LTS Futures Closedown Report

2026

Contents

Foreword

The Local Transmission System (LTS) is a critical part of the UK's energy infrastructure, underpinning the safe, efficient and resilient supply of natural gas to millions of customers. As we look ahead to Net Zero, this very system has a vital role to play in transitioning from its traditional role to become a foundational platform for delivering low-carbon energy to the customers and sectors that need it most.

At SGN, we pride ourselves on being at the leading edge of evidence-based innovation and research. We recognise that the most sustainable and cost effective pathway to decarbonisation is to maximise the value of existing assets. By rigorously testing and validating the capability of our existing infrastructure to carry different gases such as hydrogen, we are demonstrating a solution that could deliver additional value for money for gas consumers, that avoids the prohibitive costs of full network replacement, while maintaining system resilience. Our ambition is clear: the LTS will enable a future-ready network capable of delivering low-carbon energy to key demand sectors, particularly to high-capacity industrial and commercial hubs that are critical to our economy.

The LTS Futures project has been instrumental in providing the confidence required to support this transition. Through a combination of detailed research, full-scale testing and real-world demonstration, the project has demonstrated that gas networks can successfully pivot from natural gas to low-carbon alternatives such as hydrogen while maintaining safety and security of supply. This is a significant step in reinforcing the long-term value of the gas infrastructure within a decarbonised energy system.

Central to this success has been a comprehensive programme of laboratory and full scale testing to understand the fundamental behaviour of hydrogen within our existing asset base and future operating parameters, alongside the completion of a UK-first demonstration on a 30 km representative pipeline running from Grangemouth to Granton. Critical operations were carried out that focused on live hot works involving welding and drilling into an in-service hydrogen pipeline to prove that the same techniques used today can safely maintain the hydrogen networks of tomorrow. Collaboration with partners such as INEOS, who provided a supply of hydrogen for the live trial, has further strengthened our understanding of how gas transporters will interface with future hydrogen production, particularly in industrial clusters.

Antony Green
Chief strategy and regulation officer

All evidence gathered through this programme has culminated in the project's overarching objective: a Blueprint methodology for repurposing LTS pipelines and installations from natural gas to hydrogen. This is not only a milestone for SGN but a critical roadmap for all gas network operators and the wider sector. It provides the technical foundation for any future transitioning of SGN's 3,300 km of LTS across Scotland and Southern England, as well as a wider, scalable solution for the 11,000 km of Great Britain's Local Transmission System (GB LTS) infrastructure. It strengthens the case for gas networks as an enabler of Net Zero and a key component of a whole system energy approach.

Finally, I would like to thank our key partners and colleagues across SGN, whose expertise, commitment and collaboration have made this possible. This project represents a critical step in transforming our asset base for the future, ensuring our network continues to deliver value for customers and supports the UK's decarbonisation ambitions for decades to come.

1. Executive Summary

The LTS Futures Project has successfully evidenced the viability of transitioning our Local Transmission System (LTS) to 100% hydrogen. A critical deliverable has been the development of a blueprint methodology that supports conversion of the wider 11,000 km LTS asset base. The LTS is a vital network that connects the national gas supply to local communities and industrial clusters.

The LTS Futures project is a flagship programme within the UK's national hydrogen research effort, designed to enable a practical, scalable transition to low carbon energy. It provides the first comprehensive, real world evidence that the UK's LTS, a critical national asset base spanning approximately 11,000 km of pipelines across Great Britain, could be safely and economically repurposed to transport hydrogen at scale.

