Parmelia Gas Pipeline

Hydrogen Conversion Technical Feasibility Study

Public Knowledge
Sharing Report
May 2023

Acknowledgement of Country

APA acknowledges the Traditional Custodians of the lands on which it operates throughout Australia and their connections to land, sea and community. We pay our respects to their Elders past and present and seek to find meaningful ways to ensure APA operates in a manner that genuinely and consistently reflects that respect.

GOVERNMENT OF WESTERN AUSTRALIA

Department of Jobs, Tourism, Science and Innovation

Acknowledgement of Grant Funding

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Disclaimer

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Contents

About APA

APA is a leading Australian Securities Exchange (ASX) listed energy infrastructure business, which owns and/or operates and manages a diverse $22 billion portfolio of gas, electricity, solar and wind assets. Consistent with our purpose to strengthen communities through responsible energy, our portfolio delivers energy to customers in every state and territory in Australia.

Our 15,000 kilometres of natural gas pipelines connect sources of supply and markets across mainland Australia. We operate and maintain networks connecting 1.4 million Australian homes and businesses to the benefits of natural gas. And we own or have interests in gas storage facilities and gas-fired power stations.

We also operate and have interests in 593 MW of renewable generation infrastructure, including 88 MW under construction. Our asset portfolio also includes high voltage electricity transmission assets that connect Victoria with South Australia, New South Wales with Queensland, and Victoria with Tasmania.

In August 2022, we published our inaugural Climate Transition Plan which outlines our commitments to support Australia's energy transition and pathway to achieve net zero operations emissions by 2050.

Through APA's Pathfinder Program, we are helping to unlock energy solutions for tomorrow, and we continue to grow our experience and expertise in hydrogen generation and other clean fuel technologies which support a lower carbon future.

Diverse energy infrastructure portfolio

Gas infrastructure

Transmission
>15,000 km transmission pipelines

Storage
12,000 tonnes LNG

18 PJ gas

Distribution
>29,500 km gas mains and pipelines

>1.4 million gas customers

Power Generation

Renewable energy
342 MW Wind
251 MW Solar

Gas fired
440 MW

Electricity transmission

243 km high voltage lines

370 km deep-sea cable
(including overland section)

Executive Summary

APA, as the owner and operator of the Parmelia Gas Pipeline (PGP) in Western Australia, is considering the conversion of the most southern section of the pipeline to a pure hydrogen service. This would be the first conversion of a natural gas transmission pipeline to pure hydrogen in Australia.

This report details the methodology and results of the Parmelia Gas Pipeline Hydrogen Conversion Project Technical Feasibility Study. The study successfully demonstrates that it is technically feasible, safe and efficient to operate the section of pipeline at current operating pressure using 100 per cent hydrogen. The success of the study will enable APA to progress with developing detailed safety studies and conversion plans, ahead of moving to physical modifications and upgrade works, operational testing, and commercialisation.

Transmission of hydrogen at scale is a critical part of delivering the Australian Government's hydrogen economy ambition and to support state government initiatives, including the WA Government's hydrogen blending goal of 10 per cent by 2030. With billions of dollars invested in gas infrastructure across the country, it is critical to look at ways to use our existing energy infrastructure to support Australia's transition to a low carbon future.

APA internal estimates and overseas benchmarks place the cost of conversion of a suitable pipeline at 10-20% of a new build, with the schedule associated with conversion 25-40% shorter. Therefore, where a pipeline can be shown to be safely converted there is material benefit to the approach.

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, hydrogen atoms are absorbed into the steel and affects the material properties, known as hydrogen embrittlement.

The primary objective of the Feasibility Study is to understand and quantify the effect of hydrogen on the pipeline material so that the safety of the pipeline can be assessed with due diligence.

The 43km section of pipeline that is being considered for conversion was selected due to its location near the Kwinana Industrial Area (KIA) south of Perth where a number of potential hydrogen offtakes are located, including for industrial processing, export and hydrogen transport (mobility).

The project tested representative samples of pipeline materials in a hydrogen environment at conditions equivalent to pipeline operation. It was concluded that the steel could deliver satisfactory performance, providing a safe operating envelope similar to its current operating profile.

Conversion design evaluation has utilised the intent of Australian pipeline standard, AS 2885 for risk-based design, with reference to ASME B31.12 to address hydrogen specific design requirements not addressed in the current Australian Standard.

The study confirmed the pipe steel and proposed design generally meets the requirements of the American hydrogen pipelines and piping standard, ASME B31.12.

The design calculations, components and assemblies' materials compatibility review, integrity review, and Safety Management Study completed as part of this project have been collated into a feasibility level conversion plan and design basis. This includes an action register to be addressed in the next phase of the project.

Importantly, this project supported the creation of an Australian Hydrogen Pipeline Code of Practice, and also includes the development of a template roadmap for future conversion projects, which is detailed in this report.

1 Project Overview

1.1 Background

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 the Kwinana Industrial Area and Pinjarra, south of Perth.

The PGP also interconnects with the ATCO Gas distribution network in the Perth metropolitan area, providing future opportunities for injection into the gas distribution network.

APA is considering the conversion of the most southern section of the PGP to a pure hydrogen service. This would be Australia's first hydrogen-ready transmission pipeline.

The 43km section of pipeline that is being considered for conversion is located near the Kwinana Industrial Area (KIA) south of Perth where a number of potential hydrogen offtakes are located, including industrial processing, export, and hydrogen transport (mobility). APA's converted pipeline could facilitate the transmission of hydrogen from point of generation south of Pinjarra to point of use and/or export.

There are cost, schedule, approvals, operational, and technical safety decisions when considering conversion or building of new pipeline assets. Overseas benchmarks place cost of conversion at 10-20% of new build, with the schedule associated with conversion 25-40% shorter, primarily due to reduced requirements around approvals and land access. There are further benefits of conversion over new builds that are associated with reduced disruption and impact to community and stakeholders. Where a pipeline can be shown to be technically and safely converted, there is material benefit to this approach.

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, hydrogen atoms are absorbed into the steel and affect the material properties, known as hydrogen embrittlement. In particular, the ductility, toughness and fatigue life of the steel is impacted. This has potential to compromise the pipeline's performance.

Australia's high-pressure pipeline standard AS(/NZS) 2885 does not currently provide requirements for hydrogen service, and 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 for hydrogen pipelines ASME B31.12, but it is largely intended for newly build hydrogen pipelines. As such, some of its requirements cannot always be applied retrospectively.

APA has partnered with the Future Fuels Cooperative Research Centre (Future Fuels CRC) and the University of Wollongong (UoW) to support the engineering, material testing, and applied research required to support the pipeline conversion. Additional engineering support in the project has been provided by GHD and GPA Engineering.

1.2 Objectives

The primary objective of the Feasibility Study is to provide the engineering and data that allows for a safe and efficient conversion of the southern 43km of the Parmelia Gas Pipeline to hydrogen service and achieve optimal performance (that is, the capacity of the pipeline is safely and reliably maximised).

The work aims 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. In the absence of clear direction from mature standards, responsible engineering means demonstration of safety from first principles.

The final output of this work is to identify:

- How the pipeline can be converted to hydrogen
- Allowable pipeline operating profile (pressure, cycling)
- Activities required prior to conversion, e.g. in-line-inspection, detailed technical assessments, facilities modifications, stakeholder engagement
- Providing a template roadmap for future conversion projects

1.3 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. 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 safe operating envelope within which the capacity of the pipeline will be maximised. The study follows the AS/NZS 2885.6 Safety Management Process to thoroughly review the risks posed by hydrogen.

To reach these primary objectives, activities were planned over two phases of the project to understand and quantify the effect of hydrogen on the pipeline material(s):

- **Phase 1:** developed a hypothesis for hydrogen performance by conducting material tests of base metal in air and completing mathematical modelling to predict its behaviour when exposed to hydrogen.
- **Phase 2:** validated the hypothesis by completing material tests in pressurised hydrogen. providing additional confidence of pipeline conversion.

The suite of material tests undertaken in air and then in a pressurised hydrogen environment provided detailed materials engineering performance data. The material test results fed into the engineering calculations, the pipeline failure mode analyses, and the Safety Management Study (SMS).

In parallel to the work being undertaken to understand and manage the impact of hydrogen embrittlement on the pipeline material, a conversion plan was developed to identify the activities required to be completed prior to the conversion. These include activities such as stakeholder and community engagement, inspections, testing and engineering assessments, and facilities and pipeline modifications.

2 PGP Overview

The Parmelia Gas Pipeline mainline is approximately 416 kilometres long and transports gas from the Perth Basin gas fields near Dongara, the Carnarvon Basin (via the Dampier to Bunbury Natural Gas Pipeline) and APA's Mondarra Gas Storage Facility to the Kwinana Industrial Area south of Perth.

The section of the pipeline that is south of Perth is being considered for conversion to hydrogen service (refer to Figure 1). The pipeline section nominally between Main Line Valve 17 (MLV17) and the end of line would be isolated and reversed, to provide hydrogen transport from the Pinjarra region to the Kwinana industrial estate.

The pipeline and associated laterals have operated under WA Licence 1 since 2nd December 1970.

2.1 PGP Technical Parameters

The 43km section of the PGP being considered for conversion is primarily made of vintage API 5L X52 ERW DN350 line pipe, with a standard wall thickness of 5.56 mm, with some heavy walls with a nominal 7.14 mm wall thickness, and extra heavy wall pipe of 7.92mm at pipeline assemblies. Table 1 summarises the design of the section of PGP under consideration for hydrogen conversion.

Currently this section of the pipeline has a maximum allowable operating pressure of 5.61 MPa, which is equivalent to a maximum design factor of 0.5. The southern section of the pipeline normally operates at about 4.1 MPa.

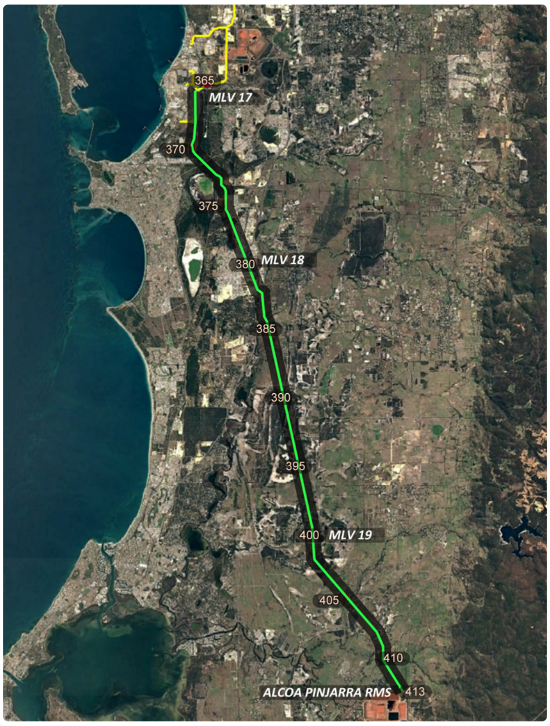

Figure 1: Location of Parmelia Gas Pipeline section subject to H2 conversion study

Attribute	Value
Material Specification	API 5L (API 5L 16th Edition 1969)
Material Grade	X52
Diameter	355.6 mm
Wall Thickness	5.56, 7.14 and 7.92mm
SMYS (Specified minimum yield strength)	360 MPa
SMTS (Specified minimum tensile strength)	460 MPa
AS 2885.1 Design factor	0.5, 0.4, & 0.35
Corrosion Allowances	0 mm
Length	43 km
Start & End KPs	364.6 to 413
Location Classes AS 2885.6	T1, T2 & R2
Design Temperature Range	-7 to +65 °C
Hydrotest pressure	10.6MPa(g)
Coating	Pipe - Factory applied HDPE Joints - heat shrink sleeves
Cathodic Protection	Impressed Current
Depth of cover	800mm (Min), 1200mm (Nominal)
Year of Construction	Circa 1970/1971
Commissioning	November 1971
Original Design Code	ANSI B31.8 (1968 edition)

Table 1: Basic pipeline design data

3 Project Approach

The overall approach to the pipeline conversion is to follow the Safety Management Study methodology of AS/NZS 2885.6 to demonstrate 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).

As AS/NZS 2885.1 is silent on the specific topic of hydrogen fluid service from an embrittlement, fluid properties, or safety perspective, the study has appealed to the American standard ASME B31.12, international experience, and available research.

The high-level assessment method for the two Feasibility Study phases is as follows:

Standards Gap Analysis and Literature Review

- Identify the requirements of AS 2885.1, ASME B31.12, and other available guidance material including IGEM [a] and EIGA [b].
- Complete a gap analysis of the pipeline design against standard requirements, including the development of a full compliance matrix.

