Business Case – Capital Expenditure

Evaluating and mitigating hydrogen safety and integrity risks on the VTS

Business Case Number 200

1 Project Approvals

BUSINESS CASE – PROJECT APPROVALS	
Prepared By	Harriet Floyd, *Manager Project Development, Innovation & Assurance, APA Group* Sheila Krishnan, *Manager Capacity Planning, APA Group*
Reviewed By	Mark Fothergill, *General Manager Infrastructure Engineering, APA Group*
Approved By	Kevin Lester, *Group Executive Infrastructure Development, APA Group*

2 Project Overview

BUSINESS CASE – PROJECT OVERVIEW	
Description of Issue/Project	• As identified in the Victorian Government's Gas Substitution Roadmap published in July 2022, hydrogen is expected to play a role in the journey to net zero. This is consistent with the views of the Commonwealth Government (as outlined in the Australian National Hydrogen Strategy) and international bodies such as the International Energy Agency. • Amendments to the National Gas Law are underway to support hydrogen blends, and other renewable gas blends being brought within the national energy regulatory framework. • As Victoria transitions to net zero, hydrogen and other renewable gases are expected to play a role in this transition. Hydrogen embrittlement poses a significant risk for existing steel networks, should hydrogen enter the gas network. • This project is proposed to quantify the risks to safety and integrity of the existing pipeline material and facilities caused by the introduction of hydrogen, and identify any actions required to mitigate the risks for the VTS network. • When a steel pipeline is exposed to high pressure hydrogen (blended or 100% H_2), hydrogen is absorbed into the steel and degrades the material properties. This phenomenon is known as hydrogen embrittlement. The principal effects are an increase in fatigue crack growth rate, a reduction in fracture toughness and a reduction in ductility of the steel. This deterioration of steel properties will lead to premature degradation and failure of pipelines with unsatisfactory microstructures. • Australian Standard AS 2885 requires such risks be investigated and managed to as low as reasonably practicable (ALARP) for members of the public, our customers, and our staff. Mitigations of this risk could include: o limiting pressure cycling, o reducing the maximum allowable operating pressure, o replacement of a pipeline or o Measures to prevent hydrogen from entering a section of pipeline. • The VTS is a complex interconnected network, and gas flow paths for hydrogen will be dependent on where the demand for gas is. Starting or stopping power stations or compressor stations disrupt normal flow-paths. Flowpath complexity means that hydrogen blending will impact more pipelines than in a point-to-point pipeline system.

<table>
<tr><td></td><td>- The purpose of the proposed pipeline safety and integrity assessment is to obtain quantitative test data that allows APA to demonstrate how the VTS network can be operated once hydrogen is introduced, including any changes required to current operating parameters to mitigate safety and integrity risks, and any upgrades required for pipeline facilities associated with safety, integrity, and compliance.</td></tr>
<tr><td>Options Considered</td><td>The following options have been considered:
- Option 1: Do Nothing
- Option 2a: Technical assessment of 39 pipelines, including materials testing and facilities screening, undertaken over 5-year period
- Option 2b: As per Option 2a, undertaken over 10-year period (spanning two access arrangements)
- Option 3: Reduce operating pressure of VTS to minimise hydrogen embrittlement impacts. Technical assessment of nine pipelines to confirm ability to maintain existing operating pressure to mitigate risks of reduced capacity / supply to Ballarat region. Includes reconfiguration of Brooklyn compressor and installation of pressure regulators to restrict gas flows.
- Option 4: Development of new hydrogen network without repurposing existing infrastructure</td></tr>
<tr><td>Estimated Cost</td><td>Option 2b: $37,861,536 undertaken over a 10-year period.

The proposed capital expenditure over 2023-27 is $18.9 m ($2022) as shown below.<table><tr><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>Total</th></tr><tr><td>3.8</td><td>3.8</td><td>3.8</td><td>3.8</td><td>3.8</td><td>18.9</td></tr></table></td></tr>
<tr><td>Consistency with the National Gas Rules (NGR)</td><td>The proposed expenditure complies with the new capital expenditure criteria in Rule 79 of the NGR because:
- it is necessary to maintain the safety of services and maintain the integrity of services (Rules 79(2)(c)(i) and (ii)); and
- it is such as would be incurred by a prudent service provider acting efficiently, in accordance with accepted good industry practice, to achieve the lowest sustainable cost of providing services (Rule 79(1)(a)).</td></tr>
<tr><td>Stakeholder Engagement</td><td>- We have sought feedback from customers through APA's VTS AA Roundtable sessions, as well as stand-alone hydrogen information sessions.
- VTS stakeholders acknowledge that there is a need to quantify the impacts of hydrogen embrittlement, should hydrogen be injected into the VTS. However, there was concern raised about the lack of clarity as to the timing of hydrogen projects, and probable locations for injection into the VTS network.
- APA acknowledged the uncertainty but contended that, to keep options open for hydrogen as part of the future energy mix, it would be prudent to start testing for safety and integrity during 2023-27.
- The primary concern raised during the stakeholder consultation process was how the technical assessment would be funded and the impact to consumer tariffs.
- In response to stakeholder submissions and AER draft decision we have reassessed the study options in this revised business case and propose to undertake the study over two regulatory periods, and to depreciate the study over the life of the pipelines.
- APA's tariff modelling estimates that the bill impact of this revised assessment is less than 20c per year for domestic customers[1].</td></tr>
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[1] This tariff modelling assumes 30-year average life of the pipe consistent with APA's accelerated depreciation proposal.

3 Background

The Australian energy industry is undergoing a significant transition in response to climate change and the transition to a net zero emissions future. This transition will not be without challenges, as demonstrated recently by the market suspension by AEMO in response to soaring prices. Anna Collyer, AEMC & ESB Chair put it bluntly in her latest speech: "Before the market suspension, hydrogen was important. Now? I won't hesitate to call it urgent."[2]

In 2022, the Victorian Government released its Gas Substitution Roadmap[3]. The Roadmap presents several scenarios that explore how the gas sector might reach net zero emissions and identifies that electrification, hydrogen and biogas are all expected to play a role in the decarbonisation of gas infrastructure. This is consistent with the views of the Commonwealth Government (as outlined in the Australian National Hydrogen Strategy) and international bodies such as the International Energy Agency.

Further the 2022 AEMO Gas Statement of Opportunities (GSOO) [4] and Victorian Gas Planning Reports (VGPR) [5] identified hydrogen scenarios alongside biogas and other renewable gas pathways to decarbonise, and that there may be a greater role for these alternative gaseous fuels within the gas system. For a renewable gas market to succeed, Australia needs a supportive regulatory framework and technically capable infrastructure.

The introduction of hydrogen into the gas network has gained pace over the past 12 months; Following a request from Energy Ministers, in October 2021 the Australian Energy Market Commission (AEMC) commenced a review of the National Gas Rules and National Energy Retail Rules to determine what changes are necessary to include low-level hydrogen blends and renewable gases in regulatory frameworks. The AEMC published a draft report in March 2022 outlining draft recommendations for rule changes that will support hydrogen and hydrogen blends being supplied to customers and expects to publish a final report on 8 September 2022.

In October 2021 the AEMC also initiated a rule change process for the National Gas Rules applying to the Victorian Declared Wholesale Gas Market (DWGM). This will assess a request made by the Victorian Minister for Energy, Environment and Climate Change that seeks to enable that market to recognise distribution connected facilities. These facilities may include hydrogen and renewable gas facilities as well as others such as storage.

In addition, jurisdictional officials are conducting a related review to identify amendments for the National Gas Law and National Energy Retail Law. The Australian Energy Market Operator (AEMO) is carrying out a review of the relevant gas market procedures to make amendments that will support the use of low-level hydrogen blends and renewable gases.

3.1 Decarbonising the Victorian gas network

Victoria's journey to decarbonise the gas network is in its early stages, and there remains a significant number of unknowns including scale, speed, and cost of electrification; the economics of hydrogen and how quickly the technology cost curve will come down; and the pace of uptake and scalability for other natural gas alternatives such as bio-methane.

Despite there being significant support for electrification of homes, a recent report published by Frontier Economics[6] showed that electrification is not the most cost-effective solution for consumers. "The additional cost to Victorian

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[2] Direct quote: Anna Collyer, AEMC, "Developing hydrogen in the NEM", 30 June 2022 <Developing hydrogen in the NEM | AEMC>

[3] The State of Victoria Department of Environment, Land, Water and Planning, "Victoria's Gas Substitution Roadmap", July 2022 <Help Us Build Victoria's Gas Substitution Roadmap | Engage Victoria>

[4] AEMO, Gas Statement of Opportunities - For eastern and south-eastern Australia, March 2022 <2022-gas-statement-of-opportunities.pdf (aemo.com.au)>

[5] AEMO, Victorian Gas Planning Report Update, March 2022 <https://aemo.com.au/-/media/files/gas/national_planning_and_forecasting/vgpr/2022/2022-victorian-gas-planning-report-update.pdf?la=en>

[6] Frontier Economics, "Cost of switching from gas to electric appliances in the home", 24 June 2022

households of replacing their existing gas appliances with electric alternatives, compared to replacing them with new hydrogen fuelled gas appliances, will fall somewhere between $4 and 31 billion".

In addition, part of Victoria's industrial base cannot be electrified economically and will need a clean fuel in a decarbonised economy. Hydrogen is the prime candidate to be the fuel of choice for those heavy industries.[7,8]

In summary, utilising the existing natural gas pipeline network to transport hydrogen provides several advantages for customers including:

1. **Lower system costs -** repurposing existing gas infrastructure for hydrogen is lower cost than building entirely new pipeline network or full electrification of the energy system[9,10]
2. **Maintaining high reliability and energy security** – historically, Victorian gas customers experience an outage once every 36-years[11] compared with electricity network outages which occur frequently due to storms and system maintenance.
3. **Maintaining choice for customers** – providing options means that customers have choices available to them; both electrification and low-carbon gas solutions.
4. **Supporting industrial users to decarbonise -** hydrogen offers a viable decarbonisation pathway for hard-to-abate end users, such as industrial processing facilities that require high temperature heat.

3.2 Hydrogen in gas networks

Distribution networks in Victoria are already investing in projects[12] and readying their networks for hydrogen blending. It is therefore important that the transmission network is also prepared for hydrogen blending to enable the renewable gas transition, ensure safe operation of the network connecting to these with hydrogen-ready distribution pipelines, and to ensure that Victorian customers continue to benefit from competitive supply from multiple hydrogen gas sources.

The gas distribution networks have a number of hydrogen projects in operation (including AGIG's HyP SA project and Jemena's Western Sydney Green Gas project). Learnings from these projects are transferable between distribution networks, however, cannot be applied for transmission projects. This is for several reasons:

- Distribution networks are designed and operate under a different prescriptive standard AS 4645 compared to the risk based AS 2885 pipeline standard.

- The networks prescriptive design standard has inherent risk controls such as maximum design factor of 20% and 1050 kPa MAOP meaning networks pipes are not subject to rupture, and consequence such as heat release are controlled.

- Hydrogen embrittlement of steel pipe properties is related to partial pressure rather than hydrogen blend % alone. Distribution networks operate at much lower pressures than the transmission network, thus reducing the impacts of hydrogen embrittlement

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[7] State of Victoria Department of Environment, Land, Water and Planning, 2021 <https://www.energy.vic.gov.au/__data/assets/pdf_file/0021/513345/Victorian-Renewable-Hydrogen-Industry-Development-Plan.pdf>

[8] ClimateWorks Australia, Australian Industry Energy Transitions Initiative Phase 1 Technical Report, June 2021 <https://energytransitionsinitiative.org/wp-content/uploads/2021/06/Phase-1-Technical-Report-June-2021.pdf>

[9] Australian Pipelines and Gas Association, "Gas Vision 2050", September 2020, <https://www.apga.org.au/sites/default/files/uploaded-content/website-content/gasinnovation_04.pdf>

[10] Clean Energy Finance Corporation, Australian hydrogen market study, 24 May 2021, <https://www.cefc.com.au/media/nkmljvkc/australian-hydrogen-market-study.pdf>

[11] Australian Energy Regulator, Gas distribution performance report, 2012, p13

[12] Australian Gas Infrastructure Group, "Hydrogen proposed for 40,000 customers in Albury-Wodonga", February 2021 <https://www.agig.com.au/media-release---hydrogen-proposal-in-albury-wodonga>

Injecting hydrogen into the VTS supports diversity of energy sources and additional resilience for end users. Hydrogen projects that are positioned close to demand centers, producing hydrogen using a local electricity grid connection are at risk of intermittency caused by electricity network outages i.e., if there is an outage on the local electricity network the hydrogen will not be produced and will result in a hydrogen supply issue. Energy security can only be guaranteed by a diverse suite of energy supply arrangements, and this is why APA believes that diversity of energy sources supports resilience for end users.

Further to supply reliability challenges detailed above, injecting hydrogen into distribution networks in some locations is sensitive to the variations in gas flowrates. When accounting for seasonal fluctuations in demand in Victoria, our analysis on demand profiles through the custody transfer stations in the VTS indicates that gas flows across some parts of the distribution network during warm weather periods will be insufficient for a distribution-connected hydrogen electrolyser to operate on a constant basis. This can introduce operational challenges for electrolyser technologies that may not lend themselves well to ramping and/or intermittent use whilst seeking to achieve high gas supply reliability standards.

As renewable gases become an increasing part of the gas supply mix, the storage of renewable gases will become a critical network function, to respond to peaks in demand. Natural gas peak demand periods are currently supported by the VTS, through line-pack and supply of gas from storage facilities such as Iona and the Dandenong LNG facility. If the gas supply transitions to a distributed delivery model, then alternative storage facilities may need to be located in residential zones. The storage of large volumes of gas, which is flammable, will have Hazardous Area implications for some locations within a distribution network. This again substantiates the need for the transmission system to underpin the end-to-end supply chain of renewable gas. By utilising the VTS to transport renewable gases, storage can be located in remote areas where Hazardous Area Zones can be located away from local communities.

A report recently published by APGA[13] analysed the costs of storing and transporting energy via powerlines and via pipelines and demonstrated that transporting and storing energy via hydrogen or natural gas pipelines is more cost effective than electricity transport and storage. Coupled with the economies of scale that can be achieved through centralised renewable hydrogen projects, this report reinforces that the transportation of hydrogen via transmission pipelines, compared with transporting electricity to distributed hydrogen electrolysers, is a lower cost outcome for consumers.

3.3 Assessing gas transmission networks

A report recently published by APGA[14] analysed the costs of storing and transporting energy via powerlines and via pipelines and demonstrated that transporting and storing energy via hydrogen or natural gas pipelines is more cost effective than electricity transport and storage. Coupled with the economies of scale that can be achieved through centralised renewable hydrogen projects, this report reinforces that the transportation of hydrogen via transmission pipelines, compared with transporting electricity to distributed hydrogen electrolysers, is a lower cost outcome for consumers.

The current challenge with repurposing the existing high pressure (transmission) natural gas pipeline network is understanding what impact the introduction of hydrogen might have on the gas pipeline's integrity and their operation. This is a technical challenge that was identified in Australia's National Hydrogen Strategy, which noted that further evidence is required to confirm that hydrogen embrittlement issues can be safely addressed before blending of hydrogen in existing gas transmission networks can be supported.[15]

In assessing the suitability of a pipeline for hydrogen service there are several components that must be considered:

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[14] APGA, "Pipelines more affordable for energy transport and storage: report", 15 February 2022 < Pipelines more affordable for energy transport and storage: report - Australian Pipelines and Gas Association (apga.org.au)>

[15] Action 3.15 from: COAG Energy Council, "Australia's National Hydrogen Strategy", 2019 <https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf>

- The line pipe material
- Assemblies (including valves and scraper stations)
- Facilities (including compressor stations)

When a steel pipeline, like the existing VTS network, is exposed to high pressure hydrogen, hydrogen is absorbed into the line pipe steel and can degrade the material properties. This phenomenon is known as hydrogen embrittlement. The principal effects are an increase in fatigue crack growth rate, a reduction in fracture toughness and a reduction in ductility of the steel. This deterioration of steel properties has the potential to impact the integrity and safe operation of the pipeline if it is not fully quantified. [16]

Although there is significant work underway (both internationally and in Australia) to quantify the impacts of hydrogen embrittlement, it is recognised that the effects vary based on the underlying steel material properties. These material properties are unique to each pipeline and are determined based on the source and grade of the steel, the manufacturing process, the construction methodology (including weld procedures, workmanship criteria, and bend forming), and operating conditions of the asset since entering service. The existing pipeline condition is also critical to understand; in-service degradation (e.g., corrosion) or construction imperfections (e.g., weld defects) which are typically deemed low or no risk for natural gas may pose a greater risk of failure in a hydrogen service environment.

International studies have reached a consensus that even at very low hydrogen blends the impact to the steel can be significant. The impact is related to hydrogen pressure rather than percentage blend of hydrogen, which is why embrittlement is a critical issue for transmission networks.

Figure 1 is a published example that shows the degradation of relative fracture resistance of high strength steel when exposed to hydrogen blends at 8,500 kPa, compared with natural gas[17]. For comparison, the VTS operating pressure varies between 2,760 kPag and 10,200 kPag[18]. Even at very low blends (1%) the hydrogen partial pressure is sufficient to reduce the pipeline's ability to resist a fracture. A reduction in ductility of up to 50% in hydrogen service have similarly been reported for other pipeline steels[19].

Similarly, Figure 2 shows the impact of hydrogen on fatigue crack growth due to pipeline cycling of various pipeline steels[20]. Typical fatigue crack growth rates of 10-30x that in natural gas have been reported in hydrogen, with higher rates in larger diameter pipelines greater than DN600[21]. This reduction in fracture resistance, ductility, and increased fatigue crack growth rate increases the risk of pipeline failure. At high pressure, a pipeline rupture could lead to grave consequences including loss of life. Our risk assessment attached in Appendix A provides an overview of key risks.

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[16] Distribution networks are designed and operate under a different prescriptive standard AS4645 compared to the risk based with the transmission pipeline standard AS2885. The AS4645 design standard has inherent risk controls such as maximum design factor of 20% and 1050 kPa MAOP has far greater capability to accommodate the change in ductility, toughness and fatigue life meaning that the pipes are not subject to rupture, and consequence such as heat rate release are controlled.

[17] Chris San Marchi, et al, "Materials Evaluation for Hydrogen Service", PRCI Hydrogen Storage Workshop 1 September 2021, SAND2021-10712PE

[18] The VNI has a design pressure of 15,300 kPa but is currently limited in operation to 10,200 kPa.

[19] Briottet.L, et al, "Quantifying the Hydrogen Embrittlement of Pipe Steels for Safety Considerations, International Journal of Hydrogen Energy, Vol. 37, Issue 22, November 2012.

[20] Ronevich et al, "Assessment of Hydrogen Assisted Fatigue in Steel Pipeline", US Department of Energy, Office of Energy Efficiency & Renewable Energy, 27 September 2017, SAND2017-10181PE

[21] Fardi et al, Fatigue Crack Growth Modelling for Safe and Efficient Hydrogen Pipeline Design, 23rd Joint Technical Meeting of EPRG, PRCI and APGA, Edinburgh June 2022.

