	-	-	-	-	-	-	-
	SFRA-T/SW	Seam weld circumferential static fracture (CT)	0	Phase 2	-	-	-	-	-	-	-	-
	SFRA-L/GW	Girth weld longitudinal static fracture (CT) WCL and HAZ	6		6	-	-	-	-	-	-	-
DYNAMIC FRACTURE	DFRA-TC/B	Base metal transverse Charpy test	30	15	-	3	3	-	3	3	-	3
	DFRA-TC/SW	Seam weld transverse Charpy test	36	6	-	6	6	-	6	6	-	6
	DFRA-TD/B	Base metal transverse Drop Weight Tear Test	25	10	-	3	3	-	3	3	-	3
FATIGUE	FATI-T/B	Base metal circumferential fatigue test (CT)	3	3	-	-	-	-	-	-	-	-
	FATI-L/B	Base metal longitudinal fatigue test (CT) WCL and HAZ	3	3								
	FATI-T/SW	Seam weld circumferential fatigue test (CT)	0	Phase 2	-	-	-	-	-	-	-	-
	FATI-L/GW	Girth weld longitudinal fatigue test (CT)	6	-	6	-	-	-	-	-	-	-

The test program for phase 1 is summarised in Table 3. A general set of tests was conducted to characterise the base metal (BM), the seam welds (SW) and the girth weld (GW) for each pipe section. It encompasses characterisation of the metallurgy, tensile properties, static and dynamic toughness, respectively J_{Ic}/K_{JIc}, Charpy V-Notch (CVN) and Drop Weight Tear tests (DWTT) as well as fatigue tests to evaluate the crack growth rate (FCGR) as function of the stress intensity factor range. The orientation of the specimens was dependent upon the nature of the sampling region, e.g. pipe/heat affected zone (HAZ)/weld centreline (CL), and the purpose of the data for the engineering calculations. Details on each test are provided in the results section of the paper.

Being most representative of the PGP section targeted for conversion, S8 was selected for an extended test program. A total of 12 static toughness tests, 9 fatigue tests, 30 CVN and 13 DWTT were conducted, with the majority focusing on the west pipe.

The preparation of the specimens was driven by a cutting diagram in which each section was divided into three regions: west (W), girth weld (G), and east (E). The cutting diagram for section S8 is provided in Figure 2 for illustration. Specimens shown in red are part of Phase 1. The others are part of Phase 2.

At least one ring was taken from each region and subsequently cut into 'plates' A, B, C and D. Similar tests were typically conducted from the same plates (i.e. A, B, etc). Specimens such as compact tension (C(T)), CVN, DWTT and tensile specimens are shown. Plates A sample the seam weld while plates from ring RG sample the girth weld.

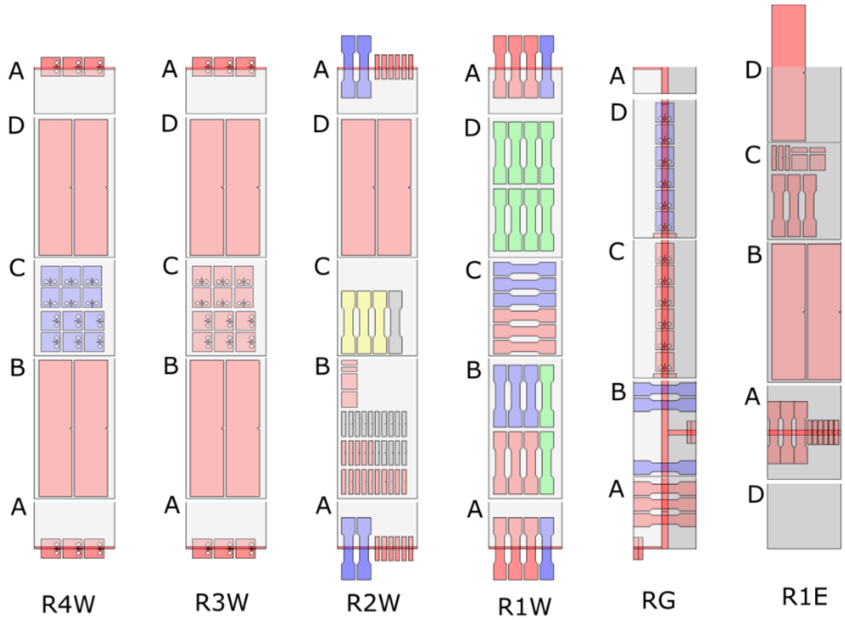


Figure 2 Sample cutting diagram for pipe section S8.

A summary of the execution of the tests undertaken as part of Phase 1 along with the results is provided in the following for each test group.

MATERIAL CHARACTERISATION

The chemical composition of the pipes was determined by Optical Emission Spectroscopy (OES). The %wt of carbon was between 0.18 and 0.23 with a carbon equivalent C_{eq} in the range of 0.32 to 0.47. Manganese content was between 0.81 and 1.31 %wt. The thin wall pipes had noticeably higher silicon and aluminium content compared to the other sections test in the range 0.22 – 0.26 and 0.016 – 0.022 %wt respectively. This indicates that the thin-wall pipes were Si-killed with addition of aluminium as part of the deoxidation process.

To the exception of pipe S8-E, the composition of this carbon-manganese X52 steel from 1970 complies with the modern specifications of API 5L PSL2 X52N welded pipes. With a %wt of Phosphorus of 0.03 and a Ceq of 0.47, pipe S8-E falls outside the modern specifications, essentially due to the larger content in carbon and manganese. API 5L PSL2 specifications were not available at the time of the construction of the PGP. It is not surprising for a 1970s steel to not fit fall within specifications imposed three decades later[2].

ASME B31.12 option B indicates that phosphorous content shall not be more than 0.015% in weight. Some pipes are above this limit. However, it is noted that toughness, FCGR and ultimately the resistance against a range of fracture modes, are the criterion from which the operating envelope is to be defined.