Data Gathering and Testing

- Collate available pipeline historic construction and operational records.
- Measure and, when available, confirm the material properties in air against the company's records.
- Measure the material properties in gaseous hydrogen environment.
- Extend the acquisition of data beyond standard practices to cater for future assessment tools and new compliance requirements.[1]

Engineering Calculations

- Quantify the impact of hydrogen on pipeline performance for safety management.
- Fatigue crack growth calculation, fracture initiation and arrest, critical defect length assessment, energy release assessment.
- Assessment of design compliance with published Standards.
- Pipeline condition assessment for change of operating conditions assessment to AS 2885.3.

Pipeline Operating Window

- Subject each 'gap' to risk assessment using the AS 2885 SMS method.
- Define safe operating window and activities required to manage safety.
- Extend the operating limits within satisfactory margins of safety.
- Assess pipeline capacity at defined operating limits.

Conversion Plan

- Develop the conversion design basis, including the fracture control plan and the pipeline integrity management plan.
- Define required pipeline and facility modifications.
- Stakeholder engagement and approvals plan.

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[1] For instance, complete stress-strain curves are recorded for future defect assessments by numerical methods while material is available for this study.

3 Project Approach

A summary of the overall approach and key activities for Phase 1 and 2 are shown in Figure 2 and Figure 3 respectively.

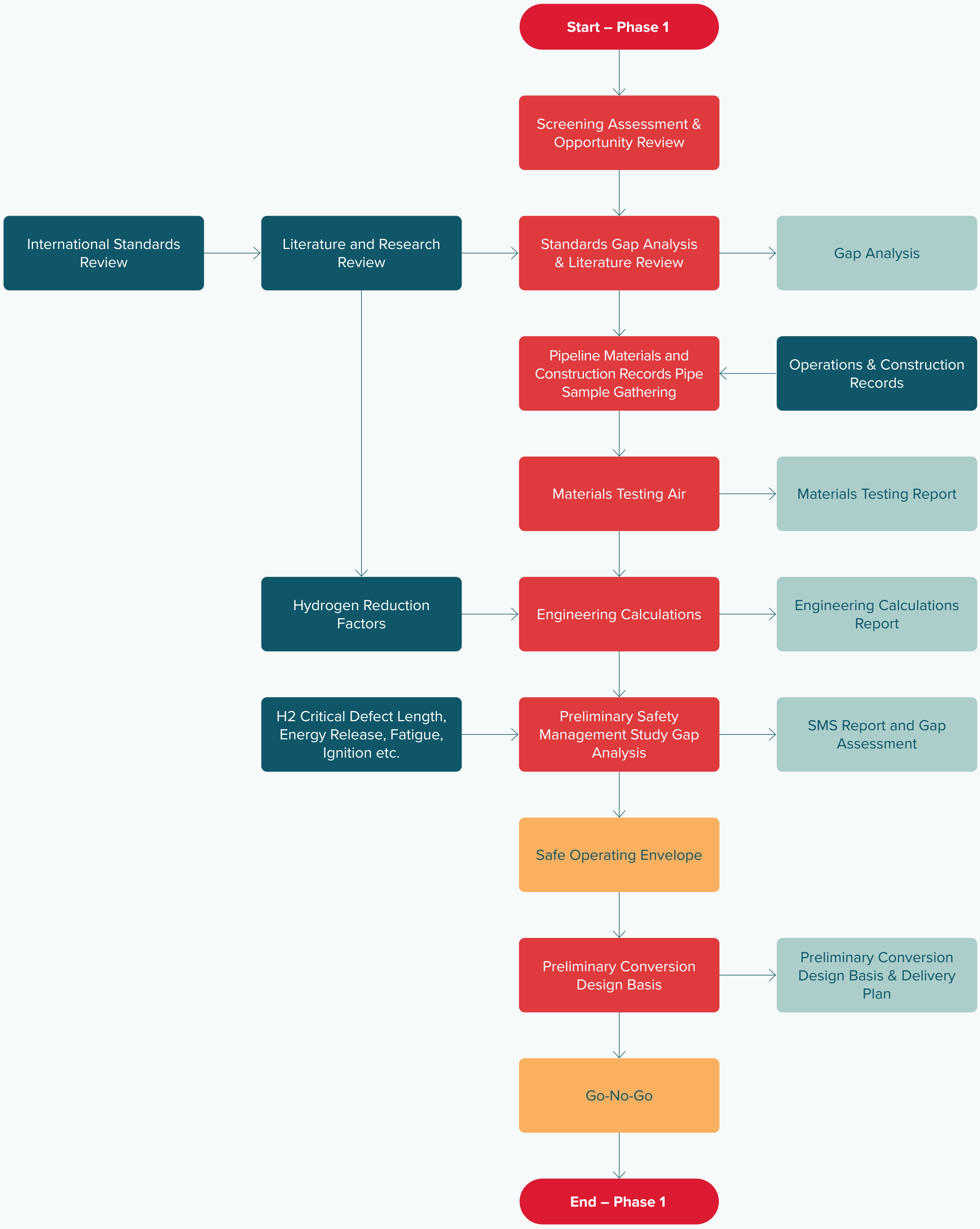

Figure 2: Phase 1 Feasibility Study activities flow chart

3 Project Approach

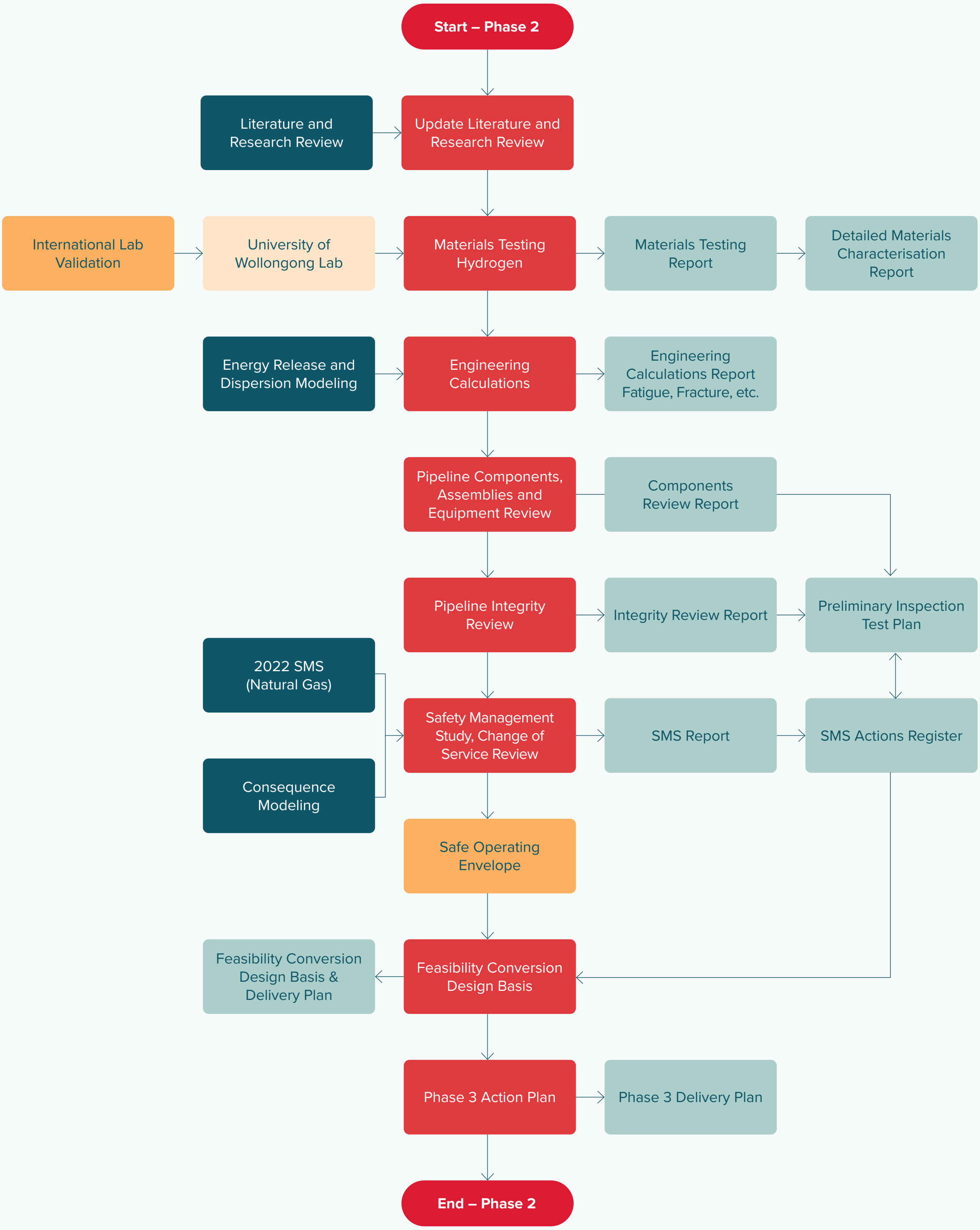

Figure 3: Phase 2 Feasibility Study activities flow chart

4 Feasibility Study Phase 1 — Test Program and Results

4.1 Scope and Objectives

The Feasibility Study Phase 1 objective was to review the PGP suitability for hydrogen service. As per the method set out in Figure 2 above, this Phase started with a detailed analysis of relevant literature, including applicable Standards and Codes.

Subsequently, this phase collated and reviewed the pipeline data relative to the line pipe steel properties and its current conditions after nearly 50 years of service.

A suite of tests was completed in air, at atmospheric pressure, to gain a good understanding of the material properties and provide a baseline for future hydrogen testing. The change in properties that results from hydrogen service was conservatively estimated from published test results on similar materials to establish baseline for engineering calculations.

Calculations were used in a safety management assessment and to support the definition of the safe operating envelope within which the capacity of the pipeline will be maximised. The study followed the AS 2885.6 Safety Management Process to thoroughly review the risks posed by hydrogen.

4.2 Codes and Standards

The Parmelia Gas Pipeline was originally designed to ANSI B31.8, most likely the 1968 edition. In 1991, it was reassessed to AS 2885.1—1987, and it is currently operated to the latest revision of AS 2885.3.

4.2.1 AS(/NZS) 2885 Series standards

AS 2885.0 Clause 1.2.2 states:

> *“The use of the AS (/NZS) 2885 series in circumstances listed below is not precluded, but is not expressly covered:*
>
> *(c) PIPELINE SYSTEMS transporting other fluids (e.g. slurries and non-hydrocarbon gas such as carbon dioxide).*
>
> *The application of the AS(/NZS) 2885 series to these circumstances requires special consideration.”*

Hence, special consideration will be made for hydrogen service. Clause 1.6.2, “departures from AS(/NZS) 2885 series Standards”, also provides guidance for applying AS 2885 standards outside their intended application:

> *“AS(/NZS) 2885 series Standards are not intended to prohibit the use of any materials, designs, methods of assembly, procedures or practices (items) that do not conform with specific requirements of the AS(/NZS) 2885 series, or are not mentioned in it, but do give equivalent or better results to those specified.*
>
> *The LICENSEE shall ensure the suitability of the item is determined against the fundamental principles of the AS(/NZS) 2885 series, and any additional requirements (including technical, quality, procedural, safety, maintenance) needed to satisfy the fundamental principles shall be developed. Prior to the item being used it shall be APPROVED.”*

AS 2885.3 provides guidance for design change assessment as a result of changes to approved operating conditions, including process fluid, and AS 2885.6 requirements of change of service SMS.

The design code for this project will be AS/NZS 2885, with ASME B31.3 nominated for pipeline facilities. To accommodate the specific issues relating to hydrogen application, the design will consider the “fundamental principles” of AS 2885.1, and apply considered technical assessment to accommodate the unique properties and impacts associated with hydrogen.

4.2.2 ASME B31.12

In many instances, design for hydrogen service will be achieved by complying to the American hydrogen pipelines and piping standard, ASME B31.12. However, there are some respects in which ASME B31.12 is considered to be irrelevant, incompatible with AS 2885 series, or where conformance is not possible. A gap analysis of ASME B31.12 has been undertaken as part of phase 1 of the Feasibility study.

An important pipeline design concept in ASME B31.12 is that there are two options to design for fracture control. Option A has reduced assessment requirements, but limits the design factor to 0.5. Option B allows higher design factors, but requires testing of the material properties in hydrogen.

4.2.3 Australian hydrogen pipelines code of practice

In parallel with the Feasibility Study, the Future Fuels CRC has managed the development of a new Code of Practice for hydrogen pipeline design (HPCoP). Though the code of practice has not been released at the time this report is published, the project team have had access to the draft of the code. Once the HPCoP is completed, it is expected that the detailed engineering of the project phase will adopt the code, and seek to comply with its requirements.

4.2.4 International codes

Hydrogen production and transportation is an emerging industry sector in Australia. Globally, the hydrogen production industry is undergoing significant change and anticipates significant expansion. As a result of this, many industry bodies are revising their codes and standards, and conducting research that may justify reduction of safety margins and improved efficiency. Future phases of the project will consider revised standards as they are released, including new revisions of ASME B31.12.