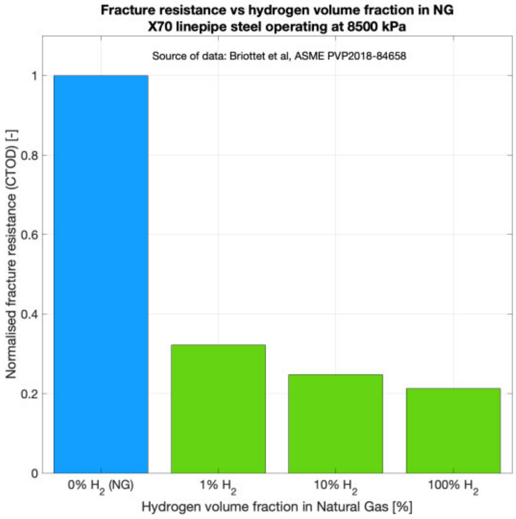

Figure 1 – degradation of fracture resistance in hydrogen

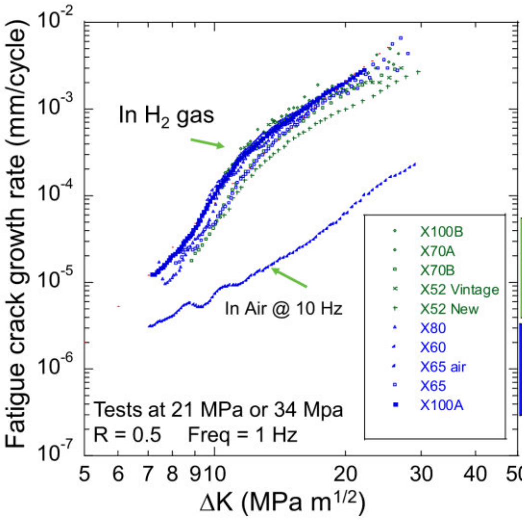

Figure 2 – increased fatigue crack growth rate in hydrogen compared with in air

Despite the deterioration of material properties, emerging knowledge (from international and Australian projects) has identified that, based on a detailed technical assessment of the pipeline, the risks to safety and integrity can be sufficiently mitigated to allow conversion of high-pressure transmission pipelines to be converted to hydrogen service.

One such Australian project is APA's Parmelia Gas Pipeline (PGP) conversion project. The Parmelia Gas Pipeline is an unregulated asset in Western Australia and APA has already committed significant investment into understanding the impacts of hydrogen embrittlement on this transmission pipeline. Our Parmelia Gas Pipeline conversion project[22] is the first high pressure pipeline in Australia that is undergoing detailed testing and analysis for conversion to hydrogen service. Through this project, APA has established an international advisory panel[23] including some of the world's most preeminent experts in the field of hydrogen materials testing and analysis. This advisory panel has provided guidance and validation on the project test plan, assessment methodology, and independent verification of results.

APA's Parmelia Gas Pipeline conversion project has been underway for over a year. Air testing results, engineering assessment and safety study have returned positive results for PGP hydrogen service conversion and indicate no service pressure de-rating will be required. Additional materials testing in hydrogen over the next twelve months will, we expect, further validate these conclusions, providing full confidence of the pipeline's likely service performance, allowing detailed safety studies and conversion plans to be developed in consultation with the Western Australia safety regulator.

A technical paper describing the outcomes of the last twelve months of testing from our Parmelia Gas Pipeline conversion project in included as Appendix B.

While APA's Parmelia Gas Pipeline study is the first of its kind in Australia, it is not the first of its kind in the world. The following case study describes the successful conversion of a natural gas pipeline in the Netherlands to hydrogen, which has been in service since 2018. Two members of APA's international advisory panel were directly involved in this conversion project by Gasunie and are instrumental in the proposed conversion of the Netherland's national gas infrastructure to hydrogen[24].

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[22] APA Group, "APA set to unlock Australia's first hydrogen-ready transmission pipeline", 23 February 2021 <https://www.apa.com.au/news/media-statements/2021/apa-set-to-unlock-australias-first-hydrogen-ready-transmission-pipeline/>

[23] The international advisory panel includes European representatives who were directly involved in the conversion of a Gasunie pipeline from natural gas to hydrogen; an independent fracture mechanics expert who authored the pipeline defect assessment manual; and the leader of Sandia's Hydrogen Materials Lab and Hydrogen Compatibility Consortium in the USA.

[24] Gasunie, "Gasunie hydrogen pipeline from Dow to Yara brought into operation", 27 November 2018 <https://www.gasunie.nl/en/news/gasunie-hydrogen-pipeline-from-dow-to-yara-brought-into-operation>; Gasunie, "Dutch-German

Case Study: Gasunie – Netherlands' gas transmission network

In November 2018, Gasunie, the Netherlands' gas transmission operator, started transporting hydrogen along a 12 km section of repurposed natural gas pipeline. The pipeline transports more than 4,000 tons of hydrogen per year for industrial purposes, saving over 10,000 tons of carbon emissions each year.

In July 2022 the government of the Netherlands announced that it will invest €750m over the next 10-years to develop a national hydrogen transport network.

The national hydrogen network will consist of 85% repurposed natural gas pipelines, resulting in costs four times lower than if entirely new pipelines were laid.

3.4 The VTS safety and integrity assessment

The VTS is made up of 51 pipelines under 46 individual licenses. Work will need to be completed to understand what impact the introduction of hydrogen might have on each one of these pipelines. Assessing an interconnected network like the VTS will be complex and APA is the only entity with the knowledge, required skillset, and access to the pipeline for testing, to assess the compatibility of the VTS pipeline and associated facilities with hydrogen.

There is currently no Australian standard for design of new hydrogen pipelines or conversion of existing infrastructure[25], but there is work in progress to incorporate hydrogen in future updates of AS 2885. In the interim, the Australian Pipelines and Gas Association (APGA) in Collaboration with Future Fuels CRC is developing a Hydrogen Code of Practice which will provide guidance to industry in the absence of formal published standards.

The proposed technical assessment is required because, when designed and constructed, the existing pipeline design only considered natural gas compatibility, so our records only contain data and information that is relevant for natural gas service. For us to understand the impacts of hydrogen, and in particular the changes to ductility, toughness, and fatigue life, we need to collect additional information about our pipelines with hydrogen service in mind.

This proposed safety and integrity assessment will gather sufficient data to quantify the impacts of hydrogen embrittlement on the VTS network, and any changes required to current operating parameters to mitigate identified safety and integrity risks.

With the change in legislation to permit hydrogen blending under the definition of natural gas, the likelihood of hydrogen blends being transported in the VTS is increasing over the next five to ten years. Before any hydrogen enters the VTS, it is critical that APA as the VTS pipeline owner and operator undertakes technical assessments that enable quantification of the specific impacts of hydrogen embrittlement on the VTS pipelines, as well as any changes that may be required to current pipeline operating parameters to mitigate safety risks.

We propose to commence the technical assessments during this access arrangement period (2023-27) given that each pipeline assessment is estimated to take ~12-18 months to complete (refer to Figure 3 below). The most time-intensive activity for each pipeline assessment is the laboratory testing. The laboratory at the University of Wollongong has several machines, so can run tests for several pipelines in parallel. Even running several pipeline assessments in parallel will require a significant timeline to complete the work. Given the interconnected nature of the VTS, there is not a simple way to isolate a small sub-set of pipelines for testing.

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cooperation secures European future of hydrogen", 6 July 2021 < https://www.gasunie.nl/en/news/dutch-german-cooperation-secures-european-future-of-hydrogen>

[25] Australia's natural gas pipeline standard AS2885 does not currently address hydrogen service. ASME B31.12 is the US standard for hydrogen pipelines, but this standard is difficult and potentially impractical to apply retrospectively to transmission pipelines such as the VTS. Our Parmelia Gas Pipeline Conversion Project assesses the gaps between these two standards and uses a risk-based approach to assess and mitigate the threats and consequences introduced or altered due to the introduction of hydrogen to the pipeline to meet the safety management intent of Australian pipeline standard AS2885.

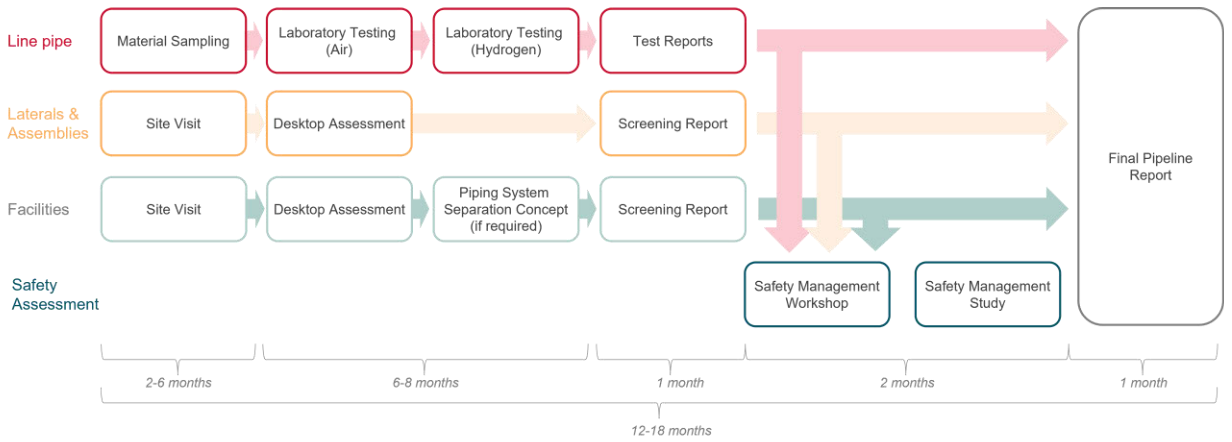

Figure 3: Assessment process for each pipeline

If the hydrogen-compatibility testing is not approved as part of this Access Arrangement, the next opportunity to commence work is from 2028 (next Access Arrangement period). Noting the publicly announced targets by AGIG (to transition their Victorian distribution network to a 10% renewable gas blend by 2030, and to fully decarbonise their networks by 2040) if APA does not commence work until 2028, this does not provide APA with sufficient time to assess the potential safety and integrity impacts on the transmission network. Under the 'Do Nothing' scenario there is a risk that projects are delayed or unable to proceed.

The results of the proposed technical assessments do not expire and remain relevant for the life of the pipeline.

4 Risk Assessment

If hydrogen enters the VTS network without completion of the proposed technical assessments, the integrity of the pipeline will be impacted which may lead to premature degradation or failure of pipeline or facilities elements. This could ultimately lead to health and safety risks for members of the public, our customers, staff, and contractors.

Refer to the full risk assessment result included as Appendix A to the Business Case. The Final Untreated Risk Rating is assessed as High.

5 Options Considered

5.1 Option 1 – Do Nothing

The Do Nothing option is to not complete any hydrogen-compatibility technical assessment on the VTS in this Access Arrangement period.

5.1.1 Cost/Benefit Analysis

The consequence of this will be to prevent any injection of hydrogen into the VTS network, including for all assets operating at 2760 kPag in the broader Declared Transmission System (DTS) owned by other gas owner/operators.

This Option is not consistent with the Victorian Gas Substitution Roadmap.

5.2 Option 2a – Technical assessment of 39 pipelines, undertaken over 5-years (this access arrangement)

The objective of this proposed option is to provide sufficient data to understand the impacts of hydrogen embrittlement on the VTS. The information will allow APA to quantify:

- the safety and integrity impacts and suitability for hydrogen blending,
- any remedial works or modifications required for facilities and assemblies, or
- changes in operation required to ensure continued safe operation of the VTS.

The intent of this Option is to provide the lowest overall lifecycle cost, with remedial works and modifications to accommodate hydrogen limited to locations where required, minimising impact to system operation and supply reliability. This Option also supports the transition to a low carbon economy in Victoria.

At the conclusion of the project, a final report will be produced for each of the pipelines that has been tested and assessed, providing a robust and engineering-based approach to determining the suitability of the VTS network for hydrogen service. Each report will collate all relevant information into a single document, including the findings and recommendations about the line pipe, pipeline laterals, pipeline assemblies and facilities, as well as the outcomes from the Safety Management Study (SMS) review with Energy Safe Victoria (ESV).

These pipeline reports will be used to support APA's VTS strategic network planning allowing us to clearly identify which parts of the network are suitable for hydrogen blending, and which are not.

APA has sought feedback from customers through APA's VTS AA Roundtable sessions, as well as stand-alone hydrogen information sessions, and through circulation of the VTS AA First Look Document as well as APA's Draft Submission.

VTS stakeholders acknowledge that there is a need to quantify the impacts of hydrogen embrittlement, should hydrogen be injected into the VTS. However, there was concern raised about the lack of clarity as to the timing of hydrogen projects, and probable locations for injection into the VTS network. APA acknowledged the uncertainty but contended that, to keep options open for hydrogen as a future source of energy, it would be prudent to start testing for safety and integrity during 2023-27.

There is recognition that significant work needs to be done to better understand the safety and integrity implications of repurposing the existing natural gas network for hydrogen blends, and that there is a genuine urgency to commence the work to support decarbonisation efforts. The primary concern raised during the stakeholder consultation process was how the technical assessment would be funded and the impact to consumer tariffs.

APA has received 14 letters of support from a broad range of stakeholders, attached as Appendix C.

5.2.1 Cost/Benefit Analysis

The total estimated cost of this Option is $37,861,536. If undertaken over 5-years and depreciated over the life of the asset, APA's tariff modelling estimates that the bill impact of this Option is 33 cents per year for residential customers. (Compared to 10 cents per year in Option 2b which proposes to undertake the study over 10-years - as discussed below).

The benefit of Option 2a is that the assessment will provide sufficient data to quantify the impacts of hydrogen embrittlement on the VTS and demonstrate how renewable gas can be safely and reliably transported in the VTS, optimising energy supply to consumers. This assessment will be used to support APA's VTS strategic planning process, clearly identifying which parts of the network are suitable for hydrogen blending, and which are not.

For those parts of the network identified as suitable for hydrogen blending, the information gathered will inform what mitigations need to be implemented to maintain the safety and integrity of the network once hydrogen is introduced. This will result in a significantly reduced risk profile, as demonstrated by the Residual Risk Ratings outlined in Appendix A.

Through this technical assessment, if we can safely accommodate hydrogen in the VTS network, there is the added benefit of supporting decarbonisation goals of the Victorian Government and as a result we may also be able to extend asset lives, thus reducing depreciation charges to customers (noting that this has not been quantified).

If commenced in 2023, the proposed assessment of 39 pipelines is estimated to be completed over the 5-year access arrangement period. At the completion of the assessment, any mitigations that are required to be implemented to manage risk, can be implemented. This option offers the best, and only, pathway for the VTS to be 'hydrogen-ready' in the early-mid 2030s.

5.2.1.1 Cost Estimation Methodology

The VTS comprises approximately 2,262 km of high-pressure gas transmission pipelines made up of 51 pipelines under 46 individual licenses. In preparation for the VTS access arrangement submission, APA has completed a desktop analysis of the network, including a high-level screening assessment for each of the pipelines and associated assemblies / facilities to determine the costs to complete the proposed safety and integrity assessment. The cost estimation methodology is summarised in Figure 4 below. Our approach is underpinned by our understanding of the potential effects of hydrogen embrittlement, balanced by a pragmatic test approach that will optimise cost impacts to customers whilst maintaining the safe operation of the network.

The desktop analysis and high-level screening assessment for this VTS safety and integrity assessment has been developed in line with industry best practice and greatly informed by our learnings from our Parmelia Gas Pipeline (PGP) Conversion Project. We have leveraged international standard ASME B31.12 to develop a test methodology that allows pipelines to be assessed for hydrogen compatibility via a Performance Based Design Approach (Option B). ASME B31.12 also offers Prescriptive Design Approach (Option A) but this is less preferred because it results in a more conservative design requirements which reduces operational capacity and flexibility and/or increases costs (e.g. thicker walled pipes and/or lower operating pressures requiring larger diameter pipelines to achieve capacity).

Through our PGP Conversion Project we have established an international advisory panel of experts[26] who have guided the development of our test program and provide ongoing input and guidance to validate our approach and test results. This PGP project and associated test program has created inhouse knowledge and has formed the foundation of the proposed VTS safety and integrity assessment.

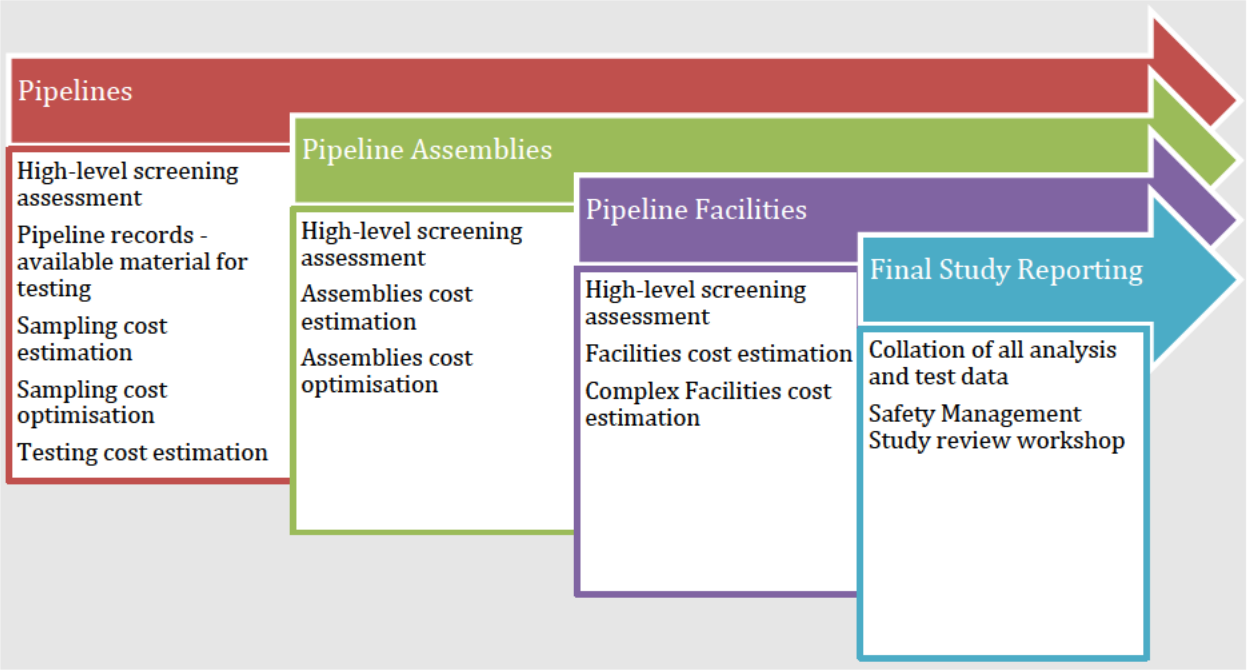

Figure 4: Overview of Cost Estimation Methodology

5.2.2 Pipelines

A high-level screening assessment was conducted to understand the operating pressure, steel grade, age, pressure cycling, fracture control, and design factor of each pipeline[27]. A sensitivity analysis was also undertaken based on known material integrity issues, diameter and design stress taking into consideration fracture behaviour of low stress and small diameter pipelines.

Recognising the scale of the assessment required, through this initial screening, APA has allocated all the VTS pipelines to one of two phases: Phase 1 (this assessment) and Phase 2 (future assessment if required). Phase 2

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[26] The international advisory panel includes European representatives who were directly involved in the conversion of a Gasunie pipeline from natural gas to hydrogen; an independent fracture mechanics expert who authored the pipeline defect assessment manual; and the leader of Sandia's Hydrogen Materials Lab and Hydrogen Compatibility Consortium in the USA.