Table 4 Pipe steel composition

		wt/wt (%)														
Section	**Side**	**Fe**	**C**	**Mn**	**Si**	**S**	**P**	**Ni**	**Cr**	**Mo**	**Cu**	**V**	**Nb**	**Ti**	**Al**	**B**	**Ceq**
S1	**E**	Bal	0.18	0.85	0.01	0.01	0.02	0.03	0.01	0.01	0.03	<0.01	0.03	<0.01	<0.005	<0.005	0.33
	W	Bal	0.18	0.82	0.01	0.01	0.01	0.03	0.01	0.01	0.02	<0.01	0.04	<0.01	<0.005	<0.005	0.32
S5	**E**	Bal	0.18	0.83	0.01	0.01	0.01	0.03	0.01	0.01	0.02	<0.01	0.04	<0.01	<0.005	<0.005	0.33
	W	Bal	0.18	0.81	0.01	0.01	0.01	0.03	0.01	0.01	0.02	<0.01	0.04	<0.01	<0.005	<0.005	0.32
S8	**E**	Bal	0.23	1.31	0.26	0.01	0.03	0.04	0.04	0.02	0.05	0.01	<0.01	<0.01	0.022	<0.005	0.47
	W	Bal	0.19	1.13	0.22	0.01	0.02	0.03	0.02	0.01	0.02	0.01	<0.01	<0.01	0.016	<0.005	0.39

Small samples were extracted to obtain macrograph and micrographs of BM, SW and GW. For each sample, images were captured throughout the thickness at 5x, 10x, and 20x magnification.

An automated hardness tester was used to measure the hardness over the majority of the cross-weld samples from GW and SW. For each sample, at least 240 locations were probed. The spacing between each location was 0.5 mm in the wall-thickness direction and 1.5 mm along the hoop direction. A force of 5000 g-f (HV5)[3] was used. Figure 3and Figure 4 illustrate the results for GW and SW specimens taken from S1 respectively. The profiles are consistent with the other cross weld tested.

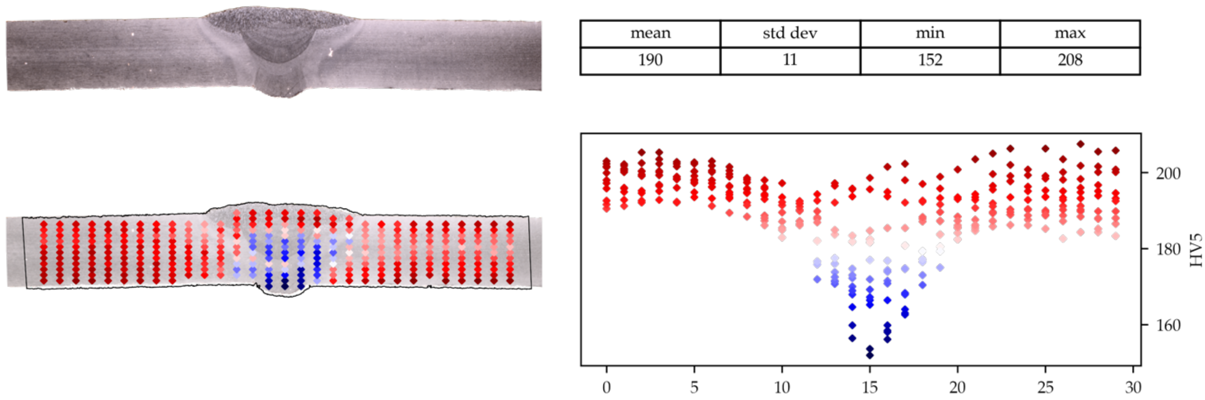


Figure 3 Cross girth weld of S1and hardness HV5.

[2] API 5L established the Product Specification levels from the 42nd edition (July 2000)

[3] B31.12 acceptance criteria is based on HV10 with the possibility to use other methods. HV5 was selected here to increase the resolution of the mapping with a spacing down to 0.5 mm.

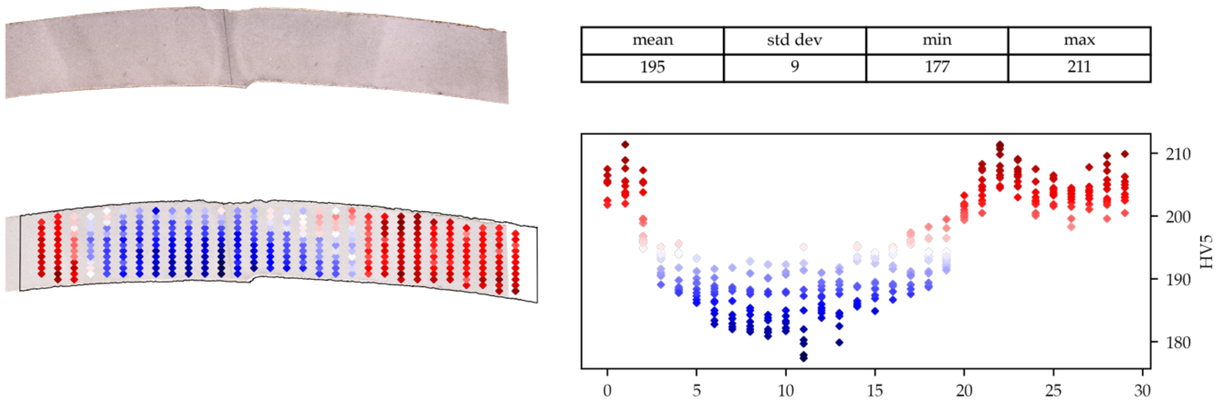


Figure 4 Cross seam weld of S1 and hardness HV5.

Maps from the GW, e.g. Figure 3, indicated a hardness typically below 180 HV5 at the root, approximately 180 HV5 at the mid wall and below 220 HV5 in the region of the cap. The hardness of the pipe metal was typically larger near the surface with a consistent through-thickness distribution about 10 mm away from the weld centreline.

Maps from the SW, e.g. Figure 4, indicated that the ERW weld region had a lower hardness than that of the pipe over a region approximately 20 mm wide, centered to the fusion line, and consistent with the post-weld heat treatment region visible in Figure 4. The hardness in that region was typically below 205 HV5 for S1 and S5, and below 220 for S8. One ERW sample from S8 exhibited a larger hardness in the vicinity of the outer surface, in the order of 230 HV5.