4 Feasibility Study Phase 1 — Test Program and Results

4.3 Test Program and Samples

Eight reclaimed pipe sections from the PGP were delivered to UoW. Three sections were selected for the test program, designated S1, S5 and S8. Section S8 is made of thin-wall pipe predominantly used in the PGP. S1 and S5 represent thick wall pipe.

Figure 4 presents an overview of the preparation of the sections prior to extraction of the test specimens. 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)[1]. The cutting diagram for section S8 is provided in Figure 5. Specimens shown in red are part of Phase 1. The others are part of Phase 2.

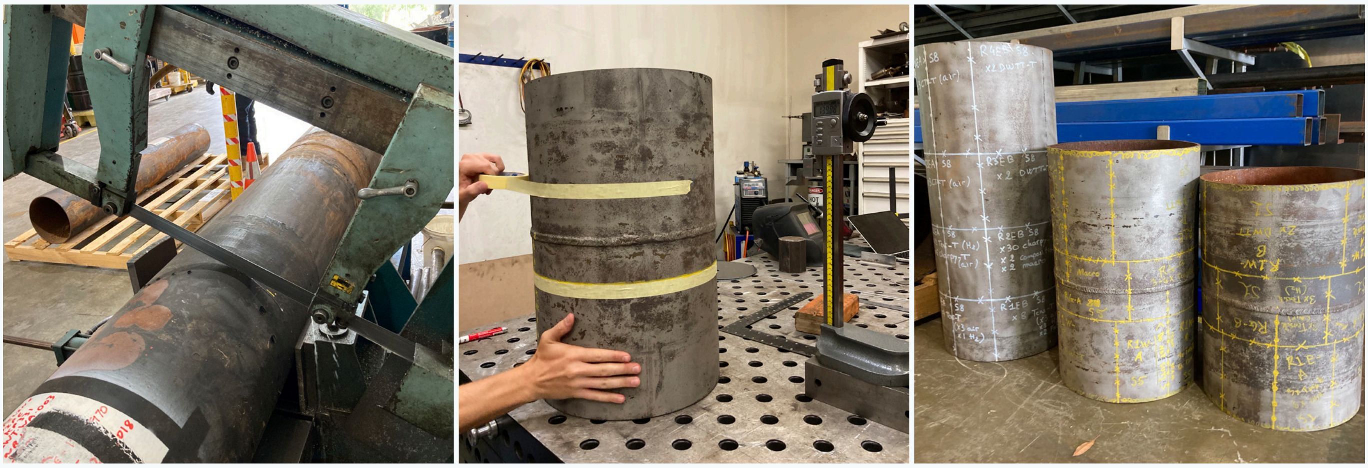

Figure 4: Preparation of the pipe sections for sampling. (a) Ring cut from section S8. (b) Marking and measuring of rings for water-jet cutting. (c) Completed markings for sections S1, S5 and S8.

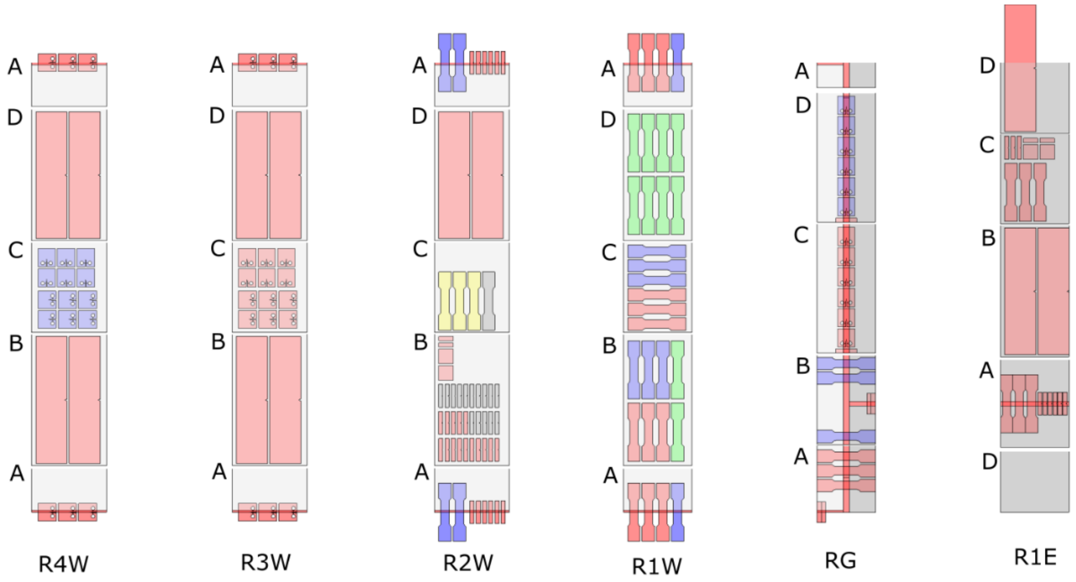

Figure 5: Sample cutting diagram for pipe section S8.

The test program for Phase 1 consisted of a general set of tests 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 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 (i.e., base metal (BM), heat affected zone (HAZ), weld centreline (CL)) and the requirements for the engineering calculations. Being the 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, 48 Tensile and 13 DWTT were conducted.

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

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[1] The East/West designation is arbitrary and should not be confused with the North South orientation of the PGP.

4 Feasibility Study Phase 1 — Test Program and Results

4.4 Results and Findings

4.4.1 Chemical Composition

The chemical composition of the pipes was determined by Optical Emission Spectroscopy (OES). The composition of this carbon-manganese X52 steel from 1970 generally complies with the modern specifications of API 5L PSL2 X52N pipes.

4.4.2 Tensile Tests

All tests were conducted on a universal testing machine to the requirements of AS1391:2020. In total 48 tensile tests were conducted for the base metal, seam weld, and girth weld. The transverse yield strength ($R_{t0.5}$) of the BM ranged between 392 MPa and 425 MPa, with S1 and S5 above 405 MPa and S8 below 400 MPa. The tensile strength (R_u) was between 534 and 568 MPa, with S1 and S5 below 550 MPa and S8 above that same value. The uniform elongation ($Ɛ_u$) was between 13 and 16%. The elongation at failure ($Ɛ_f$) between 20 and 32%. Figure 6 illustrates the results obtained from the specimens of S1.

All specimens fulfilled the requirements of modern API 5L PSL2 X52 specifications.

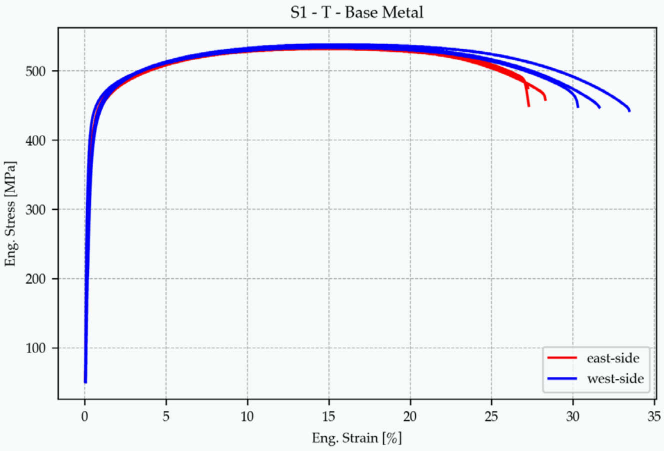


Figure 6: Engineering stress-stress curves from base metal transverse specimens from section S1.

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%. Failure of all samples 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.

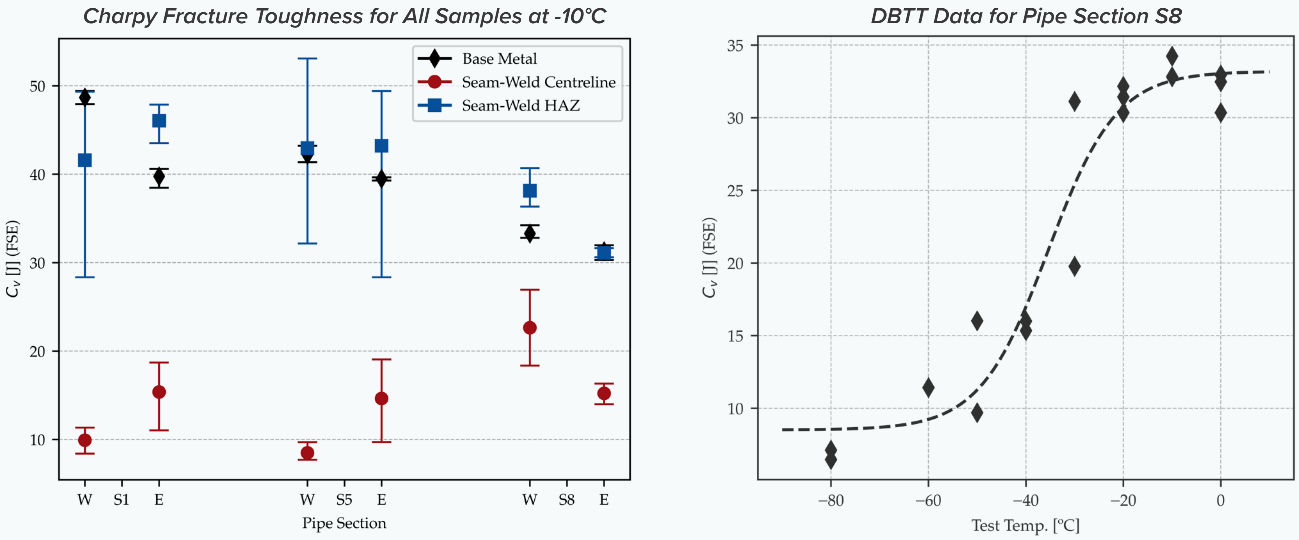
Specimens sampling the seam weld presented notably larger yield strength than the transverse BM specimens with a yield strength between 438 and 473 MPa. The tensile strength ranged from 517 to 610 MPa. API 5L PSL2 X52 specifications require the tensile strength of the seam weld to be at least 460 MPa. All specimens fulfilled that requirement.

4.4.3 DWTT and Charpy V-notch

Drop Weight Tear Tests (DWTT) were conducted in accordance with AS1330:2019[c]. At –10 °C, all samples were above 85 % shear area (SA), with all but one being at 100% SA. The ductile-to-brittle transition temperature was determined to fall between –40 and –30 °C for the thin-wall pipe S8-W.

Charpy impact tests were conducted according to ASTM A370 at -10 °C[d]. The samples were taken from BM and SW in the transverse-longitudinal direction (T-L). The samples were machined down to 4mm in thickness to match the thickness of the C(T) specimens used to assess the fatigue crack growth rate (FCGR) and fracture toughness (K_{JIc}).

The transverse CVN upper shelf energy at -10 °C ranged from 30 to 49 J for the base metal, and 8 to 27 J at the seam weld centreline (full size equivalent). The seam weld heat-affected zone absorbed between 28 and 53 J. Tests were conducted from -80 to 0 °C for samples from section 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 30 J for all specimens at or above -20 °C.


Charpy Fracture Toughness for All Samples at -10°C

DBTT Data for Pipe Section S8

Figure 7: FSE CVN toughness of BM, SW, and SW-HAZ for S1, S5 and S8 (Left), and DBTT curve for S8 showing toughness on upper shelf at >-20˚C temperatures (Right)

4 Feasibility Study Phase 1 — Test Program and Results

4.4.4 Fatigue Tests

Fatigue tests in air were conducted according to ASTM E647 using compact tension (C(T)) specimens[e]. Fatigue tests of C(T) specimens were successful, however, testing specimens from the GW-HAZ were more tedious due to residual stresses within the material. The crack growth rate was largest in the base metal when the crack was 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.m$^{0.5}$ 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 8 illustrates the results from the transverse specimens of S8-W in BM.

4.4.5 Fracture Tests

Rising displacement fracture tests in air were conducted on C(T) specimens in accordance to ASTM E1820[f] to measure the toughness JQ from which K_{JIc} can be derived.

Specimens from the pipe base 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 KJIc due to hydrogen can occur. The present results indicated the line pipe toughness in hydrogen is above the ASME B31.12 threshold (55 MPa.m$^{0.5}$). Figure 9 illustrates the result for an example toughness test.

Both longitudinal specimens sampling the pipe BM and the GW-HAZ demonstrated larger fracture resistance than the GW. 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 centerline toughnesses in the order of 75 MPa.m$^{0.5}$.