[27] Several licenses / pipelines have more than one section or pipeline steel manufacturer and will therefore require testing and assessment per section due to differing operating pressures / conditions or loops.

pipelines are those pipelines which are interstate import/export lines and are expected to remain as natural gas only pipelines for at least the period of this Access Arrangement. This results in a high-pressure natural gas “ring” around the state from Longford to Dandenong to Wollert (with the VNIE NSW interconnector), and then from Wollert to Brooklyn and onto Iona underground gas storage facility. Phase 2 pipelines can be assessed in future, if determined to be required for hydrogen blending. Refer to Appendix D for a map of the pipelines.

Phase 1 includes the balance of the network. Of the 51 pipelines, 39 pipelines have been identified as requiring detailed assessment in Phase 1[28]. Refer to Appendix D for a map of the VTS visualising this Option.

Following the high-level screening assessment, pipeline records were assessed for available material test certificates, hot-tap coupons / cut-out samples, and ER/Stock pipe to determine material available for testing and if additional samples were required to be obtained from in-service pipelines.

Where additional samples were determined to be required the type and number of samples were estimated based on the screening assessment.

Line pipe sampling involves excavating the in-service pipeline, completing non-destructive testing (NDT) to confirm condition of line pipe at the point of extraction, welding of hot tap fittings, and extraction of a sample from the live pipeline.

Based on the initial high-level screening assessment, sampling costs were found to be very high. To optimise costs and reduce sampling, a follow-up assessment was made to group where pipeline materials of the same age, steel grades and physical properties (WT and diameter) that might be tested together.

A second assessment was also made where pipelines consisted of short interconnects, offtake connections, or lengths (<2 km) with low grade and design factor and testing revised to an ‘in situ’ assessment the scope of which would include hardness, metallography, and chemical analysis of pipe, seam, and girth welds to reduce the sampling costs.

The ‘in situ’ assessment involves excavating the in-service pipeline, removing a small amount of surface material to complete in situ chemical analysis, hardness, and metallography to examine the microstructure for the base metal and girth weld (we may also be able to identify the seam weld). This will give us indication of the grade, hardness / tensile strength and the microstructure which should allow us to make an assessment on the risk and suitability for these short sections; or in a worst-case scenario identify the need for further work / assessment. Most in phase 1 are understood to be low grade, relatively low design factor, which we can then apply the existing international hydrogen pipeline standard (ASME B31.12) approach, by looking at low stress and low-grade parameters.

Table 1: Summary of Cost per Sample[29]

Sample Type	Description	Cost per Sample
HTC <DN350	Hot Tap Coupon of 14-inch diameter pipe	$160k
HTC DN400 – DN750	Hot Tap Coupon of 16-inch – 30-inch diameter pipe	$240k
HTS <DN350	Hot Tap Stopple of 14-inch diameter pipe	$650k
HTS DN400 – DN750	Hot Tap Stopple of 16-inch – 30-inch diameter pipe	$1,000k

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[28] APA notes that this preliminary screening of pipelines may be amended based on optimisation of the network driven by system modelling and potential injection points driven by market demand.

[29] A hot tap coupon (HTC) is a localised extraction of a material coupon from the pipeline. A hot tap stopple (HTS) is more invasive and requires a full bypass of the live pipeline while a sample is extracted. The pricing estimates are based on recent pricing for the two diameter ranges.

Following collection of the samples, the pipeline material will undergo materials testing to compare the baseline material properties (air test) against the material properties after exposure to hydrogen (H2 test). The pipeline material properties in hydrogen will then be used to assess the impacts of hydrogen on pipeline design and operation including fracture control, mechanical damage resistance, and fatigue performance. The pipeline condition will be assessed against revised defect assessment criteria accounting for the potentially degraded material properties. Where property degradation is determined to impact operation, a revised operating envelope will be defined for assessment by capacity planning.

Table 2: Testing Cost per Sample[30]

Test Type	Test Cost / Sample
Air Test	$5k
H2 Test	$50k

5.2.3 Pipeline Assemblies

Pipeline Assemblies include main line valves (MLV) and scraper stations. The preliminary desktop analysis of the network identified 128 MLV and 39 Scraper Stations to be assessed. Typically, MLV's are welded in line and each MLV assembly will be generally consistent along the pipeline (particularly in regional areas). It is proposed that for each pipeline a typical MLV and all Scraper Stations will be assessed by site visit and desktop assessment of the balance of MLV's. An assessment of compliance for design stresses and materials of construction will be completed. Assessment will consider changes in stress and design factor requirements for assemblies in hydrogen service with consideration of international design standards. Suitability of existing inline equipment such as instrumentation and control / actuated valves, and impacts of hydrogen on materials flow behaviour, hazardous areas and functional safety will be screened. Random sample chemical and hardness testing will be completed on piping at sites that materials records and certification is unavailable.

The estimated cost of assessing all pipeline assemblies is $2,620,800.

5.2.4 Pipeline Facilities

Pipeline facilities, including metering and offtake stations, will require assessment similar to the above for pipeline assemblies, but with potential for more complex equipment including Type B equipment such as water bath heaters. The preliminary desktop analysis of the network identified approximately 151 meter / offtake stations to be assessed. The assessment process will be similar to the pipeline assembly assessment, requiring a site visit, equipment and technical assessments and development of screening and modification requirement report for the facility. Key equipment vendors will be engaged for equipment compatibility for the likes of metering, regulating and gas quality monitoring equipment. Impacts to hazardous area classification and equipment class ratings will be reviewed. This facilities assessment is estimated to cost $7,299,072.

There are also three complex facilities that require assessment:

- Dandenong City Gate
- Wollert Compressor Station and City Gate
- Brooklyn Compressor Station and City Gate

These will require similar types of assessment works to the above however, these much larger and complex facilities will also include additional piping system separation concept works required for hydrogen and non-hydrogen system planning, and additional equipment assessment including complex equipment assessment (such as compressors). In the cases of compressor stations and Type B appliances, original equipment suppliers will be engaged to assist assess

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[30] Testing costs are based on recent Parmelia Gas Pipeline (PGP) pricing, assuming testing can be completed at University of Wollongong, rather than using commercial overseas laboratories where testing costs have been quoted in excess of 3x PGP pricing.

suitability and hydrogen limits of their equipment. Station piping capacity checks will also be completed alongside preliminary station stress analysis and acoustic induced vibration/flow-induced vibration integrity checks. This is estimated to cost a total of $900,000.

A HAZOP review will be undertaken for each facility to assess impacts of change in fluid service and effectiveness of existing protective measures.

5.2.5 Safety Management Study and Final Assessment Reporting

Once the assessment data is available, each pipeline will undergo a Safety Management Study (SMS) review workshop involving the project team, pipeline engineering, operations engineering, asset management, field services and Energy Safe Victoria (ESV).

It is proposed that for each pipeline a final report will be produced, collating the line pipe, pipeline lateral, pipeline assemblies, pipeline facilities, and SMS findings / recommendations into a single document.

5.3 Option 2b – Technical assessment of 39 pipelines, undertaken over 10-years (this access arrangement and next access arrangement)

In response to stakeholder submissions and AER draft decision we have reassessed the study options in this revised business case and propose to undertake the study over two regulatory periods and to depreciate the study over the life of the pipelines.

To support prioritisation of the test program APA will engage with stakeholders to understand likely injection points on the VTS, and any operational issues that AEMO may envisage.

5.3.1 Cost/Benefit Analysis

The total estimated cost of this Option is $37,861,536 ($18.9 m for the 2023-27 period). If undertaken over 10-years, APA's tariff modelling estimates that the bill impact of this revised assessment is less than 20 cents per year for domestic customers, assuming a 30-year depreciation period.

Option 2b allows the committed costs to be staged across two access arrangements.

The disadvantage of this Option, when compared with Option 2a, is that the assessment will not be completed until 2032 at the earliest. Following completion of the assessment, any mitigations that are required to manage risk will still need to be implemented. This option will result in a delay of 5-years when compared with Option 2a, meaning that the VTS will be 'hydrogen-ready' in the mid-late 2030s.

5.4 Option 3 – Reduction of operating pressure of VTS to minimise hydrogen embrittlement impacts; conduct testing of 9 pipelines to maintain capacity of network

APA has conducted an analysis to understand how the risks of hydrogen embrittlement might be managed through reduced pipeline operating pressure. This approach follows the internationally recognised standard ASME B31.12, Option A approach for prescriptive design. This approach for example may be considered in the event that hydrogen is introduced to the VTS network before any or all of the proposed compatibility testing (Option 2) has been completed.

5.4.1 Reduced MAOP due to Hydrogen Injection

ASME B31.12, Hydrogen Piping and Pipelines, provides an option for new pipelines providing a prescriptive design method, "Option A" that minimises the testing and detailed design requirements to achieve safe design for hydrogen pipelines by limiting material grades, fracture propagation risk, and operating stresses (design factors) based on location class.

- B31.12 requires that "A facture toughness criterion or other method of shall be specified to control fracture propagation when a pipeline is designed to operate at a hoop stress over 40% of SMYS" (design factor of 0.4)

- In high consequence areas, such as would be present in Melbourne Metropolitan areas (AS 2885 location class T1/T2 HCA), design factor is limited to 0.4
- A materials performance factor is applied to applied to steel grades higher than X52 that has the effect of reducing steel strength used in design calculations to equivalent of X52 (having the effect of reducing design factor by requiring thicker wall for same operating pressure)

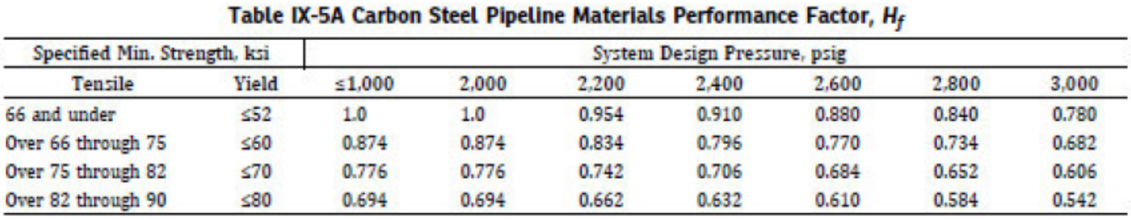

Table IX-5A Carbon Steel Pipeline Materials Performance Factor, H_f

Specified Min. Strength, ksi		System Design Pressure, psig						
Tensile	Yield	≤1,000	2,000	2,200	2,400	2,600	2,800	3,000
66 and under	≤52	1.0	1.0	0.954	0.910	0.880	0.840	0.780
Over 66 through 75	≤60	0.874	0.874	0.834	0.796	0.770	0.734	0.682
Over 75 through 82	≤70	0.776	0.776	0.742	0.706	0.684	0.652	0.606
Over 82 through 90	≤80	0.694	0.694	0.662	0.632	0.610	0.584	0.542

APA has applied the ASME B31.12 pipeline design formula to all 39 pipelines proposed in Option 2 to determine whether a reduced MAOP would be required to meet the Option A prescriptive approach. For this assessment, given no fracture toughness data is available, and potential location class, a design factor of 0.4 was applied.

$$P = \frac{2.S.t}{D} F.E.T.H_f$$

- D: Nominal Diameter (mm)
- E: Longitudinal Joint Factor (1 for all pipes as ERW, DSAW or Seamless pipe)
- F: Design Factor (0.4 for purposes of assessment)
- Hf: Materials Performance Factor (per extract from ASME B31.12 Table IX-5A, taken as 1 for all pipelines X52 or below)
- P: Pipeline Design Pressure (kPa)
- S: Steel SMYS (kPa)
- T: Temperature Derating Factor (1 for all pipelines due to operating temperature range)
- t: Nominal Thickness (mm)

Based on the above approach, 22 sections of pipeline (from the initial 39) require a reduction of MAOP if hydrogen is injected into the VTS, as summarised below in Table 6 and highlighted in Figure 6 within Appendix D.

Table 3: List of sections of VTS with MAOP reduction for H2 injection

Pipeline Name	T-Number	MAOP (kPa)	New MAOP for DF<=0.4 kPa	Zone	Regulating station
Brooklyn to Ballan	T56	7,390	5,565	Ballarat/ Bendigo	Brooklyn (existing)
Ballan to Ballarat (DN150)	T57	7,390	5,453	Ballarat/ Bendigo	Ballan (new)
Ballan to Bendigo	T70	7,390	5,453	Ballarat/ Bendigo	Ballan (new)
Mt Franklin to Kyneton	T66	7,390	5,019	Ballarat/ Bendigo	Wandong (existing)
Mt Franklin to Bendigo	T70	7,390	5,019	Ballarat/ Bendigo	Mt Franklin (new)
Ballan to Ballarat (DN300)	T57	7,390	5,058	Ballarat/ Bendigo	Ballan (new)
Wandong to Kyneton	T75	7,390	5,019	Ballarat/ Bendigo	Wandong (existing)

Pipeline Name	T-Number	MAOP (kPa)	New MAOP for DF<=0.4 kPa	Zone	Regulating station
Derrimut to Sunbury	T62	7,390	7,244	Ballarat/ Bendigo	Brooklyn (existing)
Keon Park to Wodonga and Shepparton (Wollert –Euroa PRS)	T74	8,800	5,019	Northern	Wollert (existing)
Keon Park to Wodonga and Shepparton (Euroa PRS – Wodonga)	T74	7,400	5,019	Northern	Euroa (existing)
Keon Park to Wodonga and Shepparton (Euroa – Shepparton)	T59	7,400	5,919	Northern	Euroa (existing)
Kyabram to Echuca	T85	7,390	5,476	Northern	Euroa (existing)
Tatura to Kyabram	T71	7,390	5,565	Northern	Euroa (existing)
Tatura	T71	7,390	5,565	Northern	Euroa (existing)
Chiltern Valley to Rutherglen	T96	7,400	5,258	Northern	Chiltern Valley (new)
Rutherglen to Koonoomoo	T98	7,400	5,679	Northern	Chiltern Valley (new)
Paaratte to Allansford	T81	9,890	7,244	Western	Iona (existing)
Allansford to Portland	T86	9,890	6,617	Western	Allansford (new)
Cobden (Curdievale to Cobden)	T91	9,890	6,617	Western	Curdievale (new)
Hamilton (Codrington to Hamilton)	T93	9,890	6,617	Western	Codrington (new)
Brooklyn to Corio	T24	7,390	4,498	Corio	Brooklyn /Lara (existing)
Snowy Hydro	T110	10,200	7,664	Corio	Brooklyn /Lara (existing)

VTS system capacity modelling was carried out for VTS system demands of 300TJ/d, 600 TJ/d, 1000TJ/d and 1 in 20 day, using Synergi 4.9.2 and the results checked with Next Gen with a common model shared with AEMO for 1 in 20 day case.

The modelling results indicated that for 1 in 20 peak winter days, the section of VTS near Ballarat and Bendigo would have insufficient pressure to maintain supply to the region, if the reduced MAOPs are applied. In particular, the reduced MAOP (5000 kPag) in the section of pipeline between Wollert to Euroa and Wandong to Kyneton, are the most severe constraint on capacity. In order to maintain capacity, the MAOP in this section is required to be at least 5,400 kPag, which may be possible if material testing results are favourable for hydrogen. Alternatively, capacity may be maintained if the MAOP of Brooklyn to Ballan, Ballan to Ballarat and Bendigo sections are maintained above

6,000 kPag (instead of the reduced MAOP of 5,565 kPa), also by means of material testing. Looping or partial looping of these sections of pipe could also achieve adequate operating pressure but at substantially higher cost to material testing.

The table below summarises the nine sections of the VTS that require MAOP to be maintained above the reduced MAOP target for operation at 0.4 design factor and should therefore be prioritised for material testing to determine if the MAOP reduction could be avoided, thus mitigating any capacity reduction. These pipeline sections are also highlighted in Figure 7 in Appendix D.

Table 4: List of sections requiring material testing to avoid impact on VTS capacity

Sections of pipeline for material testing	T -number	Reduced MAOP kPag	MAOP to maintain capacity kPag
Brooklyn to Ballan	T56	5,565	6,000
Ballan to Ballarat (DN150)	T57	5,453	6,000
Ballan to Ballarat (DN300)	T57	5,058	6,000
Ballan to Bendigo	T70	5,453	6,000
Keon Park to Wodonga and Shepparton (Wollert –Euroa PRS)	T74	5,019	5,400
Keon Park to Wodonga and Shepparton (Euroa PRS – Wodonga)	T74	5,019	5,400
Mt Franklin to Kyneton	T66	5,019	5,400
Mt Franklin to Bendigo	T70	5,019	5,400
Wandong to Kyneton	T75	5,019	5,400

The estimated cost of the assessment for these nine pipelines is $10.3m. This estimate includes sampling and testing the linepipe, assessment of associated assemblies and metering facilities, plus reviews of Brooklyn and Wollert compressor stations, to which T56 and T74 are connected. In addition to testing these nine pipelines, six new regulating stations are required to be installed in VTS in order to lower the MAOP. The estimated cost of installing these new regulating stations is $15.2m as per the breakdown in Table 5.

Table 5: Estimated costs for installing six regulating stations to reduce MAOP

Regulating station	Nominal pipe size	Estimated cost to install
Allansford	DN100	$2,498,865
Codrington	DN50	$2,293,715
Ballan	DN150	$2,712,243
Mt Franklin	DN150	$2,712,243
Chiltern	DN150	$2,712,243
Curdievale	DN50	$2,293,715

5.4.2 Cost/Benefit Analysis

The total estimated cost of this Option is $25.5m. Although this option is lower in capital cost than Option 2, it has several disadvantages:

- The modelling for this option is based on how the VTS operates today and current demand requirements.
- Reducing the MAOP of the network will introduce operational constraints and increases security of supply risks. Security of supply risks can result in gas being dispatched out of merit, resulting in higher gas costs.
- With reduced pressures and available linepack, AEMO will have to respond more promptly to demand changes and facilities failures to maintain supply reliability to the VTS.
- The approach is based on new pipeline design approach and does not consider all integrity risks such as low toughness vintage seam welds and pipeline materials that may not meet the other minimum materials requirements of ASME B31.12 and API 5L PSL2. As such, this approach of reducing MAOP to minimise impacts of hydrogen embrittlement may not fulfill the requirements of demonstrating that risks have been mitigated As Low As Reasonably Practicable (ALARP), therefore APA does not have confidence whether this approach would be acceptable to Energy Safe Victoria (ESV).
- If APA completes testing of the VTS (as per Option 2) and material testing results indicates that no pressure reduction is required, the costs of installing regulating stations would be avoided. Essentially, this option introduces $15.2m of capital costs for regulating stations which may become redundant as soon as further material testing is completed.

Alongside consultation with our stakeholders, APA recommends that the nine pipelines identified in Table 4 above are prioritised for testing under Option 2.

5.5 Option 4 Development of new hydrogen ‘backbone’

APA has considered an alternate case where a dedicated hydrogen backbone is developed in parallel with the existing natural gas system, allowing new hydrogen supplies to be transported separately and blended into downstream networks, or delivered direct to hydrogen ready offtakers as feedstock or energy supply.

5.5.1 Hydrogen Backbone Base Case

As a base case APA has considered an effective duplication of the metropolitan ring main and supply point connectors to Packenham and Geelong, considering prospective supply points, and the three key hubs in the Melbourne metropolitan system Dandenong, Wollert, and Brooklyn. The prospective backbone has an approximate length of 225 km.