AS 2885.2 Cl. 6.4.6 specifies a maximum hardness of 350 HV in non-sour service and 250 HV in sour service [17]. ASME B31.12 Cl. GR-3.10 requires a maximum of 235 HV for hydrogen piping and pipelines. The hardness measured in the pipe metal, HAZ and weld metal of the girth weld and seam weld fulfill these requirements.

TENSILE

All tests were conducted on a universal testing machine with a capacity of 100 kN. The engineering strain was captured by an extensometer with an initial gauge length of 40 mm. For all tests, load was applied by a constant crosshead displacement set to 0.6 mm/min throughout the entire test. This displacement rate corresponds with the requirements of Method A, range 2 of AS1391:2020 [18].

Owing to the thin wall of S8, samples extracted along the transverse direction were flattened before machining. Samples taken along the seam welds were ground along their sides and etch with Nital to reveal the location of the weld centreline. The shoulders and parallel section were machined relative to that location.

In all, 48 tensile tests were conducted for the base metal, seam weld, and girth weld. 18 tests were conducted in the transverse direction of the base metal across the three sections. Three longitudinal tensile tests were performed on the west-side of S8. Nine girth weld tests were conducted. Eighteen tests were conducted in the seam weld along the transverse direction.

The transverse yield strength ($R_{t0.5}$) of BM was between 392 MPa and 425 MPa, with that of S1 and S5 above 405 MPa and that of S8 below 400 MPa. The tensile strength (R_u) was between 534 and 568 MPa, with that of S1 and S5 below 550 MPa and that of S8 above that same value. The uniform elongation (ε_u) was between 13 and 16%. The elongation at failure (ε_f) between 20 and 32%. Figure 5 illustrates the results obtained from the specimens of S1.

API 5L PSL2 X52 specifications require $R_{t0.5}$ between 360 and 530 MPa, R_u between 460 and 760 MPa with a maximum Y/T ratio of 0.93 for pipe metal properties taken in the transverse direction, 180 degrees from the seam weld of a HFW pipe. The specified minimum elongation at failure ε_f is 19.9 % for the thin wall pipe and 21.5 % for the thick wall. All specimens fulfilled the requirements.

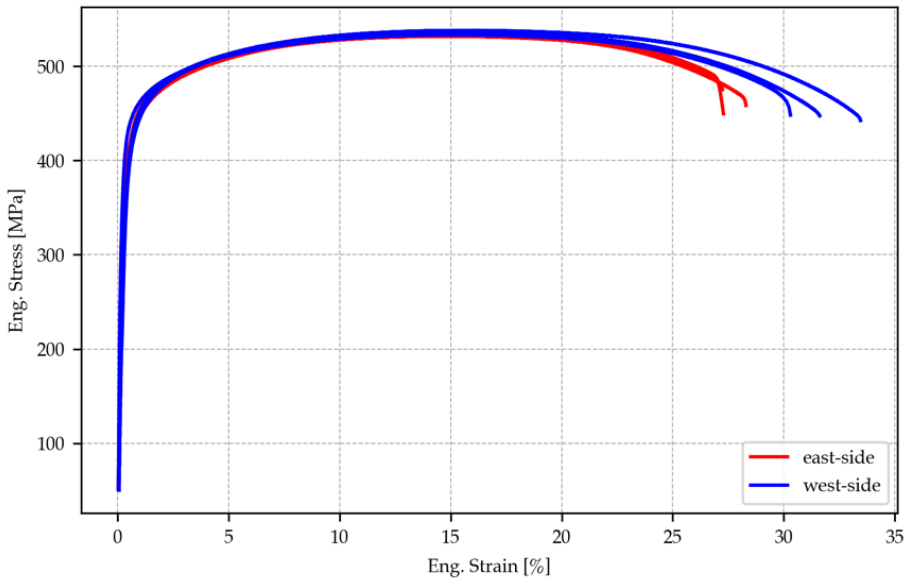


Figure 5 Engineering stress-strain curve from the base metal transverse specimens of section S1.

Tensile tests for BM of S8 in the longitudinal direction presented a larger yield strength (450 MPa) but similar tensile strength (560 MPa). ε_u was at the lower end (12.7%) and ε_f was at the higher end (28%).

Specimens from the girth weld presented a yield strength between 440 and 460 MPa, a tensile strength between 540 and 590 MPa with a uniform elongation typically around 9% and an elongation at failure between 17 and 19%. Failures of the sample occurred in the base metal. AS/NZ 2885.2 Cl. 6.4.3 require a tensile strength no less than that of the parent metal, i.e. 460 MPa. All specimens fulfilled that requirement.

Specimens sampling the seam weld presented notably larger yield strength than the transverse BM specimens with a yield strength between 438 and 473 MPa. The tensile strength ranged from 517 to 610 MPa. To the exception of one specimen with ε_u equal to 4.5%, all other specimens ranged between 6.5 and 9%. The elongation at failure was between 9% and 15.5%, except again for the same specimen with a lower value of 7.5%. API 5L PSL2 X52 specifications require the tensile strength of the seam weld to be at least 460 MPa. All specimens fulfilled that requirement.

DROP-WEIGHT TEAR TEST

DWTT were conducted in accordance with AS1330:2019 [19]. All sample preparation was done at UoW except for the press-notch. The machined samples were sent to BlueScope Steel Pty Ltd, where the press-notch was introduced, and the samples tested.

Drop-weight tear tests were conducted with the fibrosity reported as a percentage of the shear area (%SA). At –10 ºC, all samples were above 85 %SA, with all but one being at 100 %SA. The ductile-to-brittle transition temperature was determined to fall between –40 and –30 ºC for the thin-wall pipe S8-W.

CHARPY V-NOTCH

Charpy impact tests were conducted according to ASTM A370 [20] on an Instron 750MPX instrumented machine with an energy capacity of 750 J. An ISO striker with a 2 mm contact radius was used and all dimensions conformed to the Standard requirements. The samples were taken from BM and SW in the transverse-longitudinal direction (T-L[4]). The samples were machined down to 4mm in thickness to match the thickness of the C(T) specimens used to assess the FCGR and K_{JIc}.