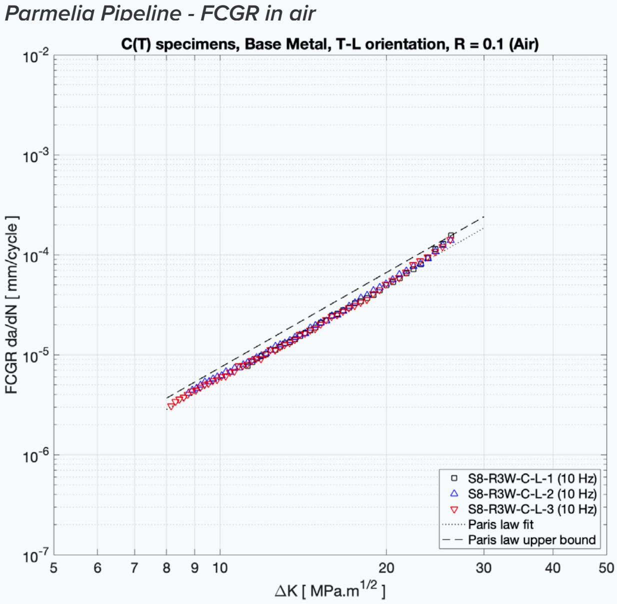


Figure 8: Fatigue crack growth rate in air for the transverse specimens from the base material of section S8W

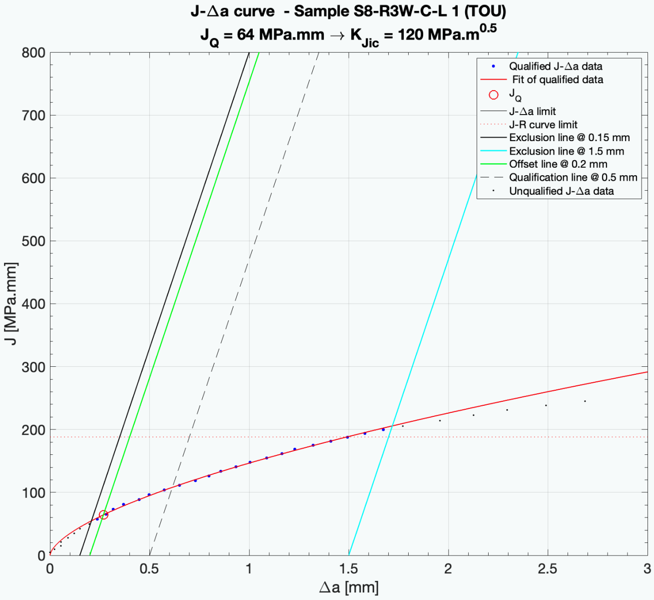


Figure 9: J-Δa curve obtained on a S8W transverse specimen (longitudinal crack) taken from the base metal (K_{JIc} of 120 MPa.m$^{0.5}$)

4.5 Engineering Calculations

To support the Safety Management Study (SMS) and determine the permissible operating window for the pipeline, calculations have been conducted using literature-based hydrogen impact factors. These were used to conservatively predict the impact of hydrogen on the existing design.

The three pressure cases and pipe material properties used through the various calculations are summarised in Table 2 and Table 3 below:

Case	Pressure	Source
Design Factor, FD = 0.4	4.5 MPA(g)	ASME B31.12 Option A for Location Class 4
Design Factor, FD = 0.5	5.6 MPA(g)	ASME B31.12 Option A for other locations
Hydrotest	10.6 MPA(g)	License PL1

Table 2: Pipeline calculation pressures

Variable	Value
Base Metal CVN (FSE)	30J at -10°C
Base Metal Actual Yield Strength	390 MPa
Base Metal Actual Tensile Strength	530 MPa
Seam Weld CVN (FSE)	10J at -10°C
Seam Metal Actual Yield Strength	430 MPa
Seam Metal Actual Tensile Strength	510 MPa

Table 3: Pipe material properties retained for the calculations (in air)

4.5.1 Fracture Initiation and CDL calculations

Fracture initiation conditions were assessed for the thinnest (5.56mm) and the thickest (7.92mm) pipe material. The Critical Defect Length (CDL) for the pipe at various toughness values (base pipe and weld) and with various internal pressures were analysed. In the calculations, it was assumed the toughness would halve in hydrogen service. Table 4 summarises the CDL results from the calculation for the thin wall pipe.

A comparison between the API 579 model [g] and the NG-18 [h,i] was performed. This comparison revealed that the overall form of the results was similar.

Case	CDL (mm)		
	4.5MPa(g)	**5.6MPa(g)**	**10.6MPa(g)**
5.56mm Wall Thickness			
High Toughness	164	125	44
30J BM-Air	150	119	44
15J BM-H2	128	104	N/A
10J SW-Air	114	93	39
5J SW-H2	91	74	N/A

Table 4: Critical Defect Length using NG-18 fracture initiation equation

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1. This is below the ASME B31.12 Option B limit of 55 MPa.m$^{0.5}$, giving a conservative fatigue life estimate.

4.5.2 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 max. 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[1]: 50 MPa.m$^{0.5}$

The results are summarised in Table 5. These results are based on significant assumptions, nevertheless, they show that even for the largest defects that can survive hydrotest, cycling in the order of 1.5 MPa on a daily basis may be permissible for a design life of 100 years at the current MAOP.

Case	Initial defect	Life with current cycling	Maximum Cycling for 100 year life
1	1.3 mm deep x infinite length (max hydrotest defect)	Historical cycling Hydrogen: 3,400 years Air: 119,000 years	2.1 MPa daily cycle Hydrogen: 100 years Air: 792 years
2	2.4 mm deep x 50.0 mm length (max hydrotest defect)	Historical cycling Hydrogen: 1,392 years Air: 62,056 years	1.5 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	5.3 MPa daily cycle Hydrogen: 100 years Air: 2,180 years

Table 5: Fatigue life from fatigue crack growth modelling.

4.5.3 Fracture Propagation

Fracture propagation is a risk on pipelines when a longitudinal fracture is able to grow so fast that the depressurisation due to the escaping gas cannot unload the crack.

In natural gas, decompression speeds are typically around 300 m/s, and ductile fractures propagate at similar velocities. Fracture propagation is assessed using the Battelle Two-Curve Method, which determines the required material toughness that will slow the crack sufficiently for fracture arrest to occur.

In hydrogen, a loss of pipe toughness is expected to increase the crack growth speed. At the same time, decompression wave-speeds of pure hydrogen increase significantly, typically about 3x that of natural gas. Due to these high decompression speeds, fracture propagation is not likely to be credible unless the pipe is fully brittle.

Due to these considerations, fracture propagation is considered controlled for the PGP when carrying pure hydrogen. This is also supported by the following high-level calculations.

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[j]. Generally, the arrest toughness was found to be highest at the design minimum temperature of -7°C.

Internal pressure	Pure methane	Pure hydrogen
4.5 MPa(g)	10.4 J	3.8 J
5.6 MPa(g)	14.5 J	5.4 J

Table 6: Minimum required ductile fracture arrest energy at -7 °C, using the BTCM.

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1. This is below the ASME B31.12 Option B limit of 55 MPa.m$^{0.5}$, giving a conservative fatigue life estimate.

4 Feasibility Study Phase 1 — Test Program and Results

4.5.4 Energy Release Rate and 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 different pressures. It can be seen from Table 7 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 maximum allowable operating pressure (MAOP).

Pressure	Natural Gas 4.7 kW/m2	Natural Gas 12.6 kW/m2	Pure H2 4.7 kW/m2	Pure H2 12.6 kW/m2
4.5 MPa(g)	244 m	149 m	235 m	144 m
5.6 MPa(g)	271 m	166 m	263 m	160 m

Table 7: Full-bore rupture radiation contours.

4.6 Pipeline Safety Management

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 SMS for the PGP H2 conversion project was assessed by workshop, with the following hydrogen impacts identified as requiring further 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.
- 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, venting operations, accelerated material fatigue, etc.

4.7 Pipeline Capacity Review (Safe Operating Envelope)

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 that was confirmed in the SMS is that the MAOP will be retained in future use.

A pipeline capacity review was completed. At a pressure of 4 MPa(g), the pipeline capacity is estimated to be about 20 to 50 TJ/day, (equivalent to 140-350 tonnes of H2/day) which results in 5 to 15 m/s flow velocity.

Initial fatigue calculations have indicated that the pipeline might safely be permitted to fluctuate by up to about 1.5 MPa per day, but that there will be necessary controls to prevent larger cycles.

The use of the pipeline for storage will be limited by permissible pressure fluctuations, therefore it is not an operational recommendation for PGP once converted to hydrogen.

5 Feasibility Study Phase 2 — Test Program and Results

5.1 Scope and Objectives

The primary aim of the tests undertaken in Phase 2 of this study was to identify the properties of PGP's pipeline materials when exposed to hydrogen gas, which will inform on the changes from the current natural gas service at pressures relevant to the pipeline design. Most of the specimens tested within Phase 1 were duplicated and tested in a high-pressure hydrogen atmosphere to quantify the effects of hydrogen embrittlement.

Other test data was used to support classification of the material against literature or Standards, or to infer properties via correlation.

Information gathered from the Phase 2 test program was used in the updated engineering calculations (refer to Section 5.4), providing confidence in the quantification of the safety margins. In turn, this provided input into the Safety Management Study (refer to Section 8) and determined the pipeline safe operating envelope (refer to Section 9), and Conversion Design Basis (refer to Section 10).

5.2 Test Program and Samples

Phase 2 carried on from Phase 1 by performing a more detailed microstructural analysis, and by characterising the fatigue and fracture toughness properties in a hydrogen atmosphere.

For tests conducted in a hydrogen atmosphere, the samples were exposed to a high-purity hydrogen gas (>99.999%) at varying pressures up-to and slightly above the MAOP of pipeline. All samples were tested at pressures between 5.6 and 6.0 MPa.

A round-robin testing arrangement was established with Sandia National Laboratories (SNL) in the USA to complement the C(T) fatigue and toughness tests conducted in gaseous hydrogen at UoW. SNL has a long history of testing in hydrogen conditions. The research conducted there has been widely used to establish our current understanding of linepipe steels' response to hydrogen atmospheres. Furthermore, the testing done by SNL assisted in validating the procedures in the newly established hydrogen lab at UoW.

5.3 Results and Findings

5.3.1 Metallurgical Characterisation

Detailed material characterisation was undertaken to expand the knowledge base on microstructural influence of hydrogen embrittlement in conjunction with mechanical and fracture testing results. Hardness mapping and microstructural examination have been performed for the 3 pipe sections, S1, S5 and S8.

5.3.1.1 Hardness Testing

Hardness tests were performed using an automated Vickers Hardness Tester. A spatial hardness map was obtained with a resolution of 0.5 mm between each probe location, following the AS 2205 Standard.

Figure 10 shows an example of hardness maps around Girth Weld and Seam Weld, respectively, for pipe section S8. Table 8 provides the statistical hardness values collected across the 3 pipe sections.

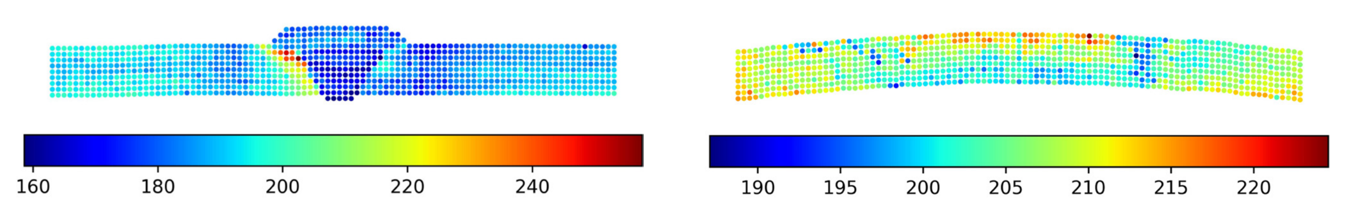

Figure 10: Hardness map for sample S8 girth weld showing softening of root and filler runs from subsequent weld passes and harder caping run HAZ (Left), Hardness map for seam weld for sample S8 showing softening around weld and HAZ from post weld heat treatment (Right).

All girth weld and seam weld average hardness results were less than 250HV, with a single S8 hardness value at the cap slightly exceeding 250HV. AS 2885.2 Cl 6.4.6 requires <250HV in sour service environments and <350HV in non-sour service. ASME B31.12 Cl. GR-3.10 requires <235HV 1.5mm below surface. All base metal, HAZ and girth welds meet the requirements of AS 2885 and ASME B31.12.

Location	Sample ID	Mean (HV5)	Max (HV5)	Min (HV5)
Girth Weld	S1-RG-D-GW	176.1	197.1	139.9
	S5-RG-A-GW	175.4	198.3	132
	S8-RG-D-GW	181.6	251.6	152.6
Seam Weld	S1-RG-D-SW	190.8	211.2	166.5
	S1-R1E-A-SW	189.1	207	175.2
	S5-R1E-A-SW	187.1	208	165.6
	S5-R1W-A-SW	194.3	211.6	172.3
	S8-RG-D-SW	205.8	224.5	187.1
	S8-R1E-A-SW	206.6	222.2	193.4

Table 8: Summary of Girth Weld and Seam Weld Hardness Results.