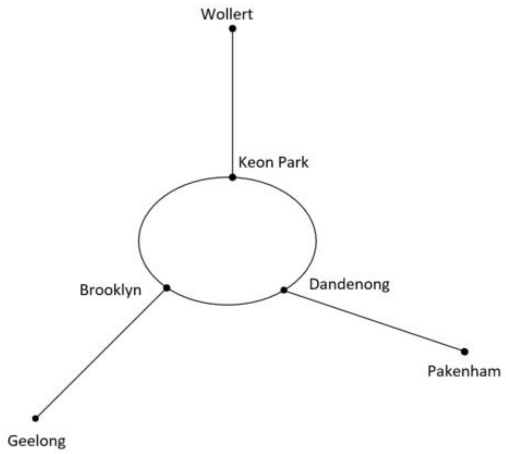

Figure 5: Hydrogen backbone schematic

Recent project estimates for Melbourne pipelines including the Hastings to Packenham and WORM pipelines have had construction pricing of $120k to $150k per inch kilometre respectively, however given the higher density metropolitan nature of the ring main, this may be substantially higher. A high-level estimate for a range of diameters for a new backbone shows the substantial cost of investment compared to repurposing approach, that have been reported as 10-20% cost of new build[31].

	DN400	DN550	DN750
Low Case	$ 720,000,000	$ 990,000,000	$1,350,000,000
High Case	$1,078,920,000	$1,483,515,000	$2,022,975,000

5.5.2 Cost Benefit Analysis

The total estimated cost of this Option is $720m-$2bn. Repurposing existing VTS infrastructure will provide customers with a lower cost option, compared to comparative new infrastructure development. This conclusion is supported by overseas experience and studies comparing similar repurpose vs. new build assessments.

5.6 Summary of Cost Benefit Analysis

Table 6: Summary of Cost/Benefit Analysis

Option	Option description	Benefits	Risks	Total Costs (AUD)
Option 1	Do Nothing	Deferred costs	Prevent growth of hydrogen economy in Victoria	$0
Option 2a (preferred option)	Technical assessment of 39 pipelines, undertaken over 5-years (this access arrangement)	Able to quantify the risks to safety and integrity for the VTS network, and support decarbonisation pathway	Timing misaligned with requirement for hydrogen transport via VTS	$37.86m
Option 2b	Technical assessment of 39 pipelines, undertaken over 10-years (this access arrangement and next access arrangement)	As per 2a, but allows the committed costs to be staged across two access arrangements	Timing misaligned with requirement for hydrogen transport via VTS	$18.9m in this access arrangement period
Option 3	Reduction of operating pressure of VTS to minimise hydrogen embrittlement impacts, including	Could provide an operating solution if hydrogen is required to be transported before VTS testing completed	Safety case pathway undefined Reduced operating flexibility	$25.5m
Option 4	Develop new hydrogen backbone	Eliminates need for testing	Significantly higher costs to consumers	$720m-$2bn

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[31] European Hydrogen Backbone, April 2022, ehb-report-220428-17h00-interactive-1.pdf

5.7 Proposed Solution

5.7.1 Proposed Solution – Option 2b – Technical assessment of 39 pipelines, undertaken over 10-years (this access arrangement and next access arrangement)

APA, through a high-level screening assessment has identified 39 pipelines within the VTS that require sampling, materials testing, and detailed assessment to quantify the impacts of hydrogen embrittlement. The proposed technical assessment includes the pipeline as well as integrity and safety assessments of the associated pipeline assemblies and facilities connected to these 39 pipelines for hydrogen blending.

The proposed solution (Option 2b) stages the assessment across two access arrangements. APA will prioritise the nine pipelines identified in Option 4 for material testing. Other pipelines will be prioritised for testing based on stakeholder feedback on likely injection points for hydrogen.

At the conclusion of the project, the information will allow APA to quantify the impacts of hydrogen embrittlement, and any remedial works to pipelines and facilities, or changes in operation required to ensure continued safe operation of the VTS with the introduction of hydrogen.

These final reports will be used to support APA’s VTS strategic network planning allowing us to clearly identify which parts of the network are suitable for hydrogen, and if any are not. These inputs will also support the Victorian Government’s long-term planning for a low-carbon future with clean molecules; as well as the AEMO systems planning process to ensure the ongoing security of supply of energy.

5.7.2 Why are we proposing this solution?

As described above, it is critical that APA as the VTS pipeline owner and operator undertakes technical assessments that enable quantification of the impacts of hydrogen embrittlement before *any* quantity of hydrogen gas enters the VTS network.

In the context of the changing regulatory landscape, and the expedited amendments to the National Gas Law to incorporate hydrogen and hydrogen blends, biomethane, and other renewable methane gas blends, the urgency of completing this assessment has increased significantly.

In the context of broader government policy, both Victorian State and Federal Government have made commitments to decarbonization and energy transformation including Hydrogen. Readying the VTS in parallel with committed regulatory changes aligns the VTS to ensure readiness for acceptance of alternate fuels such as hydrogen into the system to support these policies.

There is a clear responsibility for implementing this solution. The Gas Safety Act and the Pipelines Act require APA as owner of these pipelines to minimise risks so far as practicable. The Acts and Regulations also demand adherence to AS 2885 which demands a similar risk tolerance.

Until sufficient technical assessment has been undertaken, APA is unable to demonstrate that safety and integrity risks of operating the VTS with hydrogen blend have been mitigated ALARP.

5.7.3 Consistency with the National Gas Rules

Consistent with the requirements of Rule 79 of the National Gas Rules, APA considers that the capital expenditure is such as would be incurred by a prudent service provider acting efficiently, in accordance with accepted good industry practice, to achieve the lowest sustainable cost of providing services:

- Prudent – The expenditure is necessary to maintain public safety and the safety of APA VTS personnel and to maintain the integrity of pipelines in light of government policy decisions to include hydrogen in the national gas market framework. The technical assessment will provide information to assess the viability of transporting hydrogen on VTS pipelines and aligns with ALARP principles and is of a nature that a prudent service provider would incur.

- Efficient – The technical assessment is bespoke for the VTS and we have drawn on APA's work on the Parmelia gas pipeline conversion, and international expertise and experience. APA has selected the least number of pipelines to study (39 out of 51) to ensure scope and cost is minimised, prioritising 9 pipelines that have been identified as potential capacity constraints. The field work will be carried out by APA approved contractors, who have demonstrated specific expertise in completing hot tap welding in a safe and cost-effective manner. The expenditure can therefore be considered consistent with the expenditure that a prudent service provider acting efficiently would incur.
- Consistent with accepted and good industry practice – The current evolution of our industry and the focus on decarbonisation through alternative energy sources means we must address the risks associated with introducing hydrogen to a high-pressure natural gas system. We are required to ensure risk is as low as reasonably practicable in a manner that balances cost and risk, consistent with Australian Standard AS 2885. The proposed technical assessment is consistent with good industry practice.
- To achieve the lowest sustainable cost of delivering pipeline services – The sustainable delivery of services includes reducing risks to as low as reasonably practicable and maintaining reliability of supply.

5.7.4 Forecast Cost Breakdown

The costs summarised in Table 6 below have been derived through the high-level screening assessment, as described in Section 5.2.

Table 7: Summary of costs for technical assessment of pipeline, including materials testing and facilities screening

Activity	Estimated Total Cost	Estimated Costs for this 2023-27 period[32]
Line Pipe Sampling (collection / extraction of samples)	$ 12,780,000	$ 6,390,000
Line Pipe Testing (laboratory testing of samples)	$ 4,266,000	$ 1,963,000
Lateral in Situ Inspections	$ 5,808,000	$ 2,90,4000
Pipeline testing data collation, assessment, and reporting (one report per pipeline tested)[33]	$ 2,021,760	$ 1,010,880
Pipeline Assemblies Assessment	$ 2,620,800	$ 1,310,400
Facilities Assessment	$ 7,299,072	$ 3,649,536
Complex Facilities Assessment	$ 900,000	$ 600,000
Safety Management Workshops and Studies[34]	$ 1,491,984	$ 745,992

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[32] Prioritisation subject to engagement with stakeholders to understand likely injection points on the VTS, and any operational issues that AEMO may envisage

[33] An allowance of 4 weeks for screening assessment and data collection plus 2 weeks for a senior engineer to prepare the report has been included for each of the 39 pipelines tested

[34] An allowance of 4 days for each of the 39 pipelines has been included – the Safety Management Study assessment team will include representatives from: the project team, pipeline engineering, operations engineering, asset management, field services, Energy Safe Victoria, plus an external facilitator

Activity	Estimated Total Cost	Estimated Costs for this 2023-27 period[32]
Final Reporting (one report per pipeline tested, incorporating analysis and conclusions for line pipe, associated laterals, pipeline assemblies, facilities, and safety management study recommendations)[35]	$ 673,920	$ 336,960
Total	**$ 37,861,536**	**$ 18,910,768**

5.7.5 Exclusions and Assumptions

The focus of this assessment will be on the VTS only. The assessment will seek to understand the integrity impacts and suitability for hydrogen blending, and any remedial works or changes in operation required to ensure continued safe operation of the VTS with the introduction of hydrogen.

- No remedial works to make pipelines ready for hydrogen operation is included in the estimate.
- Activities such as making consequential updates to existing documents or updating documents for AS 2885 compliance for hydrogen blending (including preparing revised fracture control plans, isolation plans, and vent blow down studies based on engineering assessment findings) are not included in the estimate.
- No physical works for hydrogen readiness including re-hydrotest, replacement / upgrade of equipment at facilities is included in the estimate.

5.8 Stakeholder Engagement

APA has undertaken extensive stakeholder engagement in preparation of the overall VTS access arrangement. In total, APA hosted 16 stakeholder roundtable sessions and two information sessions which were designed as open feedback forums where interested parties could ask questions, seek clarifications, and constructively challenge assumptions underpinning the access arrangement submission.

Over the course of the stakeholder engagement journey, we have been discussing the potential to repurpose the VTS to transport hydrogen. At the Capital Issues Workshop in July (prior to the Energy Ministers' announcement), we suggested undertaking an assessment of VTS pipelines to ascertain their ability to accommodate hydrogen in the gas stream. At this suggestion, stakeholders raised several points including:

- Some stakeholders considered there was merit in an assessment being undertaken
- There were concerns about the cost and who should fund such an assessment; some stakeholders did not support customers funding the assessment
- There was a request for APA to work with gas storage facility owners on the implications for them
- More generally there was a question about whether hydrogen 'was the answer' and concerns about costs to customers for changing to hydrogen compatible appliances
- There was a general concern at the lack of a policy on energy and climate change overall to drive these types of policy decisions.

In response to the above queries, APA hosted a one-hour hydrogen workshop on 26 August 2021 to provide stakeholders with further details on the challenges and opportunities posed by introducing hydrogen into the VTS network. During this workshop, stakeholders posed a range of questions and raised several points including:

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[35] Collation of all pipeline test information and associated assemblies / facilities – an allowance of 2 weeks for a senior engineer to prepare the report has been included for each of the 39 pipelines tested

- A broad desire and need for public education campaigns about hydrogen and safety
- Acknowledgement that the transition from town gas (which was a mixture of hydrogen and carbon monoxide) to existing natural gas specifications required users to update their appliance burner configurations; and that this transition from natural gas to potential hydrogen blends will require similar appliance upgrades
- Suggestion for APA to align the scope of the technical assessment with distribution networks who are investigating the introduction of hydrogen
- Concern about the economics of hydrogen and the likelihood of achieving the Government's target of $2/kg
- Emphasis that there needs to be optimisation of costs between gas and electricity, noting that hydrogen causes sector coupling of both
- A question as to whether APA would consider producing hydrogen in future
- General interest in other hydrogen projects and programs that APA is pursuing.

Further to the roundtable stakeholder engagement sessions, APA circulated a First Look document on 15 October 2021 which included a high-level overview of the proposed hydrogen test program, the estimated costs, and subsequent tariff impacts.

APA received two written submissions providing feedback on the hydrogen assessment in response to the First Look document. Feedback from one organisation requested further details about the test program and called for information to be provided to consumers about required appliance upgrades[36] as well as reiterating concerns about funding the test program by customers.

A second written response was received from AEMO who is responsible for operating the VTS network. AEMO's response acknowledged the benefits of the proposed assessment and its contribution to providing information about the possible future of pipelines as Australia decarbonises. AEMO also identified the need to assess the network as a whole: "as the pipelines in the VTS are interconnected, if hydrogen is blended into one pipeline, it will most likely disperse into the other pipelines. Therefore, the approach should be to assess all the VTS pipelines".

In December 2021, APA submitted its draft Access Arrangement to the AER, including a business case for evaluating and mitigating hydrogen safety and integrity risks on the VTS. The approach proposed in the draft submission was Option 2a (to complete the hydrogen test program over a 5-year period).

At subsequent roundtable discussion, APA has discussed the importance of the test program to understand and mitigate the safety and integrity implications of the Government's policy to expedite bringing hydrogen into the national gas market framework. Stakeholders have acknowledged the need to complete an assessment of hydrogen-compatibility to support the transition of the gas network in a decarbonised future but continued to raise concerns about the best source of funding, and customer tariff impacts.

During Roundtable 17, stakeholders questioned whether the study could be undertaken over two or more regulatory periods. There was also discussion about whether there were areas of the VTS that APA could prioritise for testing.

In response to this feedback, and the AER's draft decision, APA has reassessed the study options in this revised business case and proposes to undertake the study over two regulatory periods, and to depreciate the study over the life of the pipelines. In addition to this, further detailed network modelling has allowed us to identify 9 pipelines that will be prioritised for testing.

APA's tariff modelling estimates that the bill impact of this revised assessment is approximately 10c per year for domestic customers[37].

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[36] APA notes that customer appliance testing is outside of the scope of this technical assessment. This assessment is focused only on the safety and integrity of the transmission pipeline network in response to the expedited amendments to the National Gas Law

[37] This tariff modelling has also been adjusted to assume depreciation over a 55-year period. If recovered over the 30-year life of the asset, then the bill impact will rise to 13.8c per residential customer per year

In addition to the VTS roundtable discussions, APA has received 14 letters of support. A diverse range of stakeholders have provided feedback on the importance of completing this hydrogen test program to facilitate the growth of the hydrogen economy in Victoria. These include:

- Victoria's gas distribution owners/operators: Australian Gas Infrastructure Group (AGIG) and AusNet
- Industry bodies including: The Australian Pipelines and Gas Association (APGA), Energy Networks Australia (ENA), National Energy Resources Australia (NERA), the Plumbing Industry Climate Action Centre (PICAC) and CO2CRC
- Industrial users and/or potential hydrogen producers including AGL, Boral, Fortescue Future Industries, J-Power La Trobe Valley, and Victorian Hydrogen & Ammonia Industries Limited
- Local councils and committees including Wellington Shire Council and the Committee for Gippsland

Some key points raised in these letters of support are extracted below.

"With several Victorian gas distributors proposing to blend hydrogen in their upcoming access arrangements, and with the Victorian Government's RGT plans, it is paramount the gas transmission network conducts the necessary complementary hydrogen safety and integrity assessments. The technical challenges for the transmission network, particularly where the transmission and distribution networks interact, will be crucial to finding a viable pathway to a safe, reliable and affordable hydrogen future." - AusNet

"…we consider renewable gas to be an important part of the industry's contribution to a net zero emissions future and are supportive of efforts by the industry to scale up production and distribution. We consider that projects such as APA's proposed Hydrogen Safety and Integrity Assessment can contribute to the opportunity that renewable gas has to be part of Victoria's low-carbon future energy mix." – AGIG

"For Victoria, the Victorian Transmission System provides gas to the local distribution networks that serve over 2 million homes and businesses. Testing the different sections of the VTS will need to be carried out before hydrogen blending can commence at scale in Victoria, and hence contribute to both Victoria's and Australia's emission reduction targets." – ENA

"Hydrogen as an alternative to natural gas is a key component of Victoria's gas substitution roadmap. For APA, the repurposing of existing gas infrastructure for hydrogen is lower cost than building entirely new pipeline networks. Before hydrogen can be blended in the VTS, APA and the energy industry will need to characterise what the safety and integrity risks might be and find solutions to mitigate such risks." - AGL

Appendix A – Risk Assessment

	Risk Statement			Consequences (enter impact number for all)								Probability /Likelihood	Inherent risk rating	Preventing controls	Current		Current (or Residual) risk rating
Risk Case	Causes (Facts) "Due to...." (fact, requirement, environment)	Risk (Uncertainties) "there is a threat / opportunity that..." (uncertain event or circumstance)	Impact/consequences "which may result in..." (potential outcome / impact on objectives)	Health & Safety	Environment & Cultural heritage	Operational Capacity	People	Compliance	Reputation & Customer	Financial	Highest consequence rating (calc)	Likelihood	Inherent risk (use highest consequence) level on the 5 5 "our level of risk to our project objectives WITHOUT controls..." CALC DO NOT ENTER	Current Controls to prevent causes or mitigate consequences if they happen "what controls do we have in place TODAY (or plan to have) to manage the causes or consequences of the risk ..."	Consequence	Likelihood	Residual risk or Current risk rating risk level on the 5 5 "our level of risk to our project objectives WITH controls..." CALC DO NOT ENTER
VTS Not Ready for H2	Amendments to the National Gas Law are being expedited so that hydrogen blends, biomethane, and other renewable methane gas blends are brought within the national energy regulatory framework.	APA will be unble to demonstrate capability to transport H2 blends in the VTS Transmission system by 2030.	APA will not be able to comply with Gas Safety Act, AS2885, and VTS pipeline licences.					3	3		3	4	Moderate	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS	4	2	Moderate
	The Gas Safety Act and the Pipelines Act requires APA as owner of the VTS to minimise risks as far as practicable, if H2 is introduced into the VTS. The Acts and Regulations also demand adherence to AS2885 which demands a similar risk tolerance.		APA will not be able to comply with the principles of ALARP without undertaking the study of integrity of VTS pipelines to transport H2. ESV unable to approve safety case and will prevent the hydrogen production facility from injecting into VTS, and potentially development completely.					3			3	5	High	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS	3	2	Low
	The Victorian Government's Gas Substitution Roadmap highlights hydrogen to play a role in achieving Net Zero.		APA would not ready to transport H2 blend in the VTS and becomes a road block to customers in using H2 blend gas as fuel of choice.						3		3	4	Moderate	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS	3	2	Low
Loss of Pipeline Integrity due to H2	Hydrogen injected into the VTS high pressure network from adjoining pipelines and is absorbed into the pipeline steel, resulting in hydrogen embrittlement of all exposed pipelines.	Loss of pipeline integrity due to hydrogen embrittement.	The remaining life of the VTS would be reduced if hydrogen entered the VTS and pipeline pressure cycling is unconstrained, as per current operation.						3	4	4	3	High	Additional operational costs associated with increased controls required including remediation of pipeline, reduction in operating pressures, limiting pressure cycling, early retirement of pipeline.	4	2	Moderate
			<u>Overall Impact on VTS</u> Pipeline rupture resulting in potential fatality of members of public, personnel and/or customers. 2270 km of pipelines across the VTS have their integrity compromised, affecting over 2.2 m customers in the VTS. Loss of supply due to pipeline rupture affecting potentially thousands of customers in various zones (see below). Pipeline replacement - flow on impact to distribution customers; significant supply disruption for extended period while pipeline is replaced.	5	3	4			4	3	5	3	High	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS. Additional mitigation/controls are outlined for the various zones below.	4	2	Moderate
	Hydrogen injected into the inner ring main		<u>Melbourne Zone</u> Hydrogen is injected into the inner ring main (owned by AusNet, MultiNet or AGN) will be transported into APA's inner ring mains and and leaves the inner ring main via Brooklyn compressor station into the greater transmission system to Bendigo, Ballarat. 180 km of transmission pipelines compromised, and if rupture occurs, potential risk of loss of supply to 1.4 m customers and possible injury or fatality.	5	3	4			4	3	5	3	High	Brooklyn Compressor staiton 12 (10/11) will have to be disconnected from compressing gas from the inner ring main and only compress gas from the South West Pipeline. RIsk reduced once WORM is constructed. Limiting gas flows from other interconnected pipelines flowing into APA's transmission by installation of non-return valves. However, this results in reduced flexibility and functionality to VTS operation and increases the threat to system security.	4	2	Moderate
	Hydrogen injected at Culcairn		<u>Northern Zone</u> Hydrogen is injected at Culcairn annd transported into APA's northern Zone T74 or T119 pipelines to Wollert. 965 km of transmission pipelines, and potential loss of supply to 210,000 customers in that zone and possible injury or fatality.	5	3	4			4	3	5	3	High	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS.	4	2	Moderate
	Hydrogen injection west of Iona		<u>Western Zone</u> Hydrogen blend transported into APA's western zone (Iona - Portland). 370 km of transmission pipelines compromised and if rupture occurs potential loss of supply to 50,000 customers and possible injury or fatality.	5	3	4			4	3	5	3	High	Lowering operating pressure of the Western system from Iona to mitigate the risk of pipeline rupture due to H2 embrittlement. There may be sufficient capacity to supply demands but will reduce available spare capacity and linepack. Will still require integrity testing.	4	1	Low
	Hydrogen injected at Longford		<u>Gippland Zone</u> Hydrogen injected at Longford and transported into APA's Longford - Dandenong/Lurgi. The Lurgi, the oldest and with its own integrity issues will be at high risk of rupture . 410 km of transmission pipelines compromised, and if rupture occurs, potential loss of supply to 138,000 customers within those pipelines. Potentially 2.2 m customers at risk of loss of supply if Longford- Dandemong mains is ruptured and possible injury or fatality.	5	3	4			4	3	5	3	High	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS.	4	2	Moderate