Specimens sampling the welds followed a procedure with intermediate polishing and etching to reveal the location of the weld centreline for notching. See Figure 6 for an illustration of the process.

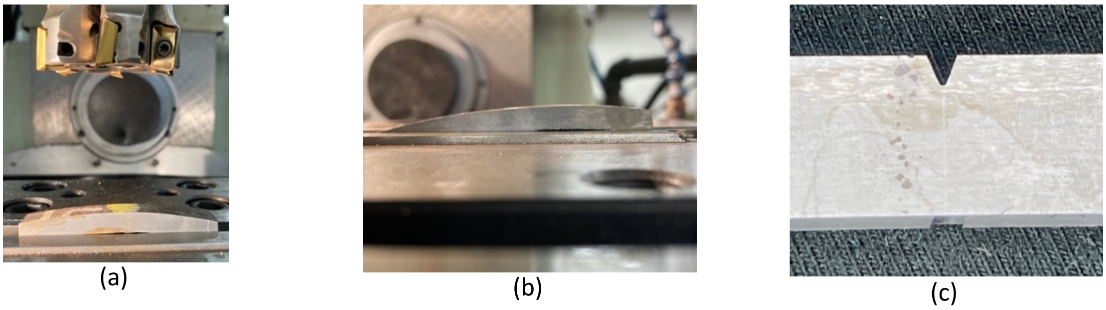


Figure 6 Preparation of Charpy specimens. (a) Milling of the top face, normal to the seam weld centreline. (b) The seam weld centreline was angled noticeably from the pipe's radial direction in several cases. (c) Notch after etching of the specimen's surface. The seam weld centreline is visible in the picture.

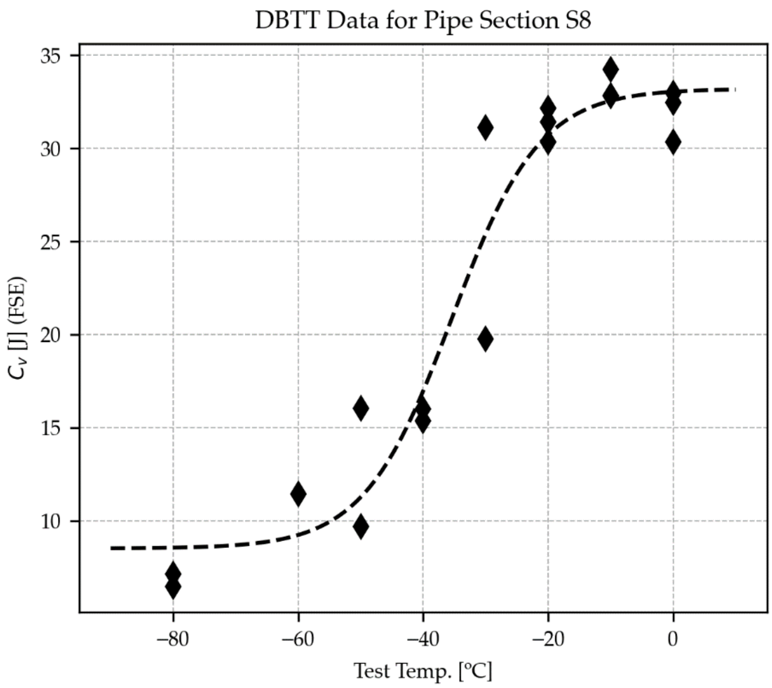


Figure 7: DBTT data for Charpy samples from the west-side of S8.

[4] i.e. the sample's length is aligned with the hoop direction. The notch is aligned with the longitudinal direction.

CVN tests were conducted at -10 ºC. The transverse CVN upper shelf energy at -10 ºC ranged from 30.3 J to 49.4 J for the base metal, all pipes considered. Transverse specimens sampling the seam weld centreline absorbed between 7.7 J and 26.9 J. Those sampling the seam weld heat-affected zone absorbed between 28.3 J and 53.1 J.

Supplementary tests were conducted from -80 ºC to 0 ºC for S8 to produce the ductile-to-brittle transition temperature curve (DBTT). The results are shown in Figure 7 with a full-size equivalent (FSE) energy above 30J for all specimens at or above -20 ºC. The transition region spans from -60 ºC to less than -20 ºC for these specimens with a 4mm thickness.

FATIGUE

Fatigue tests in air were conducted according to ASTM E647 using C(T) specimens [21]. Both the fatigue pre-crack phase and the fatigue test phase used a clip gauge with a +2.5mm/-1mm amplitude with a gauge length of 3mm.

The geometry of the pipes imposed a relatively small thickness 'B' for the C(T) . The geometry of the latter is proportional to its characteristic length W such that the ratio W/B remains within certain bounds. The limited amount of material available and the time required to perform the tests pointed to a strategy whereby each specimen was used for both the fatigue test and the toughness test. This approach implies that the geometry of the specimen complies with the requirements of ASTM E647 and ASTM E1820.

Figure 3 gives an overview of the setup with the sample, the cameras and the clip gauge (a), the crack path as seen by the cameras during the fatigue pre-crack phase (b) and (c), and an illustration of the fracture faces (d).