5 Feasibility Study Phase 2 — Test Program and Results

5.3.1.2 Microstructural Analysis

Samples used for the microstructural analysis showed that base metal microstructure for S1 and S5 primarily consists of ferrite and second phase pearlite, typical of carbon-manganese steel. The microstructures of the base metal of the two S8 pipes showed that quasi-polygonal ferrite was the dominant phase in S8 West pipe with a very small amount of pearlite, and that the S8 East pipe has a polygonal ferrite/pearlite structure.

The weld centreline and HAZ of samples S1 and S5 showed polygonal ferrite with pearlite in varied alignment and fractions through the weld explaining the lower hardness at the root and increased hardness of the cap. Sample S8 showed various ferrite phases with second phase pearlite with varied pearlite alignment and fractions through the weld. The presence of larger quantities of softer polygonal ferrite in the root explains the lower hardness. The HAZ shows presence of Widmanstätten, bainitic ferrite and martensite explaining the hardening in the weld HAZ.

Microstructures of the seam welds were similar, being polygonal ferrite and pearlite with the HAZ consisting of polygonal ferrite, quasi-polygonal ferrite and pearlite. The large polygonal ferrite grains and smaller pearlite fraction in the weld zone may explain the lower seam weld toughness (see Figure 11).

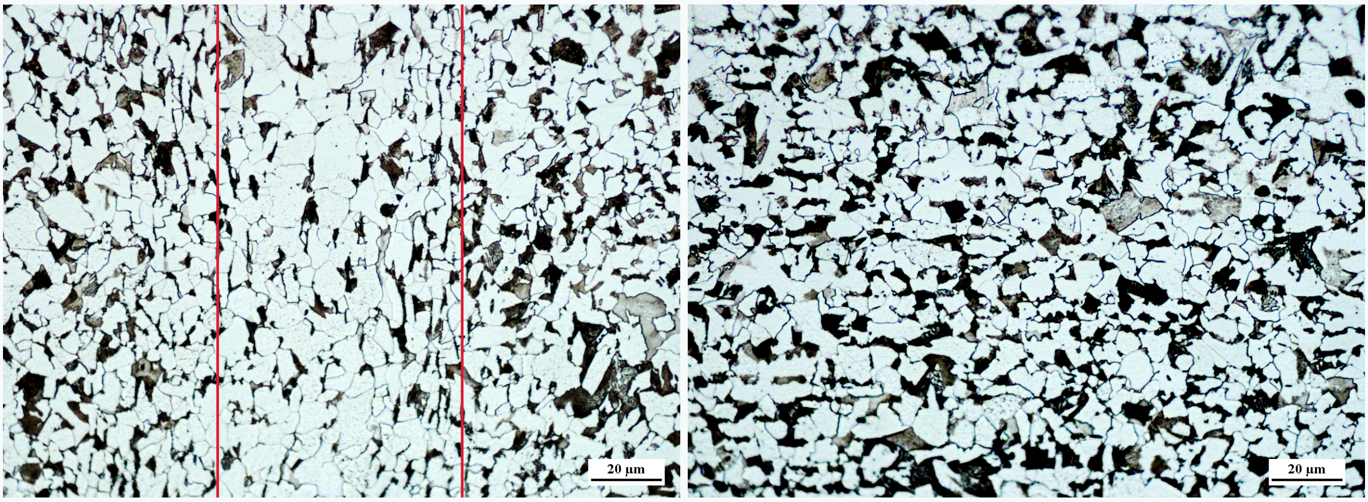

Figure 11: Optical micrograph of S8 seam weld centre P3 shown in red box (Left) and seam weld HAZ P10 at 500x magnification (Right).

The mean grain sizes were determined by intercept method from the optical micrographs using ASTM E112 [k], the grain sizes were also calculated from measurements. Non-mandatory ASME B31.12-2019 Appendix G provides guidance on microstructures for higher fracture toughness steels in hydrogen service recommending an ASTM grain size of 9 or finer. Measurements by intercept and EBSD for all samples determined average grain diameter were well below recommended diameter.

5 Feasibility Study Phase 2 — Test Program and Results

5.3.2 Fatigue and Fracture Testing Results

Fatigue and fracture testing is critical to the design of the pipeline carrying hydrogen gas because hydrogen's effect is most pronounced on these properties. The tests were conducted by the H2SAFE(TI) Lab at the University of Wollongong (UoW) and Sandia National Laboratories (SNL) in the USA on the base metal, girth weld, and seam weld material in all pipe sections. The test conducted by SNL comprised of a smaller set of reference samples from pipe section S8, testing the base metal and girth weld.

This section provides an overview of the test methods used and a summary of tests results from each lab on similar samples of pipe section S8 for comparison.

Fatigue testing was guided by the ASTM E647 standard [m], and fracture resistance testing was guided by ASTM E1820 [n]. The original notch was machined by EDM and a pre-fatigue crack was created at high frequencies in air. UoW measured the crack growth *in situ* using the compliance method, while SNL used the Direct Current Potential Drop (DCPD) technique.

For the tests discussed in this section, UoW performed the fracture toughness test after a pre-fatigue crack was initialed on three samples from pipe section S8. SNL used a combined fatigue and fracture resistance test described by San Marchi et al. 2010 [l], where a single sample was able to generate a FCGR curve along with a fracture resistance curve. SNL tested six specimens from pipe section S8.

At the conclusion of the tests, the samples were heat tinted to colourise the fracture surfaces, submerged in liquid nitrogen, and fully broken to allow for assessing the fracture appearance.

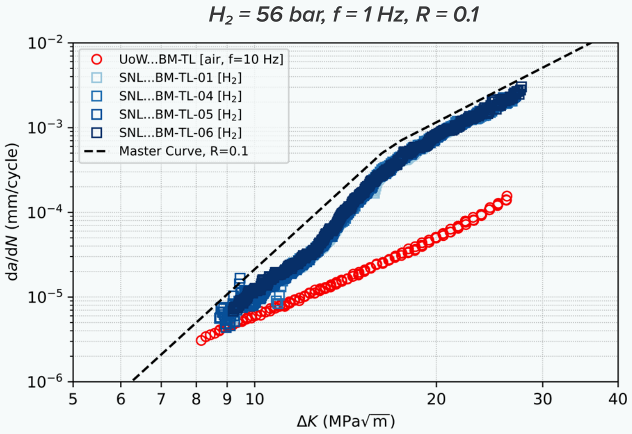

Figure 12: Fatigue crack growth rate in H_2 and air for the transverse specimens from the base material of section S8.

The pre-cracking phase targeted a a/W ratio of 0.29 with a K_{max} in the order of 9 $MPa.m^{0.5}$. The fatigue tests used an R-ratio of 0.1 at a frequency of 1 Hz. The fatigue crack growth was captured from a/W = 0.29 to 0.65, approximately. The fracture test extended the fracture to about a/W = 0.73.

FCGR results from test specimens TL-1, TL-4, TL-5, and TL-6 are shown in Figure 12. These were tested at the MAOP of the pipeline (5.6 MPa / 56 Bar), at a frequency of 1 Hz and R-ratio of 0.1. The test results for air are also shown for comparison. The repeatability is acceptable with trends in line with expectations from the literature. The reference curve from ASME Code Case 2938 [o] is also provided with a pressure correction as described by San Marchi in 2019 [p]. It provides a conservative prediction of the material performance at this R-ratio and pressure.

These results validate the engineering calculations conducted in Phase 1 of the project based on expected material behaviour.

Figure 13 provides the fracture resistance curve for samples tested by UoW and SNL. The qualified and conservative fracture K_{JQH} is at minimum 58 $MPa.m^{0.5}$ [1]. This represents a loss of ≤50% of fracture resistance compared to the cases conducted in air. The H2SAFE(TI) Lab at UoW found an average K_{JQH} value of 71 $MPa.m^{0.5}$, while SNL found an average value of 67 $MPa.m^{0.5}$. However, the lowest measured value from both labs provides the fracture resistance greater than the 55$MPa.m^{0.5}$ necessary to qualify for ASME B31.12. The lowest fracture resistance values were found in the base metal when compared to tests conducted in the girth weld and seam weld, indicating that the weld regions also surpass the minimum requirement.

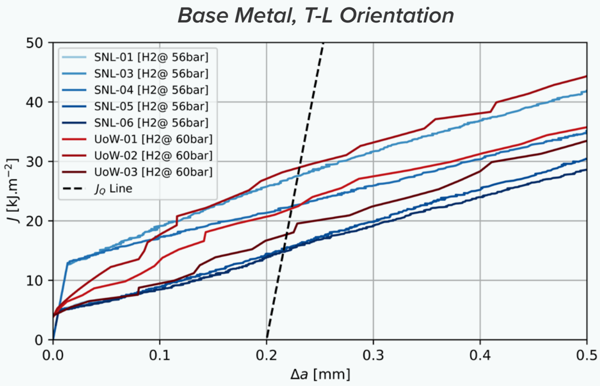

Figure 13: Fracture toughness test results as the typical J-R curve from the H2SAFE(TI) Lab at UoW and Sandia National Laboratories in the USA for samples in the T-L orientation from pipe section S8. ASME B31.12 Standard provides the fracture initiation requirements in terms of the stress intensity factor K_{JQ}. K_{JQ} is related to J_Q by $K_{JQ} = [J_Q E (1-v^2)^{-1}]^{1/2}$. J_Q is found in the graph above by the intercept between the J-R data and the dashed line.

In summary, key interpretations of the test results and conclusions are:

- The material appears to be typical of those within this class.
- The data was repeatable.
- The ASME Code Case 2938 fatigue model provides a conservative prediction of the base metal fatigue crack growth rate.
- The present data can be used for FCGR assessment.
- The critical stress intensity factor is above the minimum threshold of ASME B31.12.
- The present data can be used for fracture initiation and CDL assessment.

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1. The fracture resistance reported here is based on a measure of the initiation point leading to conservative values.

5 Feasibility Study Phase 2 — Test Program and Results

5.4 Engineering Calculations

Engineering calculations were completed using laboratory testing results to support the review of impacts of hydrogen on pipeline design for structural integrity, pipeline Safety Management Study, and to determine the safe pipeline operating envelope.

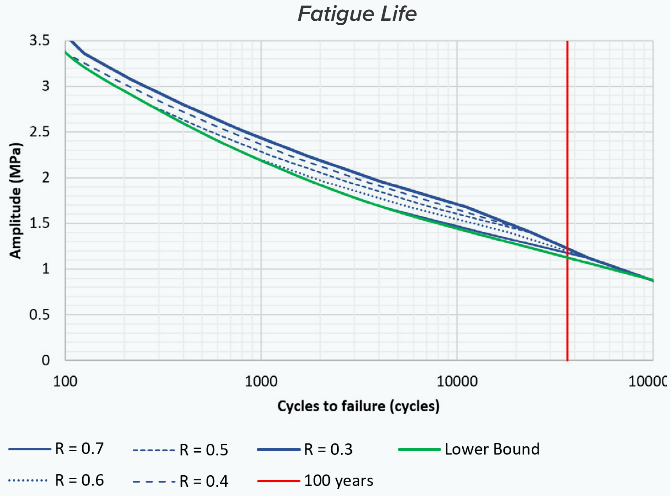
5.4.1 Fatigue Crack Growth

The purpose of the fatigue life calculations was to model the hydrogen assisted fatigue crack growth under the proposed operating conditions to determine the maximum cycling for 100-year life. The model was run until a defect reaches critical dimensions resulting in loss of containment. The 100-year life was chosen to represent a safety factor of 10x on a crack reinspection interval of 10 years.

Calculations were completed using the actual measured material data in hydrogen from the laboratory testing. The ASME Code Case 2938 FCGR model, validated by SNL on the PGP pipe materials, was used for the assessment. The initiating defect dimensions were a semi-elliptical crack 3mm depth x 40mm length, determined as a defect with high probability of detection using current inline crack detection tools.

The assessment was undertaken using API579[q] stress intensity formulae. The FCGR model was applied to the surface of the crack and the deepest point of the crack. Failure conditions were determined using API 579 applying the failure assessment diagram (FAD) method.

The calculations were undertaken on a range of loading cases (R-ratio) to develop a S-N curve for the initiating defect, allowing the maximum pressure cycle range for the pipe to be determined at 100-years daily cycling. Figure 14 shows the S-N curve for standard wall pipe with maximum pressure cycle range of 1.12MPa/day (20% MAOP) compared to the ~1.5MPa/day (25% MAOP) determined in the Phase 1 assessment.



A range of defect sizes were assessed at 100-years of daily cycling at 1.12 MPa. Figure 15 shows the initial defect sizes that would achieve the target fatigue life at the specified conditions (note that for features <30mm length the assessment terminated at 80% depth as described in API579). Results show that, for the 100-year life the critical depth is between 2 – 3mm (>35% wt.) which exceeds the detectable crack size dimensions of modern inline inspection tools. Finally, an analysis of infinitely long defects was undertaken at the 1.12 MPa pressure cycle amplitude which found a crack of 1.9mm depth has a life of 100-years.