	Risk Statement			Consequences (enter impact number for all)								Probability /Likelihood	Inherent risk rating	Preventing controls	Current		Current (or Residual) risk rating
Risk Case	**Causes (Facts)** "Due to...." (fact, requirement, environment)	**Risk (Uncertainties)** "there is a threat / opportunity that..." (uncertain event or circumstance)	**Impact/consequences** "which may result in..." (potential outcome / impact on objectives)	**Health & Safety**	**Environment & Cultural heritage**	**Operational Capacity**	**People**	**Compliance**	**Reputation & Customer**	**Financial**	**Highest consequence rating (calc)**	**Likelihood**	**Inherent risk (use highest consequence) level on the 5 5** "our level of risk to our project objectives WITHOUT controls..." " CALC DO NOT ENTER	**Current Controls to prevent causes or mitigate consequences if they happen** "what controls do we have in place TODAY (or plan to have) to manage the causes or consequences of the risk ..."	**Consequence**	**Likelihood**	**Residual risk or Current risk rating risk level on the 5 5** "our level of risk to our project objectives WITH controls..." CALC DO NOT ENTER
	Hydrogen injected at Brooklyn		Ballarat Zone Hydrogen blend transported into Brooklyn - Ballan, Ballarat pipelines. Hydrogen is injected into the inner ring main could leave the inner ring main via Brooklyn compressor station into the greater transmission system to Bendigo, Ballarat. 235 km of transmission pipelines compromised, and if rupture occurs, potential loss of supply to 128,000 customers and possible injury or fatality.	5	3	4			4	3	5	3	High	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS.	4	2	Moderate
	Hydroggen iinjected at Geelong		Geelong Zone Hydrogen is transported into Brooklyn- Corio, Brooklin Iona pipelines. 110 km of transmission pipelines compromised, and if rupture occurs, potential loss of supply to 290,000 customers and possible injury or fatality.	5	3	4			4	3	5	3	High	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS.	4	2	Moderate
Re-configuration of the VTS to accommodate H2	Reduce maximum allowable operating pressure to mitigate impacts of hydrogen embrittlement	Reduced capacity and operational flexibility of VTS due to network reconfiguration to accommodate H2 blends	Additional investment in the gas infrastructure system may be required to maintain capacity of the system. Cost of network modifications / market interventions to maintain capacity and restrict hydrogen pathways outweight costs of compatibility testing							4	4	3	High	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS	4	2	Moderate
	Ad hoc segregation of the VTS zones to prevent hydrogen blend pipeline from natural gas only pipelines, hence reduced flow paths within the VTS.		Gas market dynamics are impacted due to restricted movement of gas movements resulting in reduced supply and capacity Potential increased gas prices.						3	3	3	3	Moderate	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS	3	2	Low
			Hydrogen injection limited to specific regions within the VTS s will limit the development opportunities for hydrogen producers						3		3	3	Moderate	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS	3	2	Low
			Customer supply reliability is compromised with reduced capacity. Loss of linepack for GPG operations.			3			3	3	3	3	Moderate	Undertake technical assessment, including materials testing in hydrogen to understand the impacts of hydrogen embrittlement on the VTS	3	2	Low

Appendix B – Parmelia Gas Pipeline Conversion Project

EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland
6–10 June 2022

EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland • 6–10 June 2022

PAPER TITLE: MATERIALS TEST PROGRAM RESULTS TO SUPPORT AUSTRALIA'S FIRST HYDROGEN PIPELINE CONVERSION PROJECT (APGA)

PAPER NUMBER: 28

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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.

For this project, the new H_2SAFE(TI) laboratory developed by the Future Fuels CRC at the University of Wollongong will be used to measure material properties in both air and hydrogen environments. Tests are also being conducted at Sandia National Laboratories (SNL), USA, to provide a reference for the new laboratory and apply testing methods for which SNL has established expertise.

In conjunction with the modelling and the analysis conducted by the 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.

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1. INTRODUCTION

APA owns and operates the 416 km 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 43 km 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 wall pipes with a nominal 7.92 mm wall thickness. Table 1 summarise the design of the section of PGP under consideration for hydrogen conversion.

Attribute	Variable	Value
Material Specification		API 5L
Material Grade		X52
Diameter	D	355.6 mm
Wall Thickness	t	5.56, 7.92 mm
SMYS	σ_y	360 MPa
SMTS	σ_u	460 MPa
Allowances		0 mm
Length		42.3 km
Start & End KPs		364.6 to 406.9
Location Classes (AS2885.6)		T1, T2 & R2 (and S & CIC)
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 (likely 1968 edition)

Table 1 Basic pipeline design data.

There is potential for several hydrogen offtake industries in the KIA, 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 transportation 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

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[1] Construction of the PGP commenced in 1970.

fatigue life of the steel is deteriorated. This has potential to compromise the pipeline's integrity and service performance, and is known as hydrogen embrittlement.

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 cannot be applied retrospectively.

APA has partnered with Future Fuels Cooperative Research Centre (Future Fuels CRC), GPA Engineering and the University of Wollongong (UoW) for 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) up to 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 in Phase 1 and provides an outlook for planned work associated with Phase 2 with the current results. The focus is on the pipeline itself. Topics relevant to the impact of the conversion on facilities are/will being assessed separately including material compatibility, piping design, instrumentation and equipment compatibility, class rating & area classification etc.

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 first 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 are being undertaken in air and then in hydrogen. The results will feed into the engineering design and fitness for service calculations, pipeline failure mode analyses, 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 pipeline material, 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 along with relevant activities answering B31.12 requirements.

‘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 service. A suite of tests was 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 knowledgebase 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 [10]. During this phase, samples are also being testing at Sandia National Laboratories (SNL) in the USA to provide for comparison between the newly establish lab at UoW and the long-established hydrogen testing capabilities at SNL. The results will also be used to guide the development of Australia’s Hydrogen Pipeline Code of Practice, which is currently being development by key members of the Australian pipeline industry and research sectors.

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 [10] [11] [12];
- The participation in Standards Australia ME-093 committee and subcommittees for hydrogen in pipelines;
- A 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.
- A 2020 report for another pipeline company that ana 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 is actively consulting 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 (excluding the topic of hydrogen assisted cracking mechanisms for welded material), 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 [13] and EIGA [14];
- 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. 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.

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

Table 2 Pipe sections selected for the test program.

(a) (b) (c)

Figure 1 Preparation of the pipe sections for sampling. (a) Ring cut from section S8, using a band saw. (b) Marking and measuring of rings for extraction via water-jet cutting. (c) Completed markings for sections S1, S5 and S8.

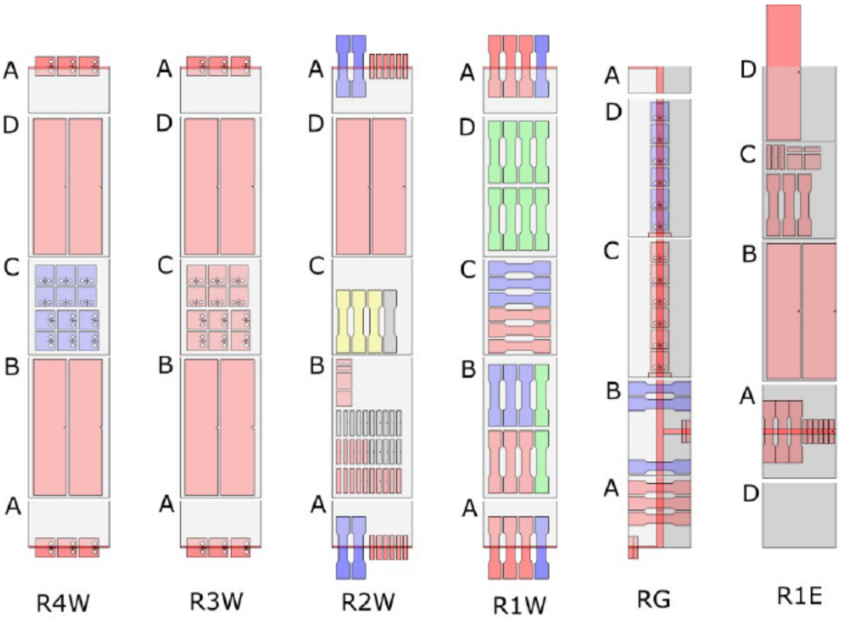

Figure 2 Sample cutting diagram for pipe section S8.

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.

				Test Material								
				Section S8			**Section S1**			**Section S5**		
Task Group	**Task Ref.**	**Task Detail**	**# Tests**	**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 C(T)	3	3	-	-	-	-	-	-	-	-
	SFRA-L/B	Base metal longitudinal static fracture C(T)	3	3	-	-	-	-	-	-	-	-
	SFRA-T/SW	Seam weld circumferential static fracture C(T)	0	(Phase 2)	-	-	-	-	-	-	-	-
	SFRA-L/GW	Girth weld longitudinal static fracture C(T); WCL and HAZ	6	-	6	-	-	-	-	-	-	--
DYNAMIC FRACTURE	DFRA-TC/B	Base metal transverse Charpy impact test	30	15	-	3	3	-	3	3	-	3
	DFRA-TC/SW	Seam weld transverse Charpy impact 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 C(T)	3	3	-	-	-	-	-	-	-	-
	FATI-L/B	Base metal longitudinal fatigue test C(T)	3	3	-	-	-	-	-	-	-	-
	FATI-T/SW	Seam weld circumferential fatigue test C(T)	0	(Phase 2)	-	-	-	-	-	-	-	-
	FATI-L/GW	Girth weld longitudinal fatigue test C(T); WCL and HAZ	6	-	6	-	-	-	-	-	-	-

Table 3 Test program for Phase 1.

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.

At least one ring was taken from each region (W, G, E) and subsequently cut into 'plates' A, B, C and D, see Figure 2. 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.

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.

4.1. Material Characterisation

The chemical composition of the pipes was determined by Optical Emission Spectroscopy (OES) and are summarised in Table 4. The %wt of carbon was between 0.18 and 0.23 with a carbon equivalent Ceq 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.

wt/wt (%)																	
Section	**Side**	**Fe**	**C**	**Mn**	**Si**	**S**	**P**	**Ni**	**Cr**	**Mo**	**Cu**	**V**	**Nb**	**Ti**	**Al**	**B**	**C_{eq}**
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	0.23	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	0.19	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

Table 4 Pipe steel composition for each section and side.

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 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.

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.

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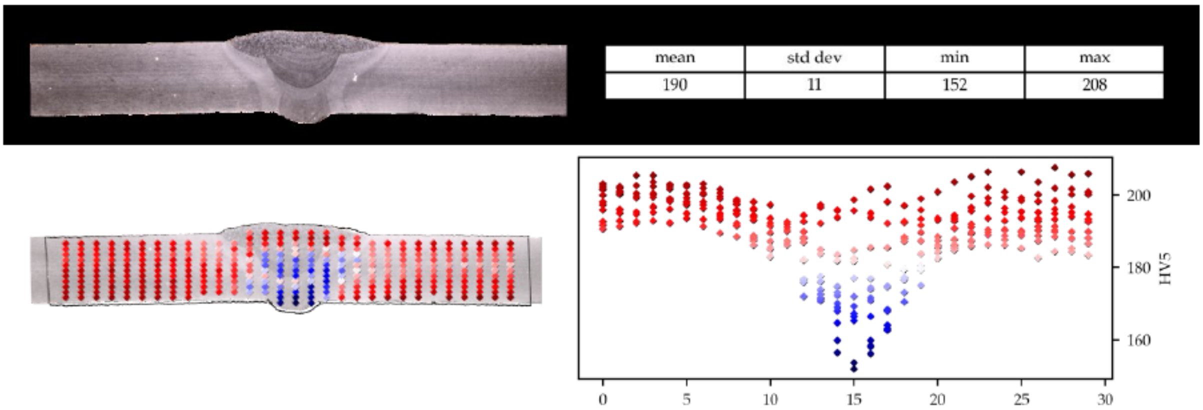
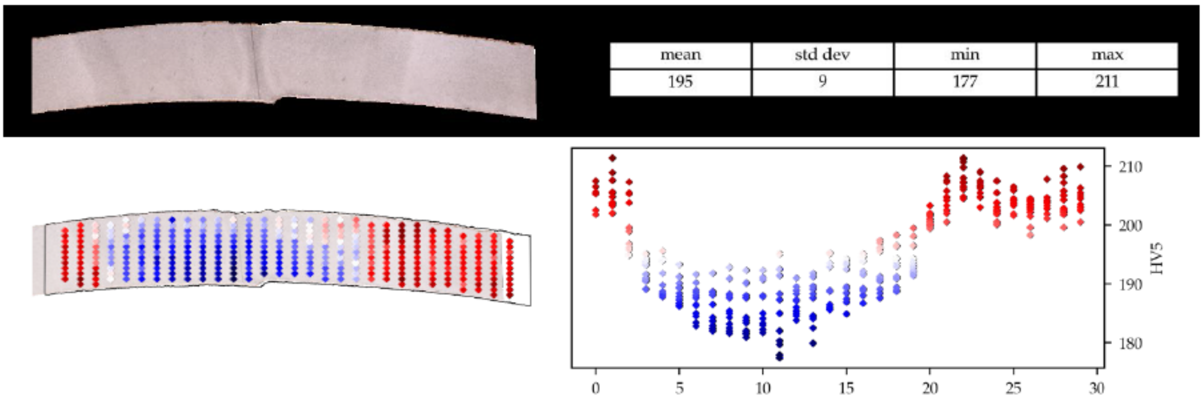
[2] API 5L established the Product Specification levels from the 42nd edition (July 2000)

An automated hardness tester was used to measure the hardness over most 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 3 and Figure 4 illustrate the results for GW and SW specimens taken from S1 respectively. The profiles are consistent with the other cross weld tested.



mean	std dev	min	max
190	11	152	208

Figure 3 Cross-section of girth weld of S1 and hardness values (HV5).



mean	std dev	min	max
195	9	177	211

Figure 4 Cross-section of seam weld of S1 and hardness values (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 higher 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, centred 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 higher 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 [15]. 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.

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[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.

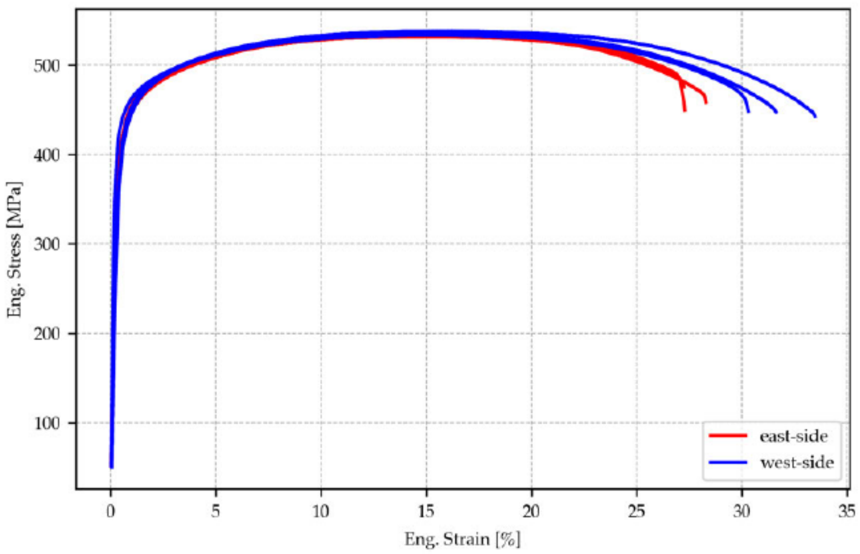

Figure 5 Engineering stress-stress curves from base metal transverse specimens from section S1.

4.2. Tensile Tests

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 [16].

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 etched 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 e_f is 19.9 % for the thin wall pipe and 21.5 % for the thick wall. All specimens fulfilled the requirements.

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

4.3. Drop-Weight Tear Tests

DWTT were conducted in accordance with AS1330:2019 [17]. All sample preparation was done at UoW except for the pressed-notch. The machined samples were sent to BlueScope Steel Pty Ltd, Port Kembla, Australia, where the pressed-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 °C, 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 °C for the thin-wall pipe S8-W.

4.4. Charpy V-notch Impact Tests

Charpy impact tests were conducted according to ASTM A370 [18] 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.