Strategic Importance of the LTS Network

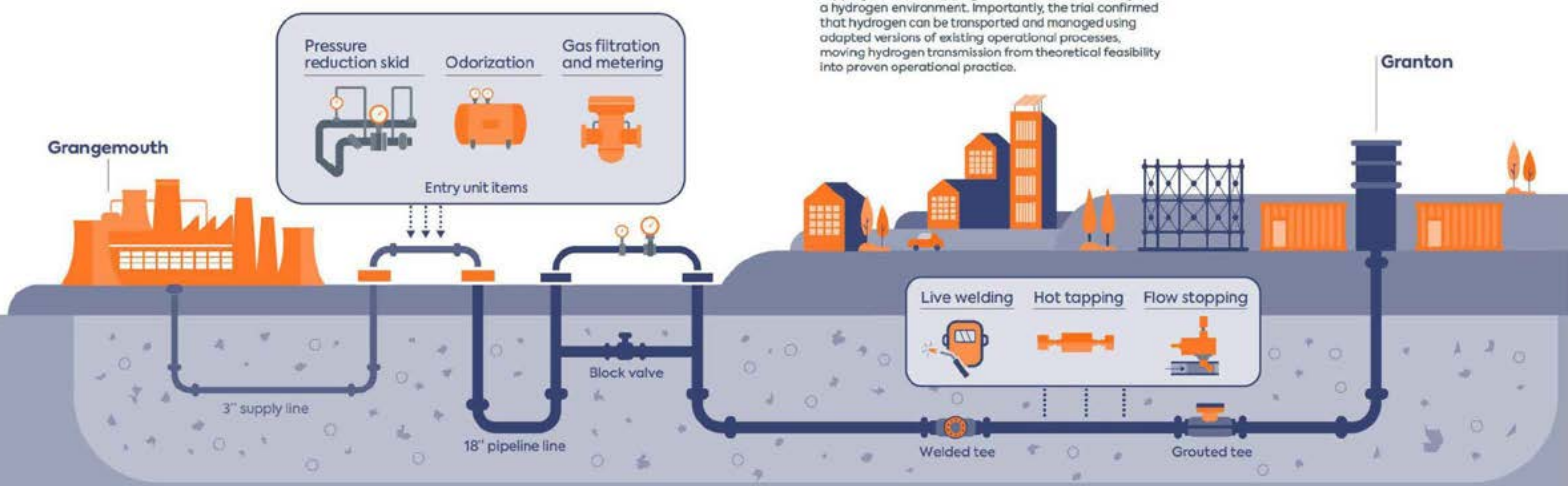
The LTS network is uniquely positioned to act as the backbone of a future hydrogen economy, as it already connects major industrial users, urban centres and regional clusters. Repurposing this extensive infrastructure could remove the need to duplicate networks and enables a faster, more efficient transition to low carbon energy. In doing so, it supports any future UK and Scottish hydrogen and net zero ambitions while maintaining system resilience and affordability. Crucially, it provides a viable decarbonisation pathway for hard to electrify sectors, such as industrial and large commercial users, which depend on high capacity gas network supply.

Key Outcomes – Proving Hydrogen Repurposing

LTS Futures has successfully delivered a first of a kind live hydrogen trial through the repurposing of a 30 km high pressure pipeline between Grangemouth and Granton. This demonstration has proven that existing LTS pipelines and installations could be safely repurposed for hydrogen service when supported by appropriate operational controls and inspection regimes. It has also shown that critical network interventions, including live welding, hot tapping and flow stopping, can be undertaken safely in a hydrogen environment. Importantly, the trial confirmed that hydrogen can be transported and managed using adapted versions of existing operational processes, moving hydrogen transmission from theoretical feasibility into proven operational practice.

Development of the LTS Futures Blueprint

A central outcome of the project is the development of the LTS Futures Blueprint, which provides a repeatable methodology for repurposing pipelines across the entire GB LTS network. The Blueprint sets out a framework covering engineering, safety, regulatory and operational considerations, drawing directly on evidence generated through laboratory research, full scale testing and the live trial. It provides a clear, practical pathway for potentially converting the LTS network to hydrogen, enabling coordinated and efficient nationwide rollout. In this way, the Blueprint is fundamental to unlocking investment confidence and accelerating deployment of hydrogen infrastructure.



Evidence Base and Risk Reduction

The project has established a comprehensive and robust evidence base that significantly reduces uncertainty around hydrogen use in transmission networks. This includes demonstrating the compatibility and integrity of representative pipeline materials in hydrogen service, validating safety frameworks through detailed quantitative risk assessments and a project-specific Case for Safety (CfS), and generating data on key technical areas, such as fatigue, fracture, defect tolerance, and hot works. Collectively, this evidence closes critical knowledge gaps and provides confidence to regulators, investors, and operators, thereby enabling informed decision making and reducing barriers to large scale hydrogen deployment.

Value for Customers and the Energy System

LTS Futures demonstrates that repurposing existing infrastructure delivers substantial value for consumers and the wider energy system. The project provides clear evidence that repurposing pipelines can be achieved at a fraction of the cost of full network replacement, with estimates indicating costs of approximately 10% compared to new build solutions. This avoids the significant capital expenditure associated with constructing entirely new infrastructure and reduces the financial burden on customers. At the same time, it enables faster delivery of hydrogen networks, allowing the benefits of decarbonisation to be realised earlier while maintaining a reliable and cost effective energy system.