In summary, based on daily cycling for 100-year life with 10-year crack detection in-line inspection interval, the recommended maximum daily cycling was 1.12 MPa (20% MAOP). Analysis found that defects of varying aspect ratios were detectable by ILI within the reinspection interval, and infinitely long defects less than 1.9mm (34% WT) have design life exceeding 100-years at the 20% pressure cycle.

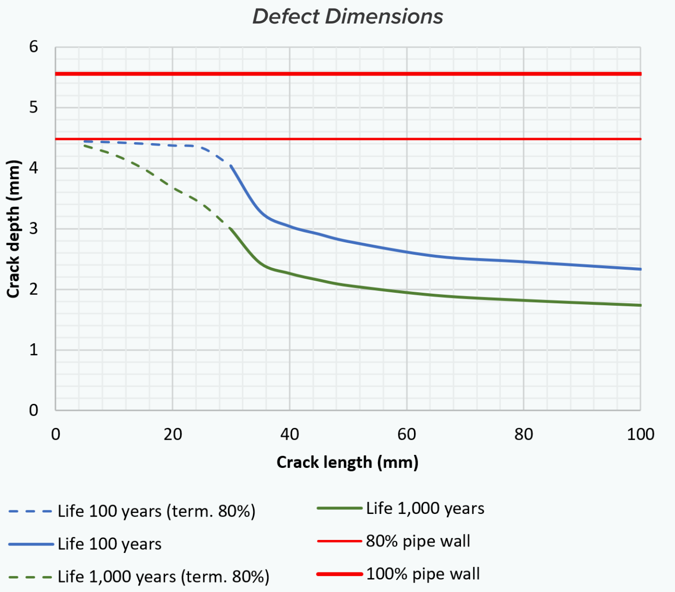


Figure 15: Analysis of defect sizes at 1.12MPa pressure cycle for 100 & 1000-year life.

5 Feasibility Study Phase 2 — Test Program and Results

5.4.2 Fracture Initiation and Critical Defect Length

Fracture initiation conditions were analysed for the material using properties measured in hydrogen. J-R curves were applied, and the material's actual stress-strain curve were also used for the sample S8W. An API 579 level 3 ductile tearing analysis was utilised for the calculations. The J-R curves were as follows:

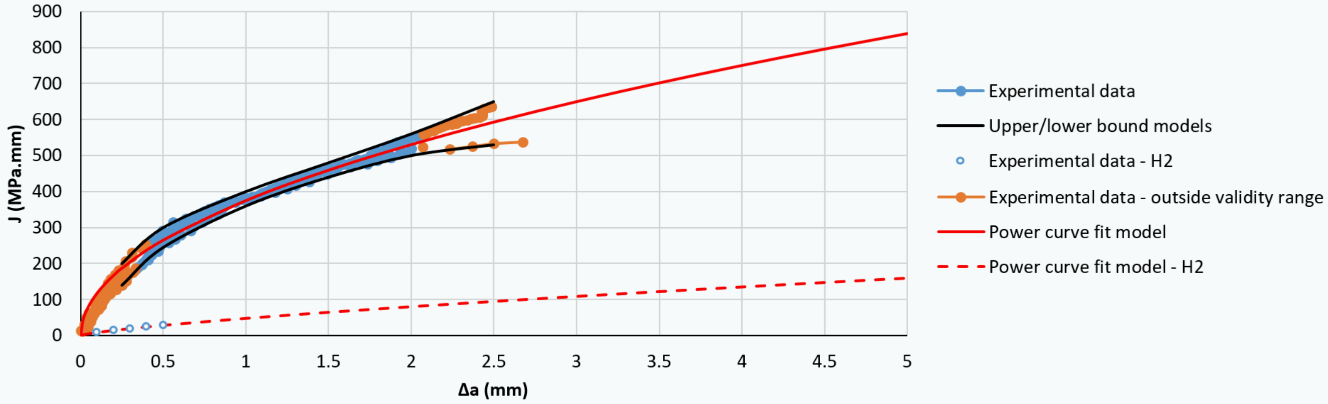


Figure 16: J-R curve for Sample S8W in air and hydrogen.

The critical defect length was analysed in detail for the pipe S8W, and then for other pipes. The critical defect length of the pipe was calculated as:

Wall thickness	5.6 mm	7.14 mm
Critical defect length – operation in H2	95 mm	153 mm
Critical defect length – Air / NG	122 mm	188 mm
Critical defect length – hydrotest	47 mm	81 mm

Table 9: Critical defect length calculation results for H2, Air and hydrotest using API579 ductile tearing analysis.

The results indicate that the critical defect length would have been less during hydrotesting than after embrittlement by hydrogen by a healthy margin.

In reality, no through-wall defects can survive hydrotest, so the hydrotest assessment ought to focus on part-through-wall defects. The calculation assessed part-through-wall defects to compare the critical dimensions during hydrotest to the critical dimensions during operation. This indicated that the through-wall results had provided an effective proxy for predicting the margin of safety on hydrotest.

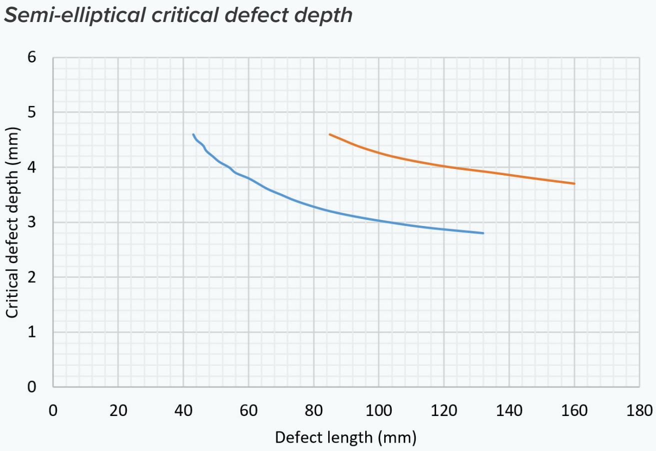

Semi-elliptical critical defect depth

Figure 17: Critical part-through-wall (semi-elliptical defect) dimensions.

6 Pipeline Integrity Assessment Review

6.1 Scope and Objectives

A review of integrity management and condition assessment records for the section proposed for conversion was undertaken. The objective was to identify the integrity inspections, assessments, and works to be completed as part of conversion detailed design to be included in the PGP Hydrogen Conversion Plan.

The integrity review included collation and review of existing pipeline integrity records including inline inspection, repair logs, corrosion growth rate assessment, and integrity assessment reports. A preliminary reassessment of ILI inspection datasets with consideration of potential hydrogen impacts was completed.

6.2 Review of Pipeline Integrity Management Plan

A review of existing integrity management planning documents identified initial recommendations for updates associated with conversion planning and introduction of hydrogen. The Pipeline Integrity Management Plan (PIMP) will need to be updated with section specific documents to address the requirements of the section integrity threats and operations and maintenance changes associated with hydrogen operation.

6.3 Impact of Hydrogen on Pipeline Condition Assessment

The Australian standard for pipeline operations and maintenance AS 2885.3 Section 9 defines the minimum requirements for management of pipe wall anomalies including assessment procedures. These current models do not address the impact of hydrogen on defect assessment methods. The European Pipeline Research Group (EPRG) commissioned a study to investigate damage assessment methods in the presence of hydrogen and provides guidance on assessment methods for typical pipeline anomalies including fatigue, dents, corrosion, and cracks [r]. ASME B31.12 also provides general guidance for some defect types.

6.3.1 Corrosion Metal Loss Assessment

ASME B31.12 GR-5.3.2 notes that remaining strength of pipelines can be determined in accordance with ASME B31G. The EPRG proposed method for assessing corrosion in pipelines transporting hydrogen applies a hydrogen reduction factor (HRF) to the steel pipe strength based on laboratory testing that has shown uniform elongation in hydrogen is reduced up to 50%. The EPRG approach was applied as a more conservative basis.

Figure 18 shows an example of the EPRG hydrogen reduction factor (HRF) applied to the corrosion assessment curve for PGP standard wall pipe.

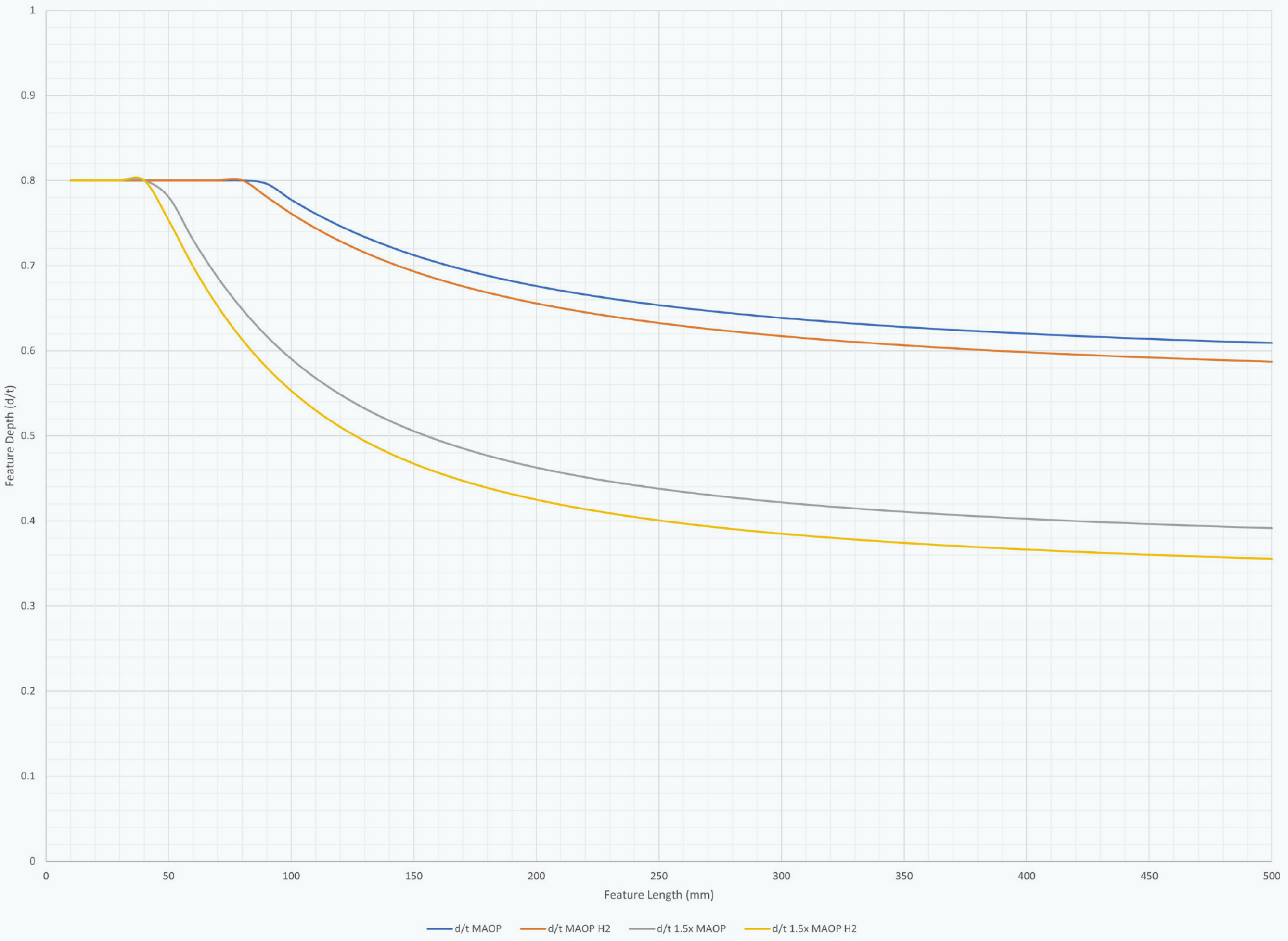


Figure 18: Example corrosion assessment curve applying EPRG HRF calculated from actual mechanical testing results.

6 Pipeline Integrity Assessment Review

6.3.2 Metal Loss Screening Assessment

Metal loss assessment was undertaken subject to the location of the feature in the pipe and the orientation of principal stresses for the feature type.

Corrosion growth rate (CGR) was determined based on multiple inline inspections (magnetic flux) analysis and verification results. For metal loss screening assessment, the P95 CGR was applied to all metal loss features.

Applying a P95 growth rate for 7 years, the current metal loss reinspection interval, no axial or circumferential metal loss features failed the repair criteria. Applying a sensitivity of 2x P95 CGR, some features failed the repair criteria at specified minimum properties. However, none of these features failed when actual material properties from the test program were applied. Results indicate no immediate metal loss features require investigation or repair as part of conversion planning works.