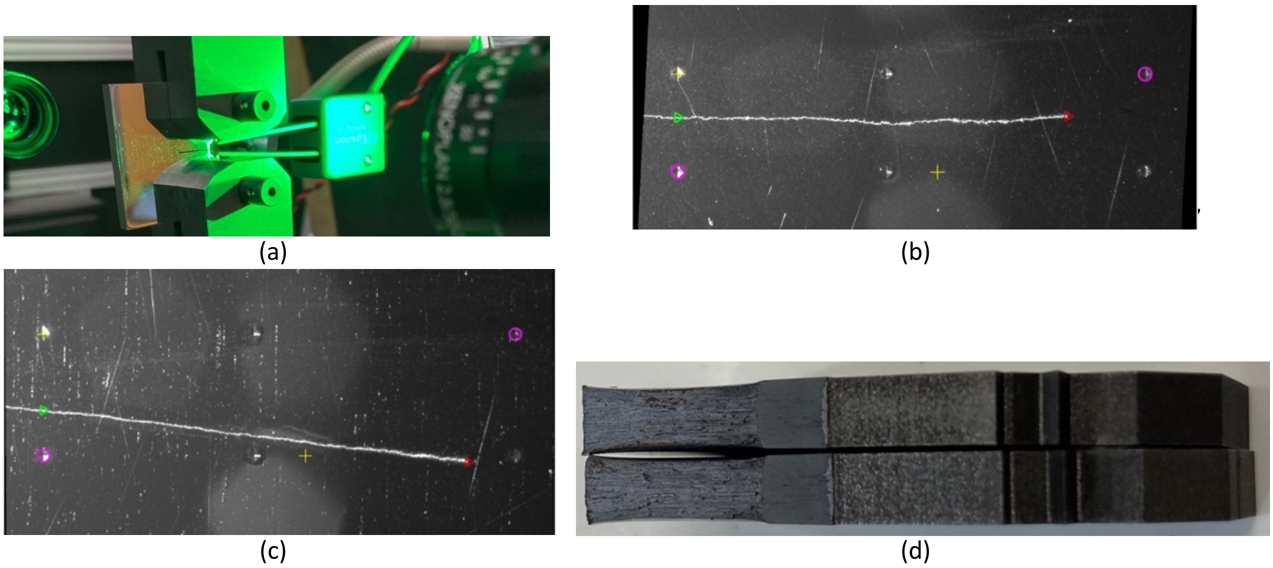


Figure 8 (a) Test setup on the tensile machine showing the C(T) specimen pinned on the clevises with the clip gauge and the two cameras used to monitor the crack during the pre-cracking phase. (b) Near straight and centered propagation of the fatigue crack in a girth weld centreline specimen from S8. (c) Deviation of crack path out of the symmetry plane in the heat-affected zone of a girth weld specimen from S8. (d) Illustration of the fracture surface after testing showing from left to right (i) the EDM notch, (ii) fatigue fracture from the fatigue pre-crack phase and (iii) ductile fracture from the toughness test.

Fatigue tests of compact tension specimens were generally successful, albeit specimens sampling the girth weld heat affected zone were affected by residual stresses which induced a curvature of the crack or imbalance of the propagation between the two main faces of the specimens. Overall, the crack growth rate was largest in the base metal with a crack oriented in the longitudinal direction.

An upper bound of the fatigue crack growth rate in air was obtained based on a fit of the Paris law. A fatigue crack growth rate below $5e^{-6}$ mm/cycle at ΔK= 8 MPa.m0.5 and below $2e^{-4}$ mm/cycle at ΔK =30 $MPa.m^{0.5}$ was observed in air, irrespective of the location or orientation of the specimen. Results indicate a crack growth rate in air similar to other X52 reported in the literature. Figure 9 illustrates the results from the transverse specimens of S8-W in BM.

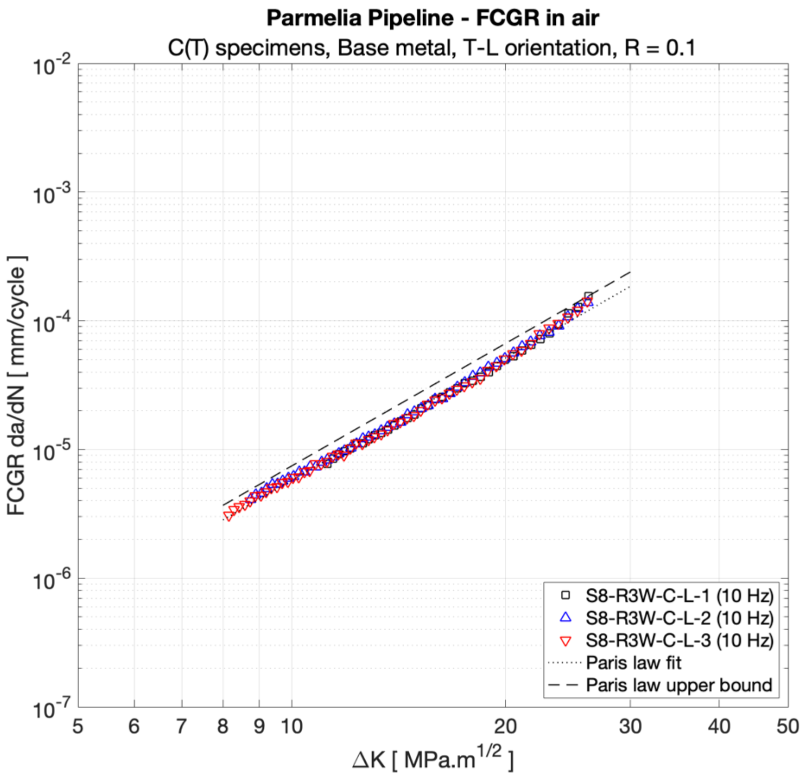


Figure 9 Fatigue crack growth rate for the transverse specimens of S8 sampled from BM.

STATIC FRACTURE

Static toughness tests in air were conducted according to ASTM E1820 [22] on C(T) specimens to measure the toughness J_Q from which K_{JIc} can be derived. While the fatigue pre-crack and the fatigue tests used a clip gauge with a +2.5mm/-1mm amplitude, toughness tests used a clip gauge with a +7mm/-1 mm amplitude. Both gauges had a gauge length of 3mm. Sample preparation followed that of the fatigue specimens.

Specimens from the pipe metal with a longitudinal crack had the lowest observed toughness with an average of 118 $MPa.m^{0.5}$. Literature indicates that a 50% decrease in K_{JIc} due to hydrogen can occur therefore results indicate line pipe toughness in hydrogen would be just above the ASME B31.12 threshold (55 $MPa.m^{0.5}$). Figure 10 illustrate the result for such a sample.

Both longitudinal specimens sampling the pipe metal and the GW-HAZ demonstrated larger fracture resistance than the GW-CL. The data from the latter supports the conclusion that the girth weld region will likely meet the requirements of ASME B31.12 in hydrogen environment. A decrease of K_{JIc} by 50% in hydrogen would result in girth weld toughness in the order of 75 $MPa.m^{0.5}$.