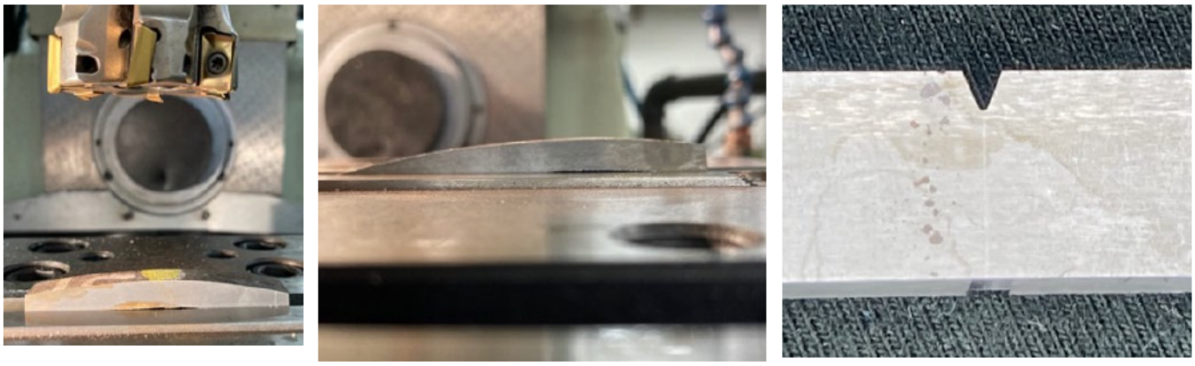
(a) (b) (c)

Figure 6 Preparation of the 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 severe cases. (c) Notch

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

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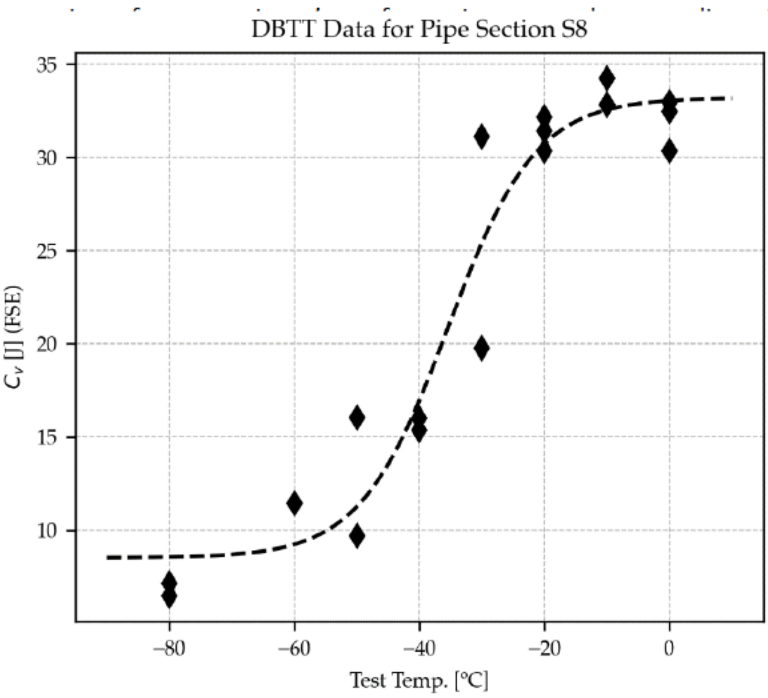


Figure 7 DBTT data for Charpy specimens extracted from the east and west side of section S8.

CVN tests were conducted at -10 °C. The transverse CVN upper shelf energy at -10 °C 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 °C to 0 °C 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 °C. The transition region spans from -60 °C to less than -20 °C for these specimens with a 4mm thickness.

4.5. Fatigue Tests

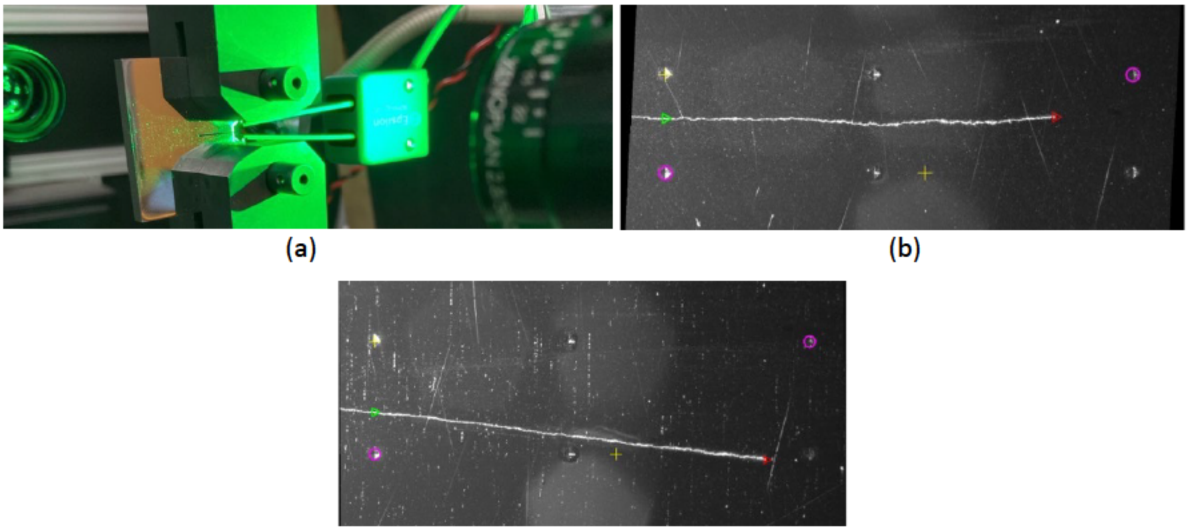
Fatigue tests in air were conducted according to ASTM E647 using C(T) specimens [19]. Both the fatigue pre-crack phase and the fatigue test phase used a clip gauge with a +2.5mm/-1mm amplitude with a gauge length of 3mm.

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 8 gives an overview of the setup with the sample, the cameras and the clip gauge (a) as well as the crack path as seen by the cameras during the fatigue pre-crack phase (b) and (c).

Fatigue tests of compact tension specimens were generally successful, albeit specimens sampling the GW-HAZ 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.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 9 illustrates the results from the transverse specimens of S8-W in BM.


(a) (b)

(c)

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 GW-CL specimen from S8. (c) Deviation of crack path out of the symmetry plane in the GW-HAZ of S8.

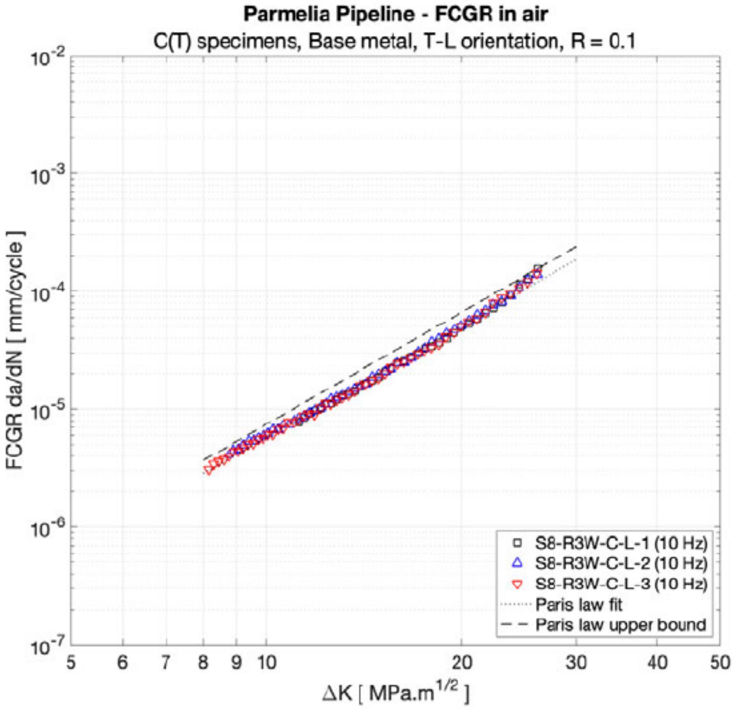


Figure 9 Fatigue crack growth rate in air for the transverse specimens from the base material of section S8.

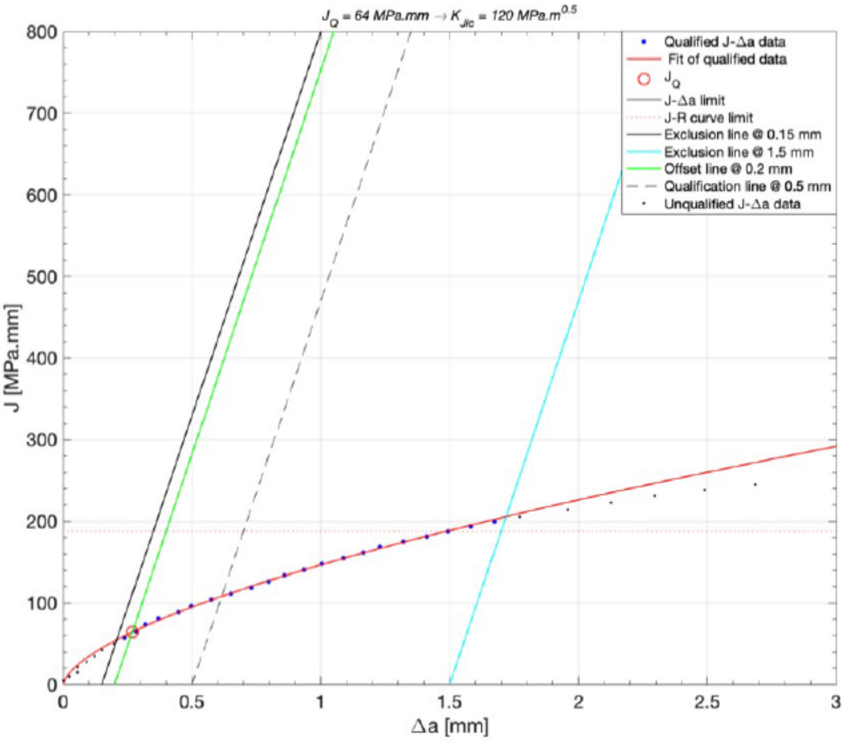


Figure 10 J-Δa curve obtained on a S8 transverse specimen (longitudinal crack) taken from the base metal. A qualified K_{JIc} of 120 MPa.m$^{0.5}$ was measured from this specimen.

4.6. Rising Displacement Fracture Tests

Rising displacement fracture tests in air were conducted according to ASTM E1820 [20] 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. The present results indicated the line pipe toughness in hydrogen could 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[5]. A decrease of K_{JIc} by 50% in hydrogen would result in girth weld toughness in the order of 75 MPa.m$^{0.5}$.

4.7. 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

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[5] The impact of residual stress on the result is not considered in this assessment.

characterisation of a longitudinal fracture, namely transverse tensile tests followed by transverse fatigue and static toughness tests.

5. TEST PROGRAM AND PRELIMINARY RESULTS – PHASE 2

The Phase 2 test program builds on the work done in Phase 1 by testing specimens in a hydrogen environment to finalise the safety management study. Many of the specimen types from Phase 1 are replicated and tested in a hydrogen environment, to quantify the effects of hydrogen embrittlement on the structural integrity analyses. All testing associated with Phase 2 is shown in Table 5.

				Test Material					
				Section S8			**Section S1**		
Task Group	**Task Ref.**	**Task Detail**	**# Tests**	**R1W to R4W**	**RG**	**R1E**	**R1W**	**RG**	**R1E**
TENSILE	TENS-T/B	Base metal circumferential tensile	6	3 @ P1 3 @ P2	-	-	-	-	-
	TENS-L/B	Base metal longitudinal tensile	3	3 @ P1	-	-	-	-	-
	TENS-T/SW	Seam weld circumferential tensile	3	3 @ P1	-	-	-	-	-
	TENS-L/GW	Girth weld longitudinal tensile	6	-	3 @ P1	-	-	3 @ P1	-
STATIC BEND	SBND-T/B	Base metal circumferential static fracture C(T)	6	3 in air 3 @ P1	-	-	-	-	-
FATIGUE	FATI-T/B	Base metal circumferential fatigue test C(T)	17	3 @ P1 3 @ P2 6 @ SANDIA	-	-	3 @ P1	-	-
	FATI-L/B	Base metal longitudinal fatigue test C(T)	3	3 @ P1	-	-	-	-	-
	FATI-T/SW	Seam weld circumferential fatigue test C(T)	9	6 in air 3 @ P1	-	-	-	-	-
	FATI-L/GW	Girth weld longitudinal fatigue test C(T); WCL and HAZ	12	-	4 @ P1 2 CL @ SANDIA	-	-	6 @ P1	-
PERMEATION	PERM/BW	Permeation tests for different pressures and hold times	84	12 @ P1 12 @ P2 12 @ P3	-	12 @ P1 12 @ P2 12 @ P3	12 @ P1	-	-
HIGH-STRAIN RATE	HSTT-TC/BW	Split Hopkinson Pressure Bar tests on base metal transverse compression	60	20 @ $\dot{\varepsilon}_1$ 20 @ $\dot{\varepsilon}_2$ 20 @ $\dot{\varepsilon}_3$	-	-	-	-	-
	HSTT-TS/BW	Split Hopkinson Pressure Bar tests on base metal transverse shear	60	20 @ $\dot{\varepsilon}_1$ 20 @ $\dot{\varepsilon}_2$ 20 @ $\dot{\varepsilon}_3$	-	-	-	-	-

Table 5 Test program for Phase 2.

Phase 2 carries on from Phase 1 by performing a more detailed microstructural analysis as well as by characterising the tensile, fatigue and fracture toughness properties in a hydrogen atmosphere. Additional tests are added which characterise the permeation characteristics of the pipe material; perform quasi-static Charpy V-notch bend tests in air and hydrogen atmospheres; and perform high-strain rate testing with pre-charged hydrogen samples to gain insight on the potential role, if any, hydrogen may play in high-speed fracture propagation.

For tests conducted in a hydrogen atmosphere, the samples are exposed to a high-purity hydrogen gas (>99.999%) at two different pressures. All tested samples are tested at pressure condition P1 = 5.6 MPa(g). Select samples are also tested at condition P2 = 2.8 MPa. For the permeation tests, and addition condition P3 = 1.4 MPa is added.

Assessment of the material response to high strain rates when pre-charged with hydrogen is conducted by a Split Hopkinson Pressure Bar system. The system can test samples at strain rates in excess 5000 s^{-1}. For these tests, 3 strain rates will be conducted ($\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$) at the provisional rates of 1000, 2000 and 3000 s^{-1}, respectively. The hydrogen gas will be trapped in the pre-charged samples by storing them in liquid nitrogen.

A small-scale round-robin testing arrangement has been established with (SNL) to complement the C(T) fatigue and toughness tests done 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 steel response to hydrogen atmospheres. Furthermore, the testing done by SNL assists in validating the procedures in the newly establish hydrogen lab at UoW. A total of 8 C(T) specimens from S8W will be tested at SNL.

5.1. Fatigue and Fracture Test Results from Sandia National Laboratories

The general test procedure for combined fatigue and fracture test methods in gaseous hydrogen is provided in [21]. The laboratory temperature is maintained at approximately 20°C. Although the pressure of interest for conversion is 5.6 MPa(g), other pressures are considered for supplementary samples.

The crack growth in fatigue is determined by the compliance method, where crack growth during the fracture test is measured using the Direct Current Potential Difference (DCPD) method. Each sample is tested in fatigue to a given crack length then the remainder of the test protocol assesses the fracture toughness. The fatigue testing conforms to the ASTM E647 standard, and the toughness testing follows ASTM E1820. At the conclusion of the tests, the samples were completely fractured to assess the fracture surfaces.

The C(T) specimens are of similar geometry to the specimens from Phase 1 with a minor adjustment to accommodate the requirements of SNL's test apparatus. The nominal thickness (B) remains the same at 4 mm. The specimen width is set to 26.4 mm. The specimens do not have side groove as per UoW requirements. Samples to be tested at UoW will use this geometry.

8 specimens will be tested in total. 2 specimens come from section S8's girth weld centreline and are tested in pure hydrogen at 5.6 MPa(g). Of the remaining 6 specimens, 2 are tested in pure hydrogen at 5.6 MPa(g) and 4 are provided to SNL to explore the effects of different conditions (e.g., varying R-ratios and different partial pressures).

To date, SNL has tested five specimens: 4 sampling the BM, and 1 sampling the GW-CL. Results from two of the BM C(T) samples at 5.6 MPa are reported here. These samples are named TL5 and TL6.

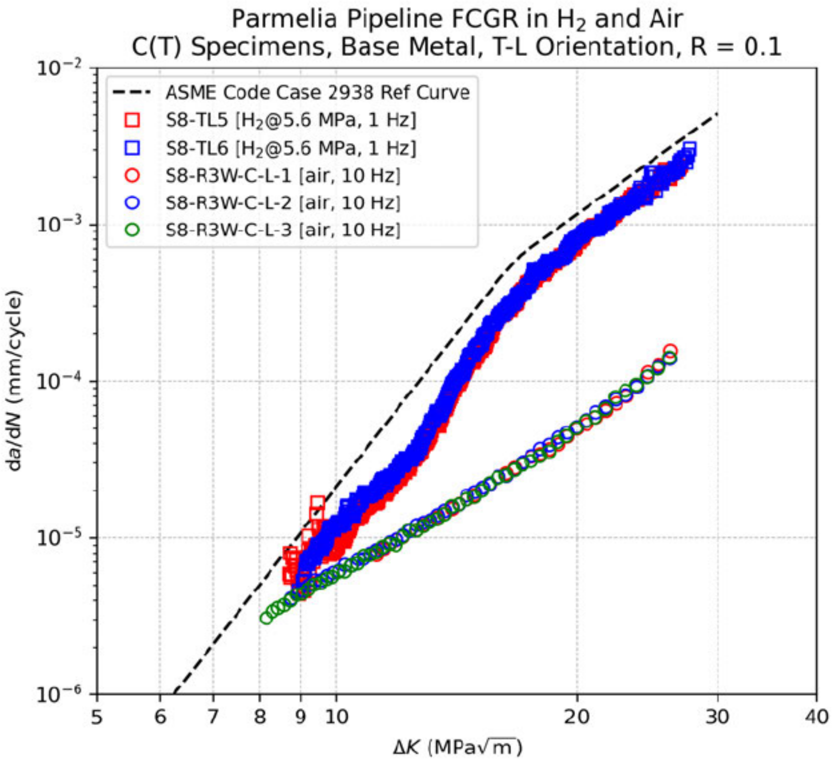

Figure 11 Fatigue crack growth rate in H_2 and air for the transverse specimens from the base material of section S8W.

The pre-cracking phase targeted a ratio a/W of 0.29 with K_{max} in the order of 9 MPa.$m^{0.5}$. The fatigue tests used a R ratio of 0.1 at a frequency of 1 Hz. The 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 TL5 and TL6 are shown in Figure 11. The repeatability is acceptable with trends in line with expectations from the literature. The reference curve from ASME Code Case 2938 is also provided with a pressure correction as described in [22]. It provides a conservative prediction of the material performance at this R ratio and pressure.

These initial observations are encouraging. They support the preliminary engineering calculations conducted in Phase 1 of the project based on expected material behaviour.

Figure 12 presents the load-displacement curve and the J-Δa curve for specimen TL5. Results are comparable for TL6. The qualified and conservative[6] fracture resistance K_{JQH} from TL5 and TL6 is at least 58 and 58.6 MPa.$m^{0 5}$ respectively. The repeatability is acceptable.

As indicated earlier, the tests conducted in air at UoW indicated an average fracture resistance of 118 MPa.$m^{0.5}$ for S8 BM in the same direction. This is a loss close to 50% in fracture resistance between the two series of tests. The measured conservative values are close but above the B31.12 threshold for these two specimens.