6.3.3 Dent Features

Geometry assessment of the pipeline section was done in 2011 and 2018. ASME B31.12 limits the depth of plain dents to 6%; this is further reduced to 2% for pipes operating above 40% SMYS and with diameter greater than DN300. For pipelines, B31.12 specifically requires removal of dents that affect the pipe curvature in the longitudinal direction or at girth welds[1]. B31.12 also limits strain to <2% in plain dents. Recent EPRG FEA assessment work supports these criteria. The B31.12 criteria were applied to the most recent geometry inspection results. The assessment results will inform future conversion works.

6.3.4 Strain Assessment

A bending strain assessment was completed for the conversion section in 2018. ASME B31.12 recognises the reduction in strain capacity of steel in a hydrogen environment by reducing plain dent strains to 2%, but that dents on welds are not permitted at any depth or strain. Applying the B31.12 criteria to the strain assessment determined that some previously acceptable strain locations with geometry features should be inspected and remediated as part of conversion works.

6.4 Crack-Like Features

The last crack detection inspection of the southern section of the PGP was undertaken in 2017. Inspection did not report any crack like anomalies in the pipe base metal. There were no features indicating of the presence of SCC or fatigue crack features. Some linear manufacturing anomalies were reported.

ASME B31.12 section GR-5.17 requires piping and pipelines be examined to verify no existing crack is approaching critical crack size. Critical crack size is calculated using API 579 FAD approach (as described above). The reported manufacturing anomalies were assessed as sharp crack like features using API 579 Level 1 assessment which found failure pressure exceeded hydrotest pressure.

6.5 Alternate Inspections

A material property and attribute verification in-line inspection is recommended. This assessment will assist to identify numbers of pipe populations and whether additional pipe samples and hydrogen environment testing is required to support the final engineering assessment. Hard spot detection inspection may be considered in the conversion detailed design inspection as well.

6.6 Proposed Inspection Program

Based on the review of existing integrity data and screening assessment for hydrogen impacts on pipeline integrity, an inline inspection program has been proposed for the next phase of the project.

6.7 Legacy Repairs

A review of repair records was completed for the conversion section. The review identified that several inspection digs had been completed and that a majority had resulted in recoating of the pipe or girth weld. Features previously repaired by coating require reassessment for change in service. In-situ inspection in the next phase will confirm whether any replacements are required as part of the conversion works.

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[1] ASM B31.12 S 2019 Section GR-5.6, PL-3.7.6 (c), Appendix D

7 Components Review

A components review was completed to assess the suitability of pipeline components, assemblies, and equipment within the PGP pipeline system for service in hydrogen.

The existing delivery stations are not proposed to be repurposed; rather new hydrogen ready receipt and delivery stations are likely to be installed as part of the project. The existing natural gas scraper station at the Alcoa Pinjarra station are proposed to be relocated to the end of the natural gas section of pipeline and two new hydrogen ready scraper stations are to be installed as part of the conversion project.

A review of the pipeline section for conversion was completed using current and legacy alignment sheets, construction drawings, and inspection reports to assess components, assemblies and equipment attached to the pipeline and subject to hydrogen service.

7.1 Valves

There are 3 original MLVs in the pipeline section: MLV-17, 18 and 19 and another post-construction MLV at the end of line facility. There are also multiple branch valves, both original and new, including vent and bypass valves immediately adjacent to the MLVs.

Typical valve specifications were API 6D or ASME B16.34. The type of valve are ball valves and plug valves. ASME B31.12 does not recommend different specifications for standard pipeline valves in hydrogen compared to natural gas.

It is almost certain that a comparable carbon steel specification to the pipeline would have been used for the valves (e.g. a carbon-manganese steel specification, such as ASTM A105). Therefore:

- The valves are generally considered suitable to be retained in hydrogen service.
- A further review of records to identify make and model of valves and detailed compatibility assessment, including seal and stem materials, is to be completed in Phase 3 of the project.
- Confirmation of valve condition and isolation is recommended before completing the conversion.
- Leak monitoring/surveying is recommended over the first few months of operation.

7.2 Fittings

The pipeline includes original fittings: tees, elbows, and flanges. Butt-weld fittings are designed to ASME B16.5 and 16.9, and MSS-SP-63 (which are permitted for hydrogen service under ASME B31.12). According to the pipeline licence, the materials of construction were ASTM A-234 WPB and ASTM A105, and considered suitable for hydrogen service. The pipeline also includes several post-construction modifications, mostly associated with relocated facilities, or hot-tap and stopple operations, also made from ASTM A105 carbon steel.

Where known, the gaskets used for the modifications are spiral wound stainless-steel gaskets with outer rings and graphite filler. For older gaskets, it is possible that compressed fibre forms could have been used. Both gasket types are considered acceptable for hydrogen service.

Good practice design philosophy is to minimise leak paths in hydrogen service with a preference for welded rather than flanged or threaded connections. Therefore, decommissioning of offtakes or branch connections should give consideration to cutting and capping as close as practical to the branch.

In summary:

- Existing flanges and fittings are generally considered suitable for hydrogen and can remain in service.
- A sample of fittings is recommended to be inspected and grade, strength / hardness and fabrication method confirmed before conversion.
- Leak monitoring of assemblies and hot taps containing flanged fittings is recommended over the first few months of operation.
- Modifications should preferably remove flanged or threaded connections to minimise leak paths, where the reduction in operability is acceptable.

7.3 Bends

From documentation available, it is expected that the original pipeline bends will be cold-bends, made per the requirements of the 1968 revision of ASME B31.8. As the pipeline can be inline inspected, it is certain that no wrought fittings are used in-line.

At pipeline relocations and replacements, it is possible that induction bends may have been used. For future phases it is proposed to:

- Assess bend radii from XYZ/Mapping inline inspection results, to confirm the types and locations of bends, and local thickness at the bends.
- Consider visual inspection of discrete bends as baseline prior to conversion.
- Aggregate XYZ/Mapping data and crack detection data to monitor changes and assess risk of cracking in bends during operations.

7.4 Other Components and Assemblies

The pipeline section also includes screw anchors and anode connections. These are not directly hydrogen-exposed and will not be affected by hydrogen conversion.

The pipeline section does not include any monolithic insulation joints (MIJs).

One pipeline anchor block has been identified in the pipeline conversion section. Typical anchor block construction consists of an anchor-flange, embedded in a large concrete block. Anchor flanges are simple solid metal components, and share the same assessment as the other pipeline fittings.

8 Safety Management Study

For Phase 2 of the Feasibility Study, a "Change of operating conditions SMS" was completed in accordance with AS 2885. The SMS addresses specifically:

- The effect of hydrogen on current threat assessments (November 2022 SMS), to reduce control effectiveness or increase threat consequences.
- New threats introduced by hydrogen.

8.1 Pipeline Failure Modes

Pipeline failure mode calculations were revised for the impact of hydrogen:

- Resistance to penetration is not expected to change significantly due to the introduction of hydrogen.
- The effect of hydrogen on the fracture initiation CDL has been discussed in detail in Section 5.4.2. The revised hydrogen CDL were used to determine excavator hole size for leak-rupture mode assessment.
- The effect of hydrogen on the fracture propagation resistance has been discussed in detail in Section 4.5.3. This toughness demand is sufficiently low that fracture propagation in the mainline pipe is considered not to be credible.

8.2 Consequence Modelling

Assessment of consequence of hydrogen failure modes for safety, supply and environment was undertaken:

- Radiation contours for leak and rupture were calculated (Section 4.5.4).
- In addition to thermal radiation, hydrogen has a higher flame-speed than natural gas and, subject to the conditions, a gas release may create an over-pressure wave more severe than a natural gas release. An SMS outcome was to further investigate the likelihood and consequence of over-pressure waves in pipeline releases.
- Hydrogen has a higher probability of ignition than natural gas, due to having lower ignition energy and broader flammability range in air. Consequently, the risk-assessment assumed a higher likelihood of ignition in a release event compared to natural gas.
- AS 2885 is primarily concerned with public safety, as well as public disruption caused by loss of supply. Due to the change in operation service and customer alternate hydrogen supply, this consequence was considered negligible.
- The environmental consequence of a release is negligible, as it was in natural gas service.

8.3 Location Class Assessment

Location class assessment was completed as part of the November 2022 natural gas SMS. The introduction of hydrogen in the PGP has a negligible impact on the calculated measurement length (refer to Section 4.5.4). Consequently, the currently defined location classes will not vary due to the introduction of hydrogen.

8.4 External Interference Threats

Hydrogen will not significantly change the threat profile of external interference, but hydrogen could impact the failure mode and consequence due to reducing the pipe material toughness and ignition probability:

- In metropolitan areas, approximately 90% of all excavator activities around the PGP utilise 1.5 to 5 tonne excavators for buried service installation and maintenance. Larger equipment (up to 30 tonne) is used for development projects and civil construction projects. Importantly, due to the sandy soils and easy digging conditions over the entire route, the excavators are almost exclusively fitted with flat buckets or general-purpose teeth.
- The soil types in the region are soft, so flat-edged sand bits will be used on HDD projects. These are unlikely to cause a pipeline failure, instead deflecting off the pipe and at most causing gouging or coating damage. Resistance to penetration is counted as an effective control.
- Vertical bores will be used for installation and relocation of power-poles, rural fence 'strainer' posts, billboards, electrified rail infrastructure and streetlights. In new developments, electrical infrastructure is buried. As such, the frequency of these threats is reduced.
- Cable ploughs were historically a significant threat, especially as NBN services were being installed around Australia. The threat was most significant where unobstructed cross-country installation was possible.

A detailed external interference threat assessment was completed as part of the SMS Workshop and reviewed for change of risk associated with hydrogen service.

8.5 SMS Findings

- The SMS considered available information about the integrity of the pipeline. Tolerance for anomalies on hydrogen pipelines may be reduced compared to natural gas pipelines. The review recommends a further program of inline inspection to complete the data set.
- It was found that hydrogen will impact several of the risk assessments. Though the frequency of the initiating event and the failure mode are generally unaltered, hydrogen releases are known to have a higher likelihood of ignition, and this caused an increase in the frequency of the potential consequences.
- A detailed review of threats found that there are appropriate means available to control the risks and reduce them to be As Low As Reasonable Practicable. The most significant risk to the pipeline that has been identified is from vertical drilling operations. It is recommended to install poly slabbing at strategic locations where this risk is higher.
- The Kwinana Industrial Area is congested and has a higher probability of external interference incidents. Therefore, it is proposed to consider strategic installation of slabbing, signage review, and a programme of landholder liaison.

9 Safe Operating Parameters

9.1 Design life

The section of the pipeline that is being converted under this project will be subject to a design life renewal. As required by AS 2885, a design life must be nominated for the new conditions. The design will be based on achieving a minimum 25 years' design life from recommissioning, with an economic life of 40 years. The next remaining life review is recommended after a minimum of 5 years of operation in hydrogen service (together with the integrity management review). This is based on ASME B31.12 Clause GR-5.2.1(b) recommendation for integrity review frequency.

9.2 Pressure

The pipeline MAOP is currently 5.6 MPa, 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.

The operating pressure of the pipeline has not been determined, and may be lower than MAOP. Two factors are relevant: Firstly, the system design may nominate to operate at electrolyser discharge pressures of 3 or 4 MPa, to eliminate the need for compression. Secondly, a reduction of MOP may be used to control pipeline integrity. The SMS has concluded that the pipeline can be safely operated at the current MAOP, but a pressure reduction will improve the margin of safety.

9.3 Temperature

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 natural gas composition. However, pure hydrogen has a negative Joule-Thompson coefficient, which means it will increase in temperature when depressurising across a pressure regulator or venting event. The current minima of -7°C and -15°C have an additional safety margin for pure hydrogen service, as 0°C would be acceptable.

9.4 Pressure cycling

The pipeline design is required to accommodate variations of flow conditions, resulting in variations in the pressure at various locations on the pipeline. Additionally, if the inventory of the pipeline itself is used to buffer differences between upstream and downstream flow-rates, the pressure will cycle with the pipeline inventory.

The permissible extent of pressure cycling is confirmed by conducting detailed fatigue capacity calculations (modelling of fatigue crack growth for a range of credible defects). Fatigue calculations from phases 1 and 2 have predicted that the pipeline might safely be permitted to fluctuate by up to about 1 MPa per day (20% MAOP of the pipeline) with a required crack reinspection frequency of 10 years, and that the design requires controls to prevent larger cycles.

If greater fluctuations are required, this can be achieved by reducing the pipeline maximum operating pressure, or by confirming the pipeline condition more frequently through effective use of inline crack detection inspection tools, or periodic hydrotesting.