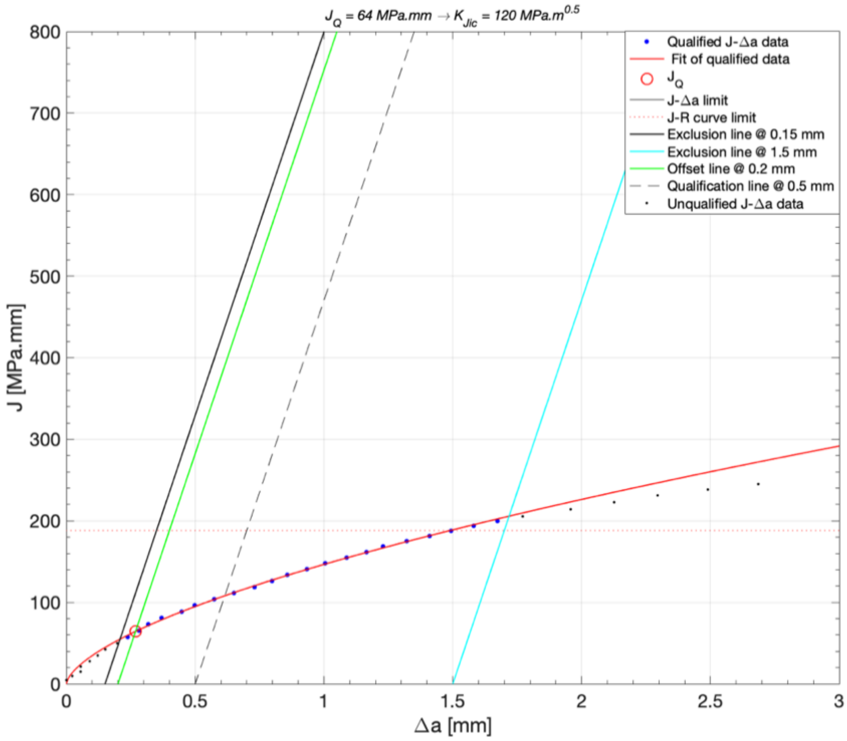


Figure 10 J-Δa curve obtained on a S8 transverse specimen (longitudinal crack) taken from the base metal. A qualified K_{JIc} of 120 MPa.m$^{0.5}$ was measured from this specimen.

OUTLOOK

Overall, the data from the thin wall pipe section indicates tensile properties to be lowest in the transverse direction of the pipe metal. Fatigue crack growth rate was largest in the axial propagation direction for the base metal and K_{JIc} was also lowest for a crack in that direction.

In light of the results obtained in air, evaluations of the properties in gaseous hydrogen are being conducted with a particular focus on the properties relevant to the mechanisms of longitudinal fracture of the pipe metal. The schedule of the test program for Phase 2 prioritises the tests relevant to the characterisation of a longitudinal fracture, namely transverse tensile tests followed by transverse fatigue and static toughness tests.

5 Engineering Calculations

To support design basis of the PGP conversion project, calculations have been conducted to assess the design and determine the permissible operating window for the pipeline. This section summarises the conclusions of these calculations.

The calculations quantify the pipeline failure-modes and consequences to facilitate an assessment of pipeline safety management. The calculations also aid an assessment of compliance against design standards. The calculations presented in this section include 'Fracture initiation', 'Fatigue crack growth', 'Fracture propagation' and 'Energy release rates'[5] these will, where practical, conservatively predict the impact of hydrogen on the existing design.

[5] Note that calculations associated with resistance to penetration and pipeline stress were conducted but are not reported in this paper. Neither is detailed failure mode and consequence analysis presented in this paper.

Pressures were defined for several scenarios as summarised in Table 5. These pressures have been used through the various calculation. The material properties obtained by UoW and used for the assessments are summarised in Table 6.

Table 5 Pipeline internal gas pressures

Case	Pressure, p	Source
Design factor, F_D = 0.4	4.5 MPa(g)	ASME B31.12 Option A design for location class 4
Design factor, F_D = 0.5	5.6 MPa(g)	ASME B31.12 Option A design for location class 3
Hydrotest	10.6 MPa(g)	License PL1

Table 6 Pipe material properties retained for the calculations (in air)

Variable	Value
Base-metal Charpy V-Notch toughness (full-size equivalent)	30 J at -10°C
Base-metal Actual yield strength	390 MPa
Base-metal Actual tensile strength	530 MPa
Seam weld Charpy V-Notch toughness (full-size equivalent)[1]	10 J at -10°C
Seam weld Actual yield strength	430 MPa
Seam weld Actual tensile strength	510 MPa

FRACTURE INITIATION

Fracture initiation conditions were analysed for the thinnest (5.56mm) and the thickest (7.92mm) pipe material. AS 2885.1 Cl 5.5.4 was used to formulate the basis of calculation and analyse the Critical Defect Length (CDL) for the pipe at various toughness's (base pipe and weld) and with various internal pressures. The flow stress was taken from the specified minimum yield strength plus 10 ksi, though actual material tensile tests are available and could be used for a better estimation.

The effect of hydrogen on toughness is not known, as the materials test program in a hydrogen environment is still ongoing. To provide a conservative estimate, it was assumed that the toughness would halve in hydrogen service. Table 7 summarises the CDL results from the calculation.

A comparison between the API 579 model [23] and the NG-18 [10] [24] was performed. This comparison revealed that the overall form of the results was similar, and that the limiting condition (high-toughness) which is driven by plastic collapse, is similar between the two analysis methods.

The NG-18 equation from AS 2885.1 uses Charpy toughness, whereas the API-579 method uses stress intensity factor, K_{IC}. Comparison between the two models shows that Charpy values have similar results to quite high K_{IC} values – higher than would be expected for the steel. Currently the reason for the difference is not well understood. The difference warrants further investigation; this will be supported by direct testing of the K_{IC} in hydrogen using C(T) in the next project phase.

Table 7 Critical defect length (mm) using the NG-18 fracture initiation equation.