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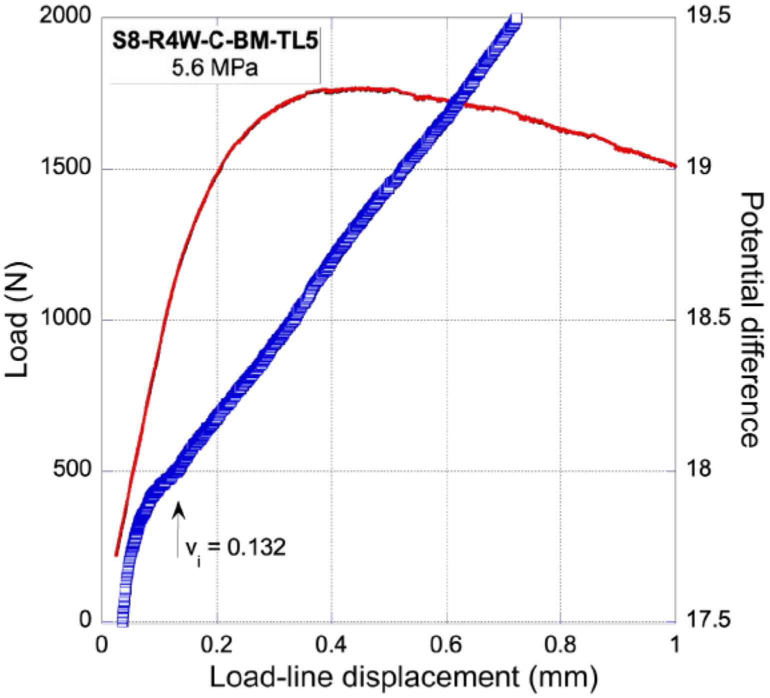
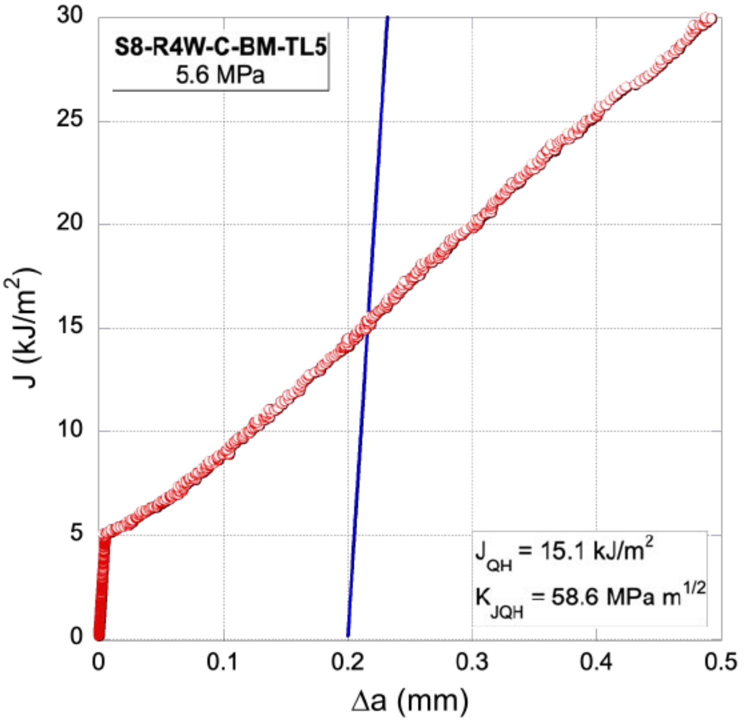
[6] The fracture initiation point is challenging to evaluate on these specimens due to factors such as small, uncracked ligament area and crack tunnelling. The fracture resistance reported here is based on a measure of the initiation point leading to conservative values.



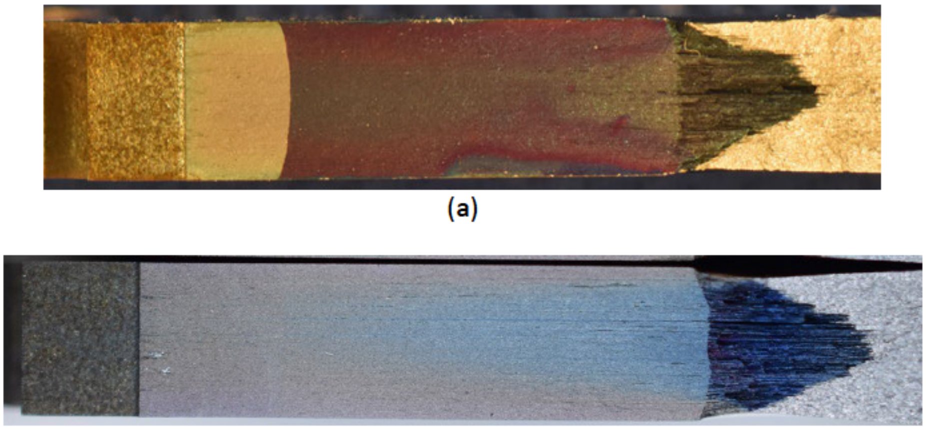
(a)



(b)

Figure *12* 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.

Figure 13 presents the fracture faces from two BM-TL specimens, one tested in air at UoW, the other tested in hydrogen at SNL. Both present similar features and tunnelling of the fracture from the fracture test. However, the test conducted in air presents a more pronounced lateral contraction, indicative of the higher degree of plastic deformation associated with the increased fracture resistance.



(a)

(b)

Figure 13 (a) Fracture face from BM-TL specimen S8-TL5 tested for FCGR and fracture resistance in pure hydrogen at 5.8 MPa(g) (SNL). (b) Fracture face from a BM-TL specimen tested in air (UoW).

In summary, while not all tests have been conducted, preliminary interpretations and conclusions are:

- The material appears to be typical of those within this class.
- The data were repeatable.
- The ASME CC2938 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 assessment.

5.2. Outlook

Phase 2 testing is still being conducted and is estimated to complete in December 2022. The results and assessments will be made available in future disseminations.

6. 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. At the time of publication, all engineering calculations have been performed based on the results from Phase 1, where only material characterisations in air were performed. The calculations in the sections below that consider a pipeline transporting hydrogen gas were made based on trends in literature and existing models in standards. Once the results from hydrogen testing are available, the engineering calculations will be updated to reflect the as-tested conditions.

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'[7] these will, where practical, conservatively predict the impact of hydrogen on the existing design.

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[7] 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 6. These pressures have been used through the various calculations. The material properties obtained by UoW and used for the assessments are summarised in
Table 7.

Case	Pressure	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 Pipeline internal gas pressures.

Variable	Value
Base-metal Charpy V-notch impact 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 impact toughness (full-size equivalent)	10 J at -10 °C
Seam weld Actual Yield Strength	430 MPa
Seam weld Actual Tensile Strength	510 MPa

Table 7 Pipe material properties retained for the calculations (air).

6.1. 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' (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 8 summarises the CDL results from the calculation.

	CDL (mm) *at an internal pressure of...*		
Case	**4.5 MPa(g)**	**5.6 MPa(g)**	**10.6 MPa(g)**
Wall thickness 5.56 mm			
High-toughness	164	125	44
30 J (base pipe)	150	119	44
15 J (base pipe with H_2)	128	104	N/A
10 J (weld)	114	93	39
5 J (base pipe with H_2)	91	74	N/A
Wall thickness 7.92 mm			
High-toughness	305*	231	102
30 J (base pipe)	242	197	98
15 J (base pipe with H_2)	199	165	N/A
10 J (weld)	175	145	77
5 J (base pipe with H_2)	138	115	N/A

* Result exceeds the range of validity of the formula

Table 8 Critical Defect Length (mm), using the NG-18 fracture initiation equation.

A comparison between the API 579 model [23] and the NG-18 [24] [25] 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.

6.2. 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 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[8]: 50 MPa.m$^{0.5}$

The results are summarised in Table 9. 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.

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

Table 9 Fatigue life from fatigue crack growth modelling.

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

6.3. 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 [26]. Generally, the arrest toughness was found to be highest at the design minimum temperature of -7°C.

Internal pressure	Pure methane	10% H_2	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

Table 10 Minimum required ductile fracture arrest energy at -7 °C, using the BTCM.

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.

6.4. 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 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).

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.

Energy release rate [GJ/s]	Pressure [MPa(g)]	Natural gas [mm]	10% H_2 Blend [mm]	Pure H_2 [mm]
10	4.5	291	294	301
	5.6	261	264	270
1	4.5	92	93	95
	5.6	83	84	85

Table 11 Full-bore rupture radiation contours.

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.

7. 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 service 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 may be required to accommodate variations between upstream hydrogen supply and downstream hydrogen consumption profiles. The difference between the upstream and downstream profiles may be accommodated by the available pipeline storage, or alternative firming solutions. This will be explored further as offtake requirements are confirmed.

If the supply and demand profiles for pure hydrogen are misaligned, e.g. hydrogen supply is intermittent (such as electrolyser production linked to renewable generation) and hydrogen demand is driven by 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[9] 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.

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[9] 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).

- 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.

8. 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. 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 will be developed in Phase 2, 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, this may prompt a revision of the formal ALARP study.

9. SUMMARY AND OUTLOOK

APA's research progresses to test the ability of 43-kilometres of Parmelia Gas Pipeline (PGP) 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 Australian Pipelines & Gas Association (APGA) Code of Practice (CoP) for Hydrogen 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. Tests conducted at Sandia National Laboratories provide a valuable support to the deployment of this new laboratory. They also provided early insight on the properties of the material which benefit the project.

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.

10. ACKNOWLEDGMENTS

This project is supported by APA Group and contracted through Future Fuels CRC. Future Fuels CRC is supported through the Australian Government's Cooperative Research Centres Program.

Phase 2 of the PGP project is supported by grant funding from the Western Australian Government's Renewable Hydrogen Fund, which is administered by the Department of Jobs, Tourism, Science and Innovation (the Department).

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. The activities conducted by Sandia National Laboratories in this project are supported by the U.S. Department of Energy, through the Office of Energy Efficiency and Renewable Energy's (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO).

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Appendix C – Letters of Support

Australian Gas Infrastructure Group

Australian Gas Infrastructure Group
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01 August 2022

APA VTS Australia (Operations) Pty Limited
Level 25, 580 George Street
Sydney NSW 2000
by email: harriet.floyd@apa.com.au

Dear Harriet

Re: Victorian Gas Transmission System – Hydrogen Safety and Integrity Assessment

As you would be aware, Australian Gas Infrastructure Group (AGIG) is the largest gas distribution business in Australia, serving more than 2 million customers through our networks in Victoria, Queensland, South Australia, and several regional networks in New South Wales and the Northern Territory. In Victoria we serve around 1.5 million residential, commercial and industrial customers through Multinet Gas Network and Australian Gas Networks (Victoria and Albury).

Like APA, AGIG supports the global transition to a lower carbon future and is focused on and invested in mitigating long-term impacts to the environment. Our Low Carbon Strategy targets 10% renewable gas in networks by no later than 2030, with full decarbonisation of our networks by 2040 as a stretch target and by no later than 2050.

Renewable gas forms a central part of our commitment to decarbonising our gas networks and we are underway with deploying numerous low carbon gas projects, including:

- Hydrogen Park South Australia – A 1.25MW electrolyser to demonstrate the production of renewable hydrogen for blending with natural gas (up to 5%) and supply to more than 700 existing homes in metropolitan Adelaide. This project is now operational and has plans to expand its reach to more than 3,000 homes by the end of 2022.
- Hydrogen Park Gladstone – A 175kW electrolyser to demonstrate the production of renewable hydrogen for blending with natural gas (up to 10%) and supply to the entire network of Gladstone, including industry. First production from this project is expected in 2023.
- Hydrogen Park Murray Valley – A 10MW electrolyser to produce renewable hydrogen for blending with natural gas (up to 10%) and supply the twin cities of Albury and Wodonga, with the potential to supply industry and transport sectors. We are working towards a positive investment decision by October this year to deliver this project.

AGIG sees that Victoria holds great potential for further renewable gas projects. We support initiatives for the scaling up of industries that supply renewable gas and hydrogen.

Key to the industry's ability to achieve this scale is a level of policy engagement and support similar to what has been provided to the renewable electricity sector over many years. It is this type of proactive support that has driven renewable electricity down the cost curve and helped to overcome the ongoing challenges and significant uncertainty that existed at the start of the low carbon transition of electricity.

We consider that support for renewable gas policies and projects will not only unlock a substantial new supply of gas at a crucial time in the energy sector, but can also accelerate decarbonisation of the electricity and transport sectors, for example through further driving down costs by providing a substantial new market for renewable electricity, providing grid-stability support and deep electricity storage.

Implicit in the above, we consider renewable gas to be an important part of the industry's contribution to a net zero emissions future and are supportive of efforts by the industry to scale up production and distribution. We consider that projects such as APA's proposed Hydrogen Safety and Integrity Assessment can contribute to the opportunity that renewable gas has to be part of Victoria's low-carbon future energy mix.

If you have any questions, please do not hesitate to contact Kristin Raman, Acting Executive General Manager People and Strategy – [_].

Yours sincerely

Craig de Laine
Chief Executive Officer

09 August 2022

To whom it may concern,

Australian Pipelines and Gas Association Support for testing the readiness of hydrogen blending in Victoria's Transmission System

The Australian Pipelines and Gas Association welcomes the opportunity to provide support to APA Group's proposed hydrogen safety and integrity study for the Victorian Transmission Systems.

APGA believes that it is in the best interest of consumers with relation to price, quality, safety, reliability and security of supply to endorse APA Group testing the readiness of Victoria's Transmission System for hydrogen compatibility. Decarbonisation of the energy system is critical to achieving net zero emissions and it is very likely the decarbonisation of the gas system will be the most affordable and reliable option for consumers.

Hydrogen blending represents one of the first steps along the journey to enabling least cost gas use decarbonisation through the uptake of renewable gases. Testing the readiness of regulated natural gas infrastructure for hydrogen is essential to deliver this first step.

As identified within the Victorian Gas Substitution Roadmap, hydrogen uptake is anticipated to account for 30 to 60 per cent of the solution to gas use decarbonization between now and 2050[1]. This renewable hydrogen industry will take time to develop, and hydrogen blending will allow for investment in Victoria's first wave of hydrogen production facilities without the need for customers to change appliances or behaviour.

This opportunity is being proved in hydrogen blending projects already operated by AGIG and Jemena today in Adelaide and Sydney respectively. AGIG is due to deliver a similar outcome for Victorian gas customers in Wodonga via the HyP Murry Valley project. Enabling hydrogen blending in gas infrastructure is a joint effort being undertaken by a breadth of APGA members to enable the least cost gas use decarbonisation future for customers.

As identified by the Australian Hydrogen Council, allowing for hydrogen blending in existing gas networks can create around 71,500tpa hydrogen demand. This first 71,500tpa worth of hydrogen production investment will be critical for de-risking investment in large scale commercial hydrogen industry of the 2030's and 2040's.

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With hydrogen blending in gas infrastructure being such a critical part of enabling Australian hydrogen industry development, it is crucial to understand how to deliver at least cost. In February 2022 APGA released a study it commissioned from GPA Engineering which identified that new hydrogen pipelines are able to transport and store energy at lower cost in Australia than high voltage powerlines, pumped hydroelectric energy storage and battery energy storage systems alike. This means that it will be cheapest to produce hydrogen at the renewable energy source and transport it to customers via hydrogen pipelines.

Data provided by the European Hydrogen Backbone (EHB) identifies that there is one mode of energy transport and storage that will cost energy customers even less than new hydrogen pipelines – natural gas pipelines which are repurposed for hydrogen transport[2]. EHB analysis anticipates that the levelized cost of hydrogen transport via repurposed hydrogen pipelines will be in the order of 25 to 50 per cent that of new hydrogen pipelines.

APA Group's proposed test program for Victoria's Transmission System not only supports de-risking of hydrogen production investment but also seeks to enable the least cost supply chain for the delivery of renewable hydrogen to Victorian energy customers. Once the National Gas Objective is amended to relate to all Covered Gases including hydrogen, acting in the best interests of hydrogen customers with relation to price, quality, safety, reliability, and security of supply will be aligned with the National Gas Objective[3].

It is on this basis that APGA believes that it is in the best interest of consumers with relation to price, quality, safety, reliability, and security of supply to endorse APA Group testing the readiness of hydrogen blending in Victoria's Transmission System.

We welcome further discussion on this critical issue. In the first instance, please contact APGA's National Policy Manager, Jordan McCollum, [_]

Yours sincerely,

Steve Davies
Chief Executive Officer
Australian Pipelines and Gas Association

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[2] European Hydrogen Backbone, Grid et al, April 2022 https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf

[3] Extending the national gas regulatory framework to hydrogen blends and renewable gases, Australian Federal Government Department of Climate Change, Energy, the Environment and Water, 2022, https://www.energy.gov.au/government-priorities/energy-ministers/priorities/gas/gas-regulatory-framework-hydrogen-renewable-gases

Building a low emissions future

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29 July 2022

APA VTS Australia (Operations) Pty Limited ACN 083 009 278
Level 25, 580 George Street
Sydney NSW 2000

Attention: Harriet Floyd

By email: [_]

Dear Harriet

Re: Victorian Gas Transmission System – Hydrogen Safety and Integrity Assessment

CO2CRC Limited confirms its support for APA Group's ("APA") hydrogen safety and integrity assessment, as part of its Victorian Gas Transmission System (VTS) 2023-2027 Access Arrangement submission to the Australian Energy Regulator (AER) ("Submission").

Hydrogen as a low carbon alternative to natural gas is a key component of Victoria's gas substitution roadmap and the repurposing of existing gas infrastructure for hydrogen presents a lower cost alternative to building entirely new pipeline networks or full electrification of energy systems.

However, before hydrogen can be blended in the VTS, the safety and integrity risks will need to be understood. CO2CRC understands that APA submitted a business case as part of their Access Arrangement Submission, which outlined the required studies to assess the preparedness of the VTS for hydrogen.

Operating since 2003, CO2CRC is a globally recognised leader in innovative carbon capture, utilisation and storage (CCUS) solutions. Our research portfolio extends to other low emission technologies including the underground storage of hydrogen which will be key to the reliable supply of large-scale, low cost, hydrogen for future power, transport and export demands.

CO2CRC, in partnership with CSIRO and Geoscience Australia, is undertaking pre-feasibility studies for Australia's first field demonstration of safe and effective geological storage of hydrogen at the Otway International Test Centre in Victoria. Greater understanding of the metallurgical effects of hydrogen, and the option of blending hydrogen into the VTS may be of benefit to the proposed field demonstration.

APA has demonstrated their commitment to enabling hydrogen to enter the Australian energy mix in a number of ways;

1. Completed Phase 1 of an investigation into the conversion of a section of the Parmelia Gas Pipeline in Western Australia to be hydrogen ready[1]. Phase 2 of this investigation is underway.
2. Executed an MoU with Wesfarmers Chemicals, Energy and Fertilisers (WesCEF) to undertake pre-feasibility study to assess the viability to produce and transport green hydrogen via APA's Parmelia Gas Pipeline.[2]
3. Executed an MoU as one of the founding consortium members of the Central Queensland Hydrogen Export Project[3]

It is for the reasons above that CO2CRC supports APA in their Submission to the AER.

If you have any questions, please do not hesitate to contact Mr David Whittam, Program Manager Hydrogen on [_].

Yours sincerely

Dr Matthias Raab,
Chief Executive Officer
CO2CRC Limited

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[1] APA set to unlock Australia's first hydrogen-ready transmission pipeline | APA Group

[2] Australia's first potential conversion of a gas transmission pipeline to pure hydrogen a step closer

[3] APA Group joins international hydrogen consortium | APA Group

1 August 2022

Australian Energy Regulator
GPO Box 520
Melbourne VIC 3001

Via: APA VTS Australia (Operations) Pty Limited ACN 083 009 278
Level 25, 580 George Street
Sydney NSW 2000

Energy Networks Australia's support for testing the readiness of hydrogen blending in Victoria's Transmission System

To whom it may concern

Energy Networks Australia (ENA) welcomes the opportunity to provide support to APA's proposed hydrogen safety and integrity study for the Victorian Transmission Systems.