9.5 Volume

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

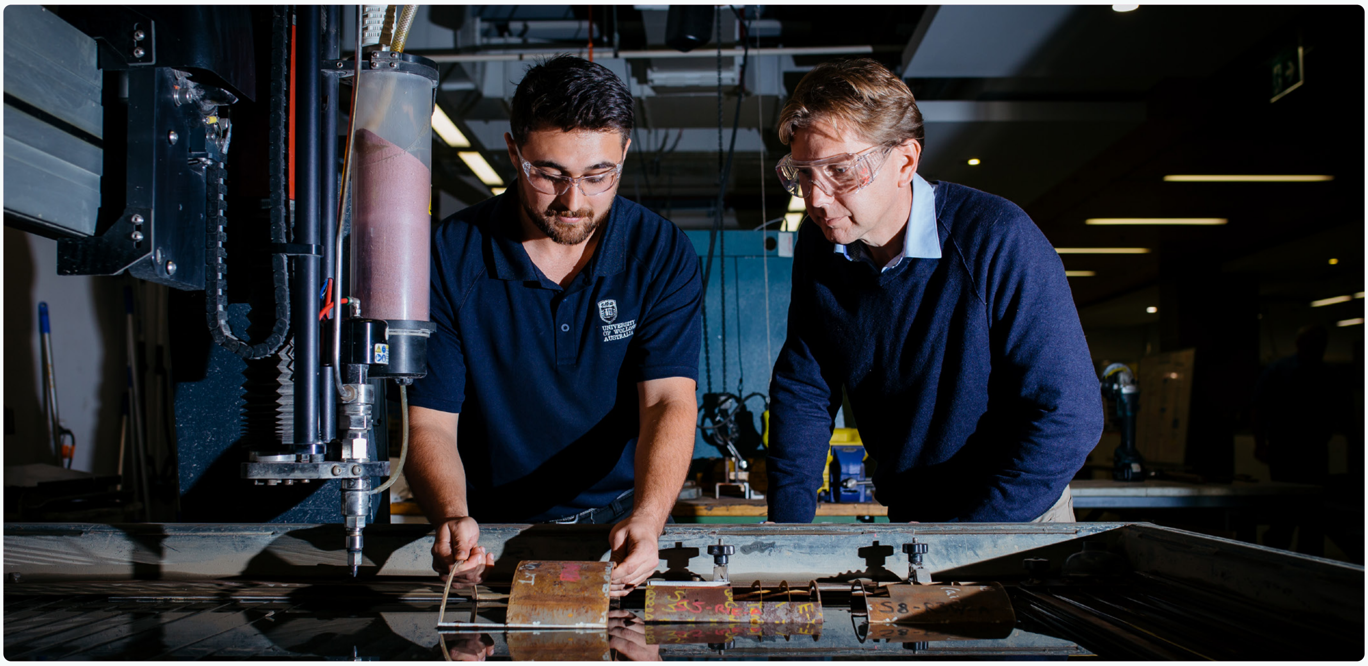
The use of the pipeline for storage will be limited by permissible pressure fluctuations. This is not a recommended operational use of the pipeline.

9.6 Flow capacity

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. Thermodynamic property differences between natural gas and hydrogen result in different pressure drop profiles and require higher velocities to achieve hydrogen throughput.
- Velocity. 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, the pipeline capacity is estimated to be about 20 to 50 TJ/day (equivalent to 140-350 tonnes of H2/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.



10 Conversion Design Basis

10.1 General

A pipeline conversion plan has been prepared for the project, the conversion plan outlines the future activities required for conversion of the pipeline and will be refined in the next phase to form a 'Basis of Design' for the pipeline. Specific actions are identified that are required to be addressed in future project phases.

The project will re-use the buried pipeline, but will replace end-of-line facilities where determined to be required by fitness for service assessment. At this stage, it is assumed that the two main-line valve sites (MLV18 and 19) will be retained.

The project features the following pipeline assemblies:

- Pigging Assemblies
- Venting Assemblies
- Pipeline Pressurisation Assemblies
- Mainline Valve Assemblies
- Branch connection assemblies.

The design code for this project will be AS/NZS 2885.1, with ASME B31.3 nominated for pipeline facilities. To accommodate the specific issues relating to hydrogen application, the design will apply considered technical assessment to accommodate the unique properties and design aspects of hydrogen. In many instances, design for hydrogen service will be achieved by complying to the American hydrogen pipelines and piping standard, ASME B31.12.

10.2 Licence and Approvals

The Parmelia Gas Pipeline is currently licensed under the Petroleum Pipelines Act 1969 (WA), and subordinate regulations. The Act and regulations are administered by the Department of Mines, Industry Regulation and Safety (DMIRS).

The project will require a modification and extension of the pipeline license. Currently, no specific regulatory framework for hydrogen pipelines exists. Therefore, ongoing engagement with the regulator is required to obtain approval to operate under the proposed conditions. In addition, active steps are required to ensure there is a pathway through the existing regulatory framework that enables petroleum pipelines to transport 100 percent hydrogen.

10.3 Pipeline Fluid

Under changed pipeline operation the pipeline is expected to transport pure hydrogen, being >99.9% hydrogen. This is to be confirmed in the next phase of the project, together with a decision on potential odorisation.

10.4 Safety in Design

Safety is a central objective of design. Technical regulators in Western Australia 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.

Consequence modelling for energy release rate and radiation contours are a key activity for characterising the severity of safety consequences from pressure piping. The release modelling will be refined in Phase 3. This may include full scale testing to support the consequence modelling approach and assumptions.

10.5 Pipeline Design

The compliance matrix to AS 2885.1 will be updated for the final design. The compliance matrix will identify how the design meets the mandatory clauses of AS 2885.1. The standard is also not intended to apply to hydrogen, so in some cases the compliance assessment will require demonstration that the pipeline design meets the intent of the standard, as per AS 2885.0 Clause 1.6.2. This will be achieved through a combination of fundamental engineering, and appealing to other relevant standards, primarily the latest revision of ASME B31.12.

The existing pipe design has been reviewed by a systematic gap analysis against hydrogen pipeline and piping design standard, ASME B31.12. Overall the pipeline is found to comply with the majority of the requirements of the ASME B31.12 Option A fracture control design pathway, detailed in section PL-3.7.1(b)(1) of the standard. This is due to having a low design factor and being constructed from grade X52 material. The gaps with ASME B31.12 were assessed in the pipeline SMS.

10.6 Pipeline Components

Valve and fitting materials, polymers, gaskets and other components were assessed for hydrogen service in Phase 2. No significant compatibility concerns were raised, and no components required to be replaced. Additionally, only a few components will be retained, because the pipeline facilities will mostly be replaced.

10.7 External Interference Protection

The pipeline is designed with protections in place to mitigate or prevent loss of containment from external interference. The Phase 2 SMS identified that the failure modes of the pipeline and the effectiveness of these controls are not significantly altered by the presence of hydrogen.

However, in the case of uncontrolled threats, the likelihood of ignition is increased, which increases the overall risk profile and may justify additional controls. These would commonly consist of increased signage, slabbing, more frequent patrols, additional liaison with third parties or, in the most severe cases, fencing the pipeline easement. This will be tracked through the pipeline SMS.

10 Conversion Design Basis

10.8 Pipeline Condition Assessment

The condition of the existing pipeline was reviewed as part of the Feasibility Study to determine any required repairs and to review the remaining life of the pipeline. The next phase of the project will complete a detailed change of service fitness for service (FFS) review of integrity anomalies on the pipeline based on planned 2023/2024 ILI inspection data.

10.9 New and Modified Facilities

New pipeline and pipeline facilities will be designed for the same operating parameters as are confirmed for the existing mainline. New construction for the pipeline (line-pipe / induction bends) will utilise materials of strength grade X52 or less. Materials and components used in new pipeline facilities and piping assemblies will comply with the standards listed in ASME B31.12. Welding of the pipeline shall be to AS 2885.2, with reference to the supplementary requirements of ASME B31.12.

The pipeline modifications include the following[1]:

- The pipeline will be fitted with new hydrogen compatible pig launching and receiving facilities.
- The pipeline assemblies vent design shall be modified to accommodate facilities for venting hydrogen from the pipeline.
- The isolation plan for the PGP for hydrogen service will be revised by the project in Phase 3. Modification requirements to MLV for actuation and excess flow valves shall be determined in conjunction with detailed SMS study.
- End of Line facilities, with hot-tap connections are to be replaced by new start-of-line facilities as part of conversion project.

10.10 Commissioning

Modelling is required to develop a commissioning procedure which, as needed, may use in-line-inspection technologies, section-by-section commissioning, and possibly dilution purging (rather than displacement purging, which is most common for pipelines). A pipeline cleaning plan is to be developed as part of the procedure.

10.11 Operational Readiness

The pipeline management system (PMS) will be updated in accordance with AS 2885.3 Clause 2.1 for hydrogen operation and with consideration of ASME B31.12 guidelines and SMS actions. The PGP PMS for the southern part of the pipeline will require revision and may be separated out from the existing natural gas PMS. The following operational documents will require modification or update before conversion commissioning:

- Operation and Maintenance procedures
- Pipeline isolation plan
- Pipeline integrity management plan
- Emergency response plan.

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[1] It is expected that new pigging assemblies need to be built and that modifications are required to the current MLV and venting assemblies. These replacements and modifications constitute the main cost items of the pipeline conversion.

11 Conclusions and Outlook

11.1 Key Outcomes

The Feasibility Study of the proposed conversion of the southern 43km section of the PGP to transport pure hydrogen has been successfully completed. The project tested representative samples of pipeline materials in a hydrogen environment at conditions representing pipeline operation, and determined the steel could deliver satisfactory performance to provide a safe operating envelope at 5.6 MPa MAOP with pressure cycles limited to 20% MAOP (daily) and 10-year maximum in-line re-inspection interval.

Testing has confirmed the pipeline and proposed design intent generally meets the requirements of ASME B31.12 Option A (prescriptive design methodology) with steel grade and design factor is generally compliant with requirements. Conversion design evaluation has utilised the intent of Australian pipeline standard, AS 2885 for risk-based design, with reference to ASME B31.12 to address hydrogen specific design requirements not addressed in the Australian standard.

As the pipeline is 50-years old, and has limited design and construction records, a detailed evaluation to confirm the performance of the pipeline steel in hydrogen has been completed to provide assurance of steel performance in hydrogen service.

Detailed design calculations were performed using material properties developed in hydrogen environment testing to assess the change in key pipeline parameters. These calculations were used to complete an integrity review assessment that re-evaluated current pipeline integrity data and historic repairs, and a change of service safety management study to AS 2885.6.

The integrity review has confirmed inspection and repair requirements for the pipeline in hydrogen service and was used to define the inspection and test requirements required for change of service.

The change of service SMS confirmed the pipeline threats are generally unchanged from the change in service fluid, however the consequence of threats is modified.

Engineering assessments and associated actions including design calculations, components and assemblies' materials compatibility review, integrity review, and SMS have been collated and a feasibility level conversion plan and design basis prepared, including an action register, which will be addressed in the next phase of the project.

11.2 Outlook

Phase 3 of the project is planned to take 18-24 months. At the conclusion of Phase 3, it is expected that all technical assessments to support the conversion, licence and regulatory amendments, and safety and risk management will be completed and scope of work for physical modifications and changes will be documented. The delivery phase, to be completed post phase 3, will involve the physical site works for modifications and installation of new facilities for the conversion of service.

Inputs to phase 3 will include hydrogen supply and delivery requirements based on customer needs. This will include information on supply and delivery pressure, fluid composition, and hydraulic operating profile in support of operating envelope assessment.

Key activities in Phase 3 will include the in-line inspection to collect material property attribute verification data to determine if further sampling and hydrogen environment testing is required for final engineering calculations. During ILI inspections, updated integrity and condition inspection data will be collected to support a detailed hydrogen change of service integrity assessment (i.e. fitness for service assessments).

To support updated engineering calculations, the requirement for full scale testing will be assessed to support failure mode and consequence analysis. If suitable data is unavailable in research, literature, or ongoing industry projects, full scale testing will be undertaken to provide data in support of consequence modelling.

In addition to potential full-scale testing, in-field inspections will be completed to validate in-line inspection results and undertake physical inspections of the condition and properties of components and the original construction, including: Girth welds, Cold field bends, MLV's and associated assemblies, and Hot taps.

Engineering calculations, in-field inspections, and further testing will be used to support:

- Updated engineering design calculation package
- Updated consequence modelling (including heat release, overpressure, and dispersion modelling)
- Isolation plan update including assessment of isolation requirements and vent and blow down equipment (for SMS)
- Update to fracture control plan
- Updated component, equipment and assemblies' compatibility assessment
- Updated Integrity assessment
- Change of Service FFS assessment
- Detailed SMS and pipeline HAZOP
- Inspection operation test plan for conversion

To support licence and regulatory discussions for licence amendment, a conversion design basis and detailed inspection, repair and modification plan will be developed. The design basis will identify all modifications required to the pipeline and the new facilities and assemblies to be installed on the pipeline as part of the conversion works. These are expected to include:

- Pipeline section separation and isolation
- New hydrogen section scraper stations
- MLV modifications
- Pipeline vent modifications
- Hydrogen production facility tie-in facility
- Delivery station facilitie(s)

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