Case	CDL (mm), at internal pressure of...		
	4.5 MPa(g)	5.6 MPa(g)	10.6 MPa(g)
Wall thickness 5.56mm			
High-toughness	164 mm	125 mm	44 mm
30 J (base pipe)	150 mm	119 mm	44 mm
15 J (base pipe – with hydrogen)	128 mm	104 mm	N/A
10 J (weld)	114 mm	93 mm	39 mm
5 J (base pipe – with hydrogen)	91 mm	74 mm	N/A
Wall thickness 7.92 mm			
High-toughness	305 mm *	231 mm	102 mm
30 J (base pipe)	242 mm	197 mm	98 mm
15 J (base pipe – with hydrogen)	199 mm	165 mm	N/A
10 J (weld)	175 mm	145 mm	77 mm
5 J (base pipe – with hydrogen)	138 mm	115 mm	N/A

* Result exceeds the range of validity of the formula

FATIGUE CRACK GROWTH

Modelling at the MAOP of 5.6 MPa(g) was used to analyse the standard wall thickness pipe for two pressure cycling cases:

- the simplified representation of historical cycling, and
- the maximum cycling that can be permitted to achieve a fatigue life of 100 years.

The modelling assessed three defect cases:

- the maximum infinitely long internal crack that could survive hydrotest,
- a semi-elliptical defect that could survive hydrotest, and
- the semi-elliptical defect recommended in ASME B31.12 (1/4t deep x 1.5t long).

The modelling assumed:

- toughness in air and natural gas: 100 MPa.m$^{0.5}$
- toughness in hydrogen[6]: 50 MPa.m$^{0.5}$

Table 8 Fatigue life from fatigue crack growth modelling.

Case	Initial defect	Life with current cycling	Maximum cycling for 100 year life
1	1.3088 mm deep x Infinite length (max hydrotest defect)	Historical cycling Hydrogen: 3,400 years Air: 119,000 years	**2.107 MPa daily cycle** Hydrogen: 100 years Air: 792 years
2	2.366 mm deep x 50.00 mm length (max hydrotest defect)	Historical cycling Hydrogen: 1,392 years Air: 62,056 years	**1.582 MPa daily cycle** Hydrogen: 100 years Air: 1,029 years
3	1.4 mm deep x 8.4 mm length (ASME B31.12 defect)	Historical cycling Hydrogen: 45,840 years Air: 1,023,000 years	**5.285 MPa daily cycle** Hydrogen: 100 years Air: 2,180 years

6 This is below the ASME B31.12 Option B limit of 55 MPa.m0.5, providing a conservative fatigue life estimate.

The results are summarised in Table 8. These results are currently based on significant assumptions. Nevertheless, they show that even for the largest defects that survive hydrotest, cycling in the order of 1 MPa on a daily basis may be permissible for a design life of 100 years at the current MAOP. If the future assessment (based on a wider variety of defects) determines there is an inadequate margin of safety for the expected fatigue, three actions are possible:

- Decrease MOP;
- Decrease pressure cycling amplitude; and
- Inspection of pipeline for crack-like defects.

FRACTURE PROPAGATION

The minimum required fracture arrest energy was calculated for the thin, 5.56 mm wall thickness, material. The energy is reported as the full-size equivalent Charpy V-Notch absorbed energy, in Joules, calculated from the Battelle Two-Curve Method implemented in EPDECOM [25]. Generally, the arrest toughness was found to be highest at the design minimum temperature of -7°C.

Table 9 Minimum required ductile fracture arrest energy at -7°C using the BTCM.

Internal pressure	Pure methane	10% H2	Pure hydrogen
4.5 MPa(g)	10.4 J	9.7 J	3.8 J
5.6 MPa(g)	14.5 J	13.4 J	5.4 J

For reference, the ASME B31.12 calculation for fracture arrest toughness was also reviewed. This review indicated that ASME B31.12 would require a specified toughness of at least 9 J, a requirement that the pipe material meets.

ENERGY RELEASE RATE & RADIATION CONTOURS

The energy release rate and radiation contours were calculated, for various loss of containment scenarios. This data has been used in the pipeline Safety Management Study (SMS), to assist understanding of the consequence of failure events.

Radiation contours for full-bore rupture were assessed for the three compositions and three pressures considered. It can be seen that in every case the radiation contour decreases with increasing hydrogen content. This indicates that the pipeline “measurement length” used for determination of the pipeline location class, will be reduced, unless there is an increase in the Maximum Allowable Operating Pressure (MAOP).

Table 10 Full-bore rupture radiation contours.

Pressure	Natural gas		10% Hydrogen blend		Hydrogen	
	4.7 kW/m²	12.6 kW/m²	4.7 kW/m²	12.6 kW/m²	4.7 kW/m²	12.6 kW/m²
4.5 MPa(g)	244 m	149 m	241 m	147 m	235 m	144 m
5.6 MPa(g)	271 m	166 m	268 m	164 m	263 m	160 m

Leak scenarios were also analysed. Limitations on the permissible leak rate are applied under AS 2885.1 for ‘high consequence areas’, which encompass location classes T1, T2 and some secondary location classes. In T1 locations, the permissible energy release rate is limited to 10

GJ/s, and in T2 locations, the permissible energy release rate is 1 GJ/s. Both of these have been analysed and are presented in the table below.

Table 11 Hole size for maximum energy release rates.

Energy release rate	Pressure	Natural gas	10% hydrogen blend	Hydrogen
10 GJ/s	4.5 MPa(g)	291 mm	294 mm	301 mm
	5.6 MPa(g)	261 mm	264 mm	270 mm
1 GJ/s	4.5 MPa(g)	92 mm	93 mm	95 mm
	5.6 MPa(g)	83 mm	84 mm	85 mm

The results indicate that a hole of a certain size in a pipe will have a lower energy release rate in hydrogen service than in natural gas, though only by a small margin. None of the external interference threats are likely to cause a release of 10 GJ/s. The hole sizes listed are like the diameter of the pipe and such holes cannot practically be created.