ENA is the national industry body representing Australia's electricity transmission and distribution and gas distribution networks. Our members provide more than 16 million electricity and gas connections to almost every home and business across Australia.

Jointly with the Australian Pipelines and Gas Association, we commissioned DNV GL to deliver a study[i] identifying the actions required to blend renewable gases in gas networks and pipelines with the aim of converting them to 100 per cent renewable gas by 2040 to 2050.

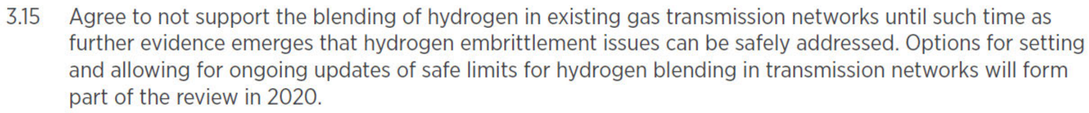
Gas distribution networks made from modern plastic materials are generally ready to transport hydrogen. However, DNV GL identified that the use of hydrogen in steel transmission pipelines has the potential to affect the ductility, toughness and fatigue life of the steel through a process known as hydrogen embrittlement. Formal testing and safety cases need to be undertaken before hydrogen is injected into transmission pipelines as part of blending programs. There is a range of work that is underway or has recently been completed in Australia including:

- Active research and testing program at Future Fuels CRC for steel pipeline materials[ii].
- GPA Engineering[iii] report completed on the potential to repurpose existing pipelines with hydrogen.
- APA is completing a test program to enable the conversion of 43 km of the Parmelia Gas Pipeline in WA into a hydrogen ready pipeline[iv].
- A new pipeline is being used for hydrogen storage as part of Jemena's Western Sydney Green Hydrogen Hub[v] project.
- AGIG[vi] has completed a feasibility study of blending hydrogen into the Dampier to Bunbury Pipeline in WA.

There is also a lot of work underway internationally on converting natural gas pipelines to transport hydrogen and work is required in each region to account for the specific materials and conditions of the pipeline infrastructure. Some examples include the European hydrogen backbone project[vii] and the work completed in the UK in the HyDeploy project[viii].

Further work is required within Australia to be able to safely provide renewable gas to customers. For Victoria, the Victorian Transmission System provides gas to the local distribution networks that serve over 2 million homes and businesses. Testing the different sections of the VTS will need to be carried out before hydrogen blending can commence at scale in Victoria, and hence contribute to both Victoria's and Australia's emission reduction targets.

The proposed APA safety study also aligns with the recommendation from Australia's Hydrogen Strategy[ix] that required further evidence to be provided prior to permitting hydrogen to be blended in natural gas transmission pipelines:



3.15 Agree to not support the blending of hydrogen in existing gas transmission networks until such time as further evidence emerges that hydrogen embrittlement issues can be safely addressed. Options for setting and allowing for ongoing updates of safe limits for hydrogen blending in transmission networks will form part of the review in 2020.

Source: Australia's National Hydrogen Strategy (2019), pg 80

Energy Networks Australia is supportive of safety and integrity studies that will enable the safe repurposing of natural gas pipelines to deliver renewable gases to customers.

Should you have any queries please contact ENA's Head of Renewable Gas, Dr Dennis Van Puyvelde, [_].

Yours sincerely,

Andrew Dillon
Chief Executive Officer

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[i] https://www.energynetworks.com.au/resources/reports/2022-reports-and-publications/national-gas-decarbonisation-plan-dnv-report/
[ii] https://www.futurefuelscrc.com/program_area/safe-and-efficient-design-construction-and-operation-of-an-integrated-fuels-infrastructure-rp3-2/
[iii] https://www.energynetworks.com.au/miscellaneous/technical-and-commercial-review-of-infrastructure-victorias-gas-infrastructure-interim-report-gpa-engineering/
[iv] https://www.apa.com.au/news/media-statements/2021/apa-set-to-unlock-australias-first-hydrogen-ready-transmission-pipeline/
[v] https://jemena.com.au/about/newsroom/media-release/2021/first-green-hydrogen-for-new-south-wales-homes-and
[vi] https://www.agig.com.au/western-australian-feasibility-study
[vii] https://ehb.eu/
[viii] https://hydeploy.co.uk/
[ix] https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy

25 July 2022

Harriet Floyd
APA VTS Australia (Operations) Pty Limited
Level 25, 580 George Street
Sydney NSW 2000

Dear Ms Floyd

Re: Victorian Gas Transmission System – Hydrogen Safety and Integrity Assessment

Fortescue Future Industries (FFI) confirms its support for APA Group's ("APA") hydrogen safety and integrity assessment, as part of its Victorian Gas Transmission System (VTS) 2023-2027 Access Arrangement submission to the Australian Energy Regulator (AER) ("Submission").

A proudly Australian company with balance sheet strength, Fortescue Metals Group (Fortescue) is a global leader in large-scale, ultra-efficient and highly complex developments with a proven track record in developing and operating assets in remote and isolated locations. Fortescue has a strong focus on decarbonisation, evidenced by its industry leading target to achieve carbon neutrality by 2030. Through its subsidiary, FFI we are establishing a global portfolio of green hydrogen production and manufacturing projects and operations that will position us at the forefront of the global green hydrogen industry.

Green hydrogen, when used as a fuel or energy source, is a zero-carbon fuel that can displace fossil fuels and contribute to the emissions reduction of our hardest to decarbonise industrial sectors. As far as practicable, repurposing existing infrastructure, is preferable to rebuilding new infrastructure to facilitate the green hydrogen industry.

To support the nascent stage that the green hydrogen industry is in, safety and integrity for our workforces must be paramount. FFI understands that APA submitted a business case as part of their Access Arrangement Submission, which outlined the required studies to assess the preparedness of the VTS for hydrogen. The inclusion of safety and integrity risks through this submission is supported by FFI.

Yours sincerely

Kim Van Hattum
Manager – East Coast

FORTESCUE FUTURE INDUSTRIES

NATIONAL
ENERGY RESOURCES
AUSTRALIA

9 August 2022

Harriet Floyd
Manager – Project Development, Innovation and Assurance
APA Group
[ ]

Letter of Support – APA Group

Dear Harriet,

Re: Victorian Gas Transmission System – Hydrogen Safety and Integrity Assessment

On behalf of National Energy Resources Australia (NERA), I am pleased to provide this letter of support for APA Group's ("APA") hydrogen safety and integrity assessment, as part of its Victorian Gas Transmission System (VTS) 2023-2027 Access Arrangement submission to the Australian Energy Regulator (AER) ("Submission").

NERA is an independent not-for-profit company funded through Federal Government grants and collaborative programs by State and Territory Governments, industry and the science and research community. NERA has formed Hydrogen Technology Cluster Australia (H2TCA) - a network of 18 regional hydrogen technology clusters across Australia, providing seed funding in partnership with governments and industry to build the skills, capability and commercialisation opportunities in the emerging hydrogen industry. This includes four regional clusters in Victoria – Gippsland, Geelong, Clayton and Mallee.

We fully support the need to find a balance between costs for the end user and enabling industry to undertake appropriate research to transition its gas network to low carbon options. But, before hydrogen can be blended in the VTS, APA will need to understand what the safety and integrity risks might be. APA has outlined a business case as part of their Access Arrangement Submission, which outlined the required studies to assess the preparedness of the VTS for hydrogen.

Please contact me at [ ]if you have any queries.

Yours sincerely

Leigh Kennedy
General Manager – Hydrogen, NERA

WELLINGTON
SHIRE COUNCIL
The Heart of Gippsland

26 July 2022

Harriet Floyd
APA VTS Australia (Operations) Pty Limited
Level 25, 580 George Street
SYDNEY NSW 2000

Via email: [ ]

Dear Harriet

Re: Victorian Gas Transmission System – Hydrogen Safety and Integrity Assessment

Wellington Shire Council confirms its support for APA Group's ("APA") hydrogen safety and integrity assessment as part of its Victorian Gas Transmission System (VTS) 2023-2027 Access Arrangement submission to the Australian Energy Regulator (AER).

Our new Council Plan (2021-2025) has a strong focus on climate change as a strategic direction. The Council's support for the transition to new forms of energy, including hydrogen, reflects this direction and is viewed as the shire's main driver of economic development. Council has already been involved in advanced conversations with a number of proponents currently looking at hydrogen, including the conversion of locally operated heavy vehicles to hydrogen.

Hydrogen as a low-carbon alternative to natural gas is a key component of Victoria's gas substitution roadmap. The Council understands that for APA, repurposing existing gas infrastructure for hydrogen is a lower cost than building entirely new pipeline networks or full electrification of energy systems. It makes sense that before hydrogen can be blended in the VTS, APA will need to understand the safety and integrity risks. Further, we understand that APA has submitted a business case as part of their Access Arrangement Submission, which outlined the required studies to assess the preparedness of the VTS for hydrogen.

Wellington Shire Council acknowledges APA's support for the global transition to a lower carbon future and has demonstrated its commitment to enabling low carbon technologies and fuels to enter the Australian energy mix in a number of ways:

1. Announced ambitions of net zero operations emissions by 2050.

2. Completed Phase 1 of an investigation into the conversion of a section of the Parmelia Gas Pipeline in Western Australia to be hydrogen ready. Phase 2 of this investigation is underway.

3. Executed an MoU with Wesfarmers Chemicals, Energy and Fertilisers (WesCEF) to undertake a pre-feasibility study to assess the viability of producing and transporting green hydrogen via APA's Parmelia Gas Pipeline.

4. Executed an MoU as one of the founding consortium members of the Central Queensland Hydrogen Export Project.

Wellington Shire Council continues to offer their support to APA in their endeavours to further investigate the potential to use existing transmission infrastructure assets.

Yours sincerely **COUNCILLOR IAN BYE**
Mayor

[redacted]

ECM: 2974820

Appendix D – VTS Pipeline map

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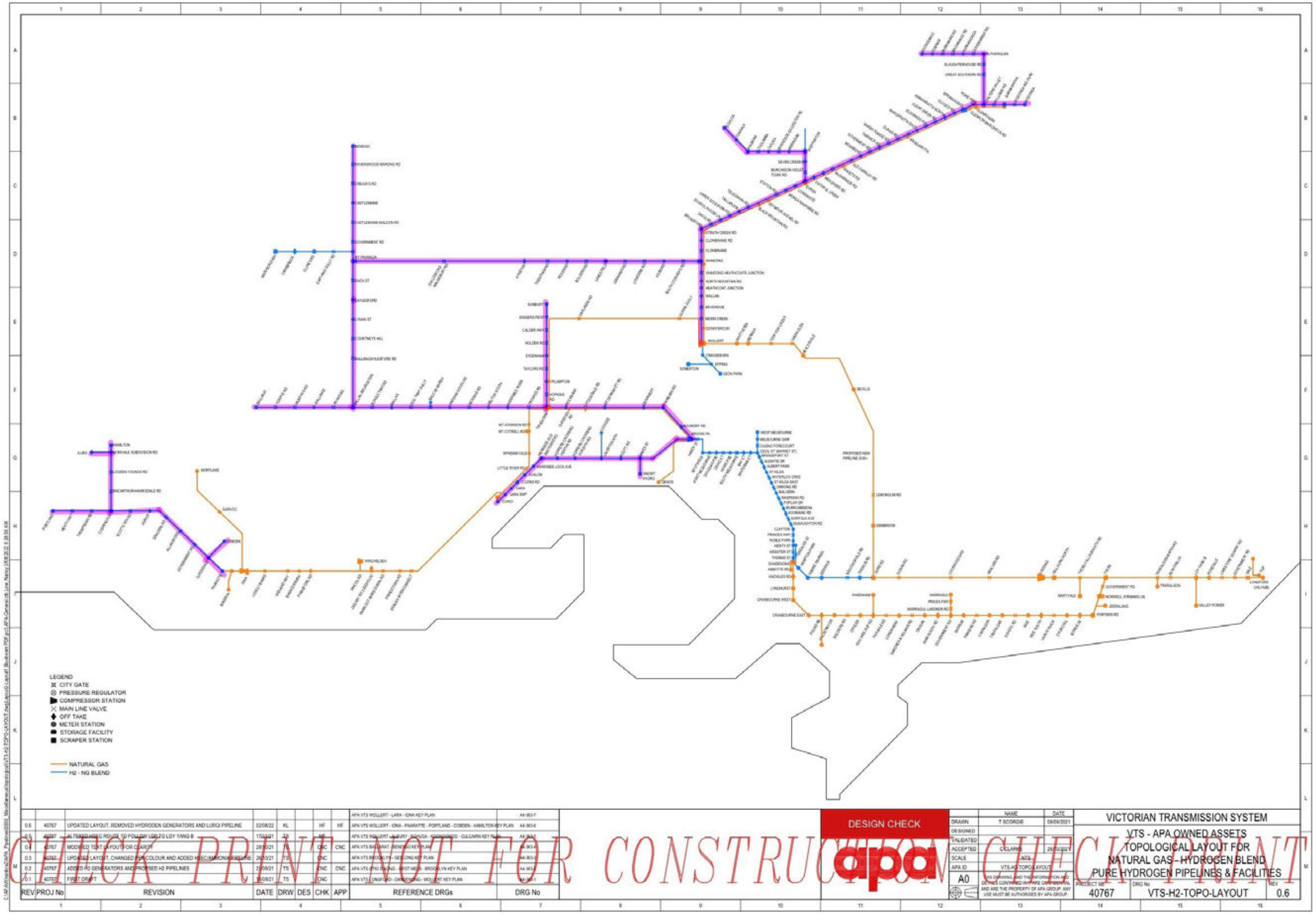

Figure 6: (Option 4) 22 sections of pipelines requiring a reduction of MAOP if hydrogen is injected into the VTS to meet ASME B31.12 Option A guidance

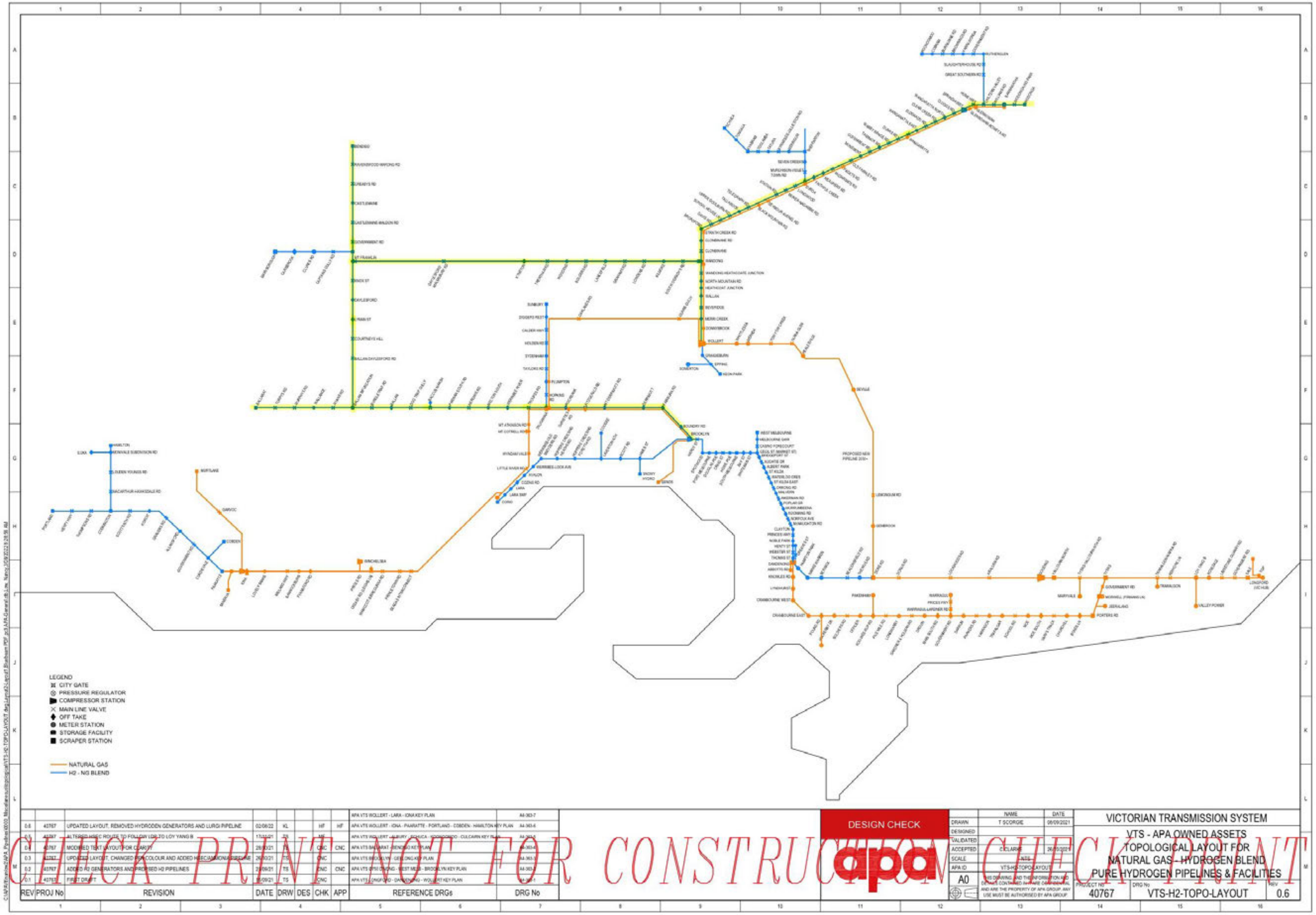

Figure 7: (Option 4) 9 sections of pipelines prioritised for material testing to mitigate capacity reduction

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Wednesday, 6 April 2022

APA VTS Australia (Operations) Pty Limited ACN 083 009 278
Level 25, 580 George Street
Sydney NSW 2000
Attention: Harriet Floyd

Dear Harriet

Re: Victorian Gas Transmission System – Hydrogen Safety and Integrity Assessment

Boral confirms its support for APA Group’s (“APA”) hydrogen safety and integrity assessment, as part of its Victorian Gas Transmission System (VTS) 2023-2027 Access Arrangement submission to the Australian Energy Regulator (AER) (“Submission”).

Boral was the first in the global construction materials industry to set FY2030 science-based Scope 1 and 2 targets aligned with a 1.5°C pathway. And in FY2022 our ambitious emissions reduction targets for FY2030 were approved by the Science Based Targets initiative (SBTi) as consistent with the levels required to meet the goals of the Paris Agreement. We are committed to net zero carbon emissions by no later than 2050, aligned with the most ambitious aim of the Paris Agreement to limit global warming to 1.5°C. We have also committed to an 18% reduction in Scope 1 and 2 emissions by FY2025, compared to an FY2019 baseline, and a 46% reduction by 2030.

Hydrogen as a low carbon alternative to natural gas and diesel is a key component of Boral’s decarbonisation pathway, and understanding the use cases for hydrogen across Victoria is an important consideration in technical and commercial feasibilities currently being explored.

For APA, as we understand it, the repurposing of existing gas infrastructure for hydrogen is lower cost than building entirely new pipeline networks or full electrification of energy systems. But, before hydrogen can be blended in the VTS, APA will need to understand what the safety and integrity risks might be.

APA and Boral actively support the global transition to a lower carbon future, and as you know, we are already working collaboratively on several early-stage projects and studies. Boral therefore supports APA in their Submission to the AER.

If you have any questions, please do not hesitate to contact me.

Regards

Mary Ann van Bodegrave

Mary Ann van Bodegraven
Head of Sustainability