6 Operating Parameters

The pipeline MAOP is currently 5.6 MPa(g), which equates to a maximum design factor of 0.5 in the section being converted. The base case for design is that the MAOP will be retained in future use. However, the maximum operating pressure (MOP) is likely to be lower. Two factors are relevant:

- The required operating pressure is likely to be lower:
  - Under current operating conditions the pressure is typically less than 4.1 MPa(g) and this would likely continue if hydrogen blending commences.
  - Conversion to pure hydrogen is likely to be limited to the outlet pressure of electrolysers (3 to 4 MPa(g)), unless hydrogen compression is also installed to boost the pressure up to 5.6 MPa(g).
- A reduction in pressure may be used to improve control of pipeline integrity. The safety management study assesses each potential pressure-related failure mode. The initial SMS has concluded that the pipeline can safely operate at 5.6 MPa(g). However, operating pressure reduction will improve the margin of safety for a number of failure modes.

Over-pressure protection will be required to meet the requirements of AS 2885.1. The measures required depend on the sources of overpressure, which are dependent on the larger system design, and will be reviewed in the project HAZOP during future design phases.

The pipeline design is required to accommodate variations between upstream hydrogen supply and downstream hydrogen consumption profiles. The difference between the upstream and downstream profiles will be accommodated by the pipeline storage. Additionally, the downstream consumer may require flow assurance, guaranteeing continuity of supply.

If the pipeline is operated with pure hydrogen, the application may be transport of hydrogen from an upstream supply with a supply profile that is typically intermittent, to a downstream consumer with a consumption profile that is more continuous. In that case, the system capacity is strongly linked to the permissible pressure cycling.

The permissible extent of pressure cycling will be confirmed by conducting detailed fatigue capacity calculations (modelling of fatigue crack growth for a range of credible defects). Initial fatigue calculations have predicted that the pipeline might safely be permitted to fluctuate by up to about 1 MPa per day, but that there will be necessary controls to prevent larger cycles, such as full pipeline blowdown. If greater fluctuations are required, then this can be achieved by reducing the pipeline MOP, or confirming the pipeline condition through effective use of crack detection inspection tools.

Depending on temperature[7] and pressure, the pipeline will store between 72 and 80 kg of hydrogen per mega Pascal per kilometre. (For the distance involved, this is approximately 3 tonnes, or 425 GJ, per mega Pascal).

The use of the pipeline for storage will be limited by permissible pressure fluctuations. It is expected that the permissible upper limit for volume access will be 3 tonnes per day.

The flow-rate of the pipeline is limited by two factors:

- Delivery pressure. A pressure drop is caused over the length of the pipeline due to flow.
- Flow velocities can be limited to prevent excessive noise at choke points and avoid erosion from entrained particulates. Note, hydrogen production will not introduce additional particulates.

At a limiting pressure of 4 MPa(g), the pipeline capacity is estimated to be about 20 to 50 TJ/day, which results in 5 to 15 m/s flow velocity. The flow capacity will be confirmed using hydraulic modelling in the next phase of the project.

7 Pipeline Safety Management Study

Safety is a central objective of design. Technical regulators in Western Australia, where the PGP is located, require submission and approval of a project Safety Case, demonstrating that safety has been managed to reduce risk to 'As Low As Reasonably Practical' (ALARP), which is also a core principal of the design code, AS 2885.1.

Safety in Design of this pipeline conversion project will be achieved through the following main activities, in accordance with AS 2885:

- Pipeline safety management study (SMS)
- Hazard and operability study (HAZOP)
- Construction hazard identification (HAZID) and job hazard analysis (JHA)
- Emergency response planning (ERP)
- Fire safety study, for above-ground facilities

The SMS process is defined in AS 2885.6. It is primarily concerned with matters of public safety, including harm to people, harm caused by interruption to supply, and harm to the environment. The PGP is already managed under an existing SMS, which was most recently reviewed in 2017.

[7] The design and operating temperatures of the pipeline will generally not be altered by this project. The minimum temperature for brittle fracture control is confirmed to be suitable for transient temperatures that result from pressure drop with the current composition. Addition of any hydrogen to the composition will decrease the magnitude of the temperature drop. That is, pure hydrogen has a negative Joule-Thompson coefficient, which means it will increase in temperature when depressurising across a pressure regulator (isenthalpic expansion).

This study identified Intermediate risks, which triggered a formal 'As Low As Reasonably Practicable' (ALARP) study, to ensure that all practicable risk reduction actions were being implemented.

The safety management is altered due to inclusion of hydrogen, with the following impacts requiring review:

- Failure mode change due to hydrogen impact on material and gas properties.
- Risk consequence change due to hydrogen impact on composition and leak rate.
- Risk likelihood change, due to increased probability of ignition. Unless evidence is found to support a reduced value, the probability of ignition is assumed to be 100%.
- Integrity management requirements change, due to hydrogen embrittlement changing the failure condition of anomalies and defects.
- Threats introduced due to operating with hydrogen, such as intelligent pig tool compatibility, ignition during venting, accelerated material fatigue, hydrogen induced cracking, risk of failure during in-service welding, and similar.

Consequently, revision of the SMS is required under this project, including two categories of SMS review:

- A Design Change SMS Report was developed in Phase 1. The Phase 1 SMS Report included a review of threats that will be affected by hydrogen. Actions were raised for further assessment in the subsequent project phases.
- A Detailed Design SMS is required in the subsequent phase of the project, to review the design of new pipeline facilities and proposed operation and maintenance changes.

Depending on the conclusion of the SMS review in Phase 2, the pipeline may also require revision of formal ALARP study.

8 Summary and Outlook

APA's research progresses to test the ability of 43-kilometres of Parmelia Gas Pipeline to carry up to 100 per cent hydrogen. The project is being carried out in stages to achieve engineering excellence and create new safety standards in parallel.

While the first phase of testing has confirmed the technical viability of the pipeline to transport hydrogen, the second phase of testing is expected to prove the operational capacity of the existing gas transmission pipeline to transport hydrogen in pure form or blended with natural gas and provide improved understanding of current conservative degradation parameters of the pipeline steel in hydrogen service.

The second phase of the project builds on the strong accumulating knowledge-base gained over the past 12 months and provides the logical next step for pipeline conversions in Australia. The PGP project results will be used in support of the APGA CoP for H2 Pipelines development.

The project will continue to use test facilities at the University of Wollongong to test hydrogen-charged pipeline steels and compare those results to the properties in air.

Rather than appealing to published literature to estimate material behaviour changes in hydrogen, actual testing of the pipeline material at pipeline pressures enables a safe and efficient design process.

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