Financial Performance

The total value of the project was £25.92 million (2018/2019 price basis), which included £2.14 million of financial benefit-in-kind (BIK) contributions. Total spend at completion of the project is expected to be £31.06 million with all project deliverables achieved in line with the project direction set out by Ofgem.

Knowledge Dissemination and Industry Engagement

A defining feature of the LTS Futures project has been its extensive programme of knowledge dissemination and stakeholder engagement, ensuring that the value of the project extends far beyond the live trial itself. Throughout delivery, the project actively shared findings with a wide range of stakeholders, including regulators, government departments, gas distribution network operators, industry bodies, emergency services, academic, and local communities. This was achieved through structured engagement, such as steering groups, technical workshops, industry forums, site visits, and live demonstrations, as well as through formal reporting and evidence submissions aligned with regulatory stage gates.

The project also facilitated collaboration across the gas networks and wider energy sector, enabling peer review of the emerging Blueprint methodology and ensuring that outputs are transferable across Great Britain. Engagement with Local Authorities (LAs)s, resilience partners and emergency services supported the development of coordinated emergency response arrangements, while wider stakeholder and community engagement helped build awareness and trust in hydrogen as a future energy vector.

In parallel, the project has contributed to academic and industry knowledge sharing through conference presentations, publication of technical findings, and the creation of training materials and competency frameworks. These activities have ensured that lessons learned from LTS Futures are embedded across the sector, directly informing future standards, regulatory approaches, and subsequent hydrogen projects. As a result, the project has not only generated critical technical evidence but has also played a pivotal role in building the industry capability, alignment, and confidence required to scale hydrogen infrastructure nationally.

Overall Conclusion

The LTS Futures project demonstrates that the UK's existing gas transmission infrastructure could be transformed into a safe, reliable and cost effective hydrogen network. By successfully delivering a live trial and producing a practical Blueprint for deployment, the project provides a critical foundation for national decarbonisation. It confirms that the LTS network will remain a strategic and high value asset in the transition to net zero, underpinning the delivery of low carbon energy to customers while enabling a resilient and affordable future energy system.

2. Details of the Work Carried Out

2.1 Project Overview

The LTS Futures Project forms part of the UK's national hydrogen research programme to deliver a net zero decarbonisation solution for customers. The project sought to research, develop, test and evidence the compatibility of the LTS assets, pipelines, associated plant and ancillary fittings, culminating in a 'first of a kind' repurposing trial and demonstration.

The aim of the project was to demonstrate that the LTS could be repurposed to convey hydrogen, providing end use decarbonisation options through delivery of a safe supply of low-carbon energy to customers both during, and after the energy transition.

This project intended to repurpose the Grangemouth to Granton pipeline for a live demonstration. This pipeline runs from the Grangemouth industrial cluster, and associated INEOS hydrogen production facility, to Granton on the outskirts of Edinburgh. This pipeline offered an ideal opportunity for the live trial due to its inherent characteristics and is an excellent proxy for the GB LTS. The completion of the full-scale and small scale testing programme along with learnings from the live trial enabled the project to produce a Blueprint methodology for uprating and repurposing the 11,000 km of pipelines in the GB LTS network.

The project was split into six main packages of work referred to as elements, as illustrated below:

2.2 Project Timescales

KEY

SG1 Stage Gate 1 | SG2 Stage Gate 2 | Blueprint methodology & closedown report

2.3 Project Contributions

The following benefit-in-kind contributions have been made to the LTS Futures project:

Gas Distribution Networks (GDNs)

All GDNs have provided critical support throughout the project through quarterly steering groups to discuss evidence and further develop test programmes. They have provided a review of the Blueprint methodology for uprating and repurposing LTS pipelines and installations. In addition to this, the following specific contributions have been made:

Cadent
Your Gas Network

£100,000
financial contribution

WALES&WEST UTILITIES

Support of a pressure reduction station (PRS) specialist to advise on full-scale testing and an in-service PRS for the completion of WP5 testing.

DNV

DNV provided and installed a grouted tee as part of the full-scale test programme. In addition, video footage of testing was provided to support knowledge dissemination and use of site facilities for meetings and stakeholder events.

STATS GROUP

As part of the additional scope of works delivered, Stats further developed their swarf management tool, which ensures that the low gas velocities in the trial did not impact the successful deployment of the BISEP tool during the live trial.

2.4 Statement of Needs

In 2022, the UK Government's ambition was to target 10 GW of low-carbon hydrogen production by 2030 [1], with Scotland aiming for 5 GW by 2030 and 25 GW by 2045 [2]. To support the development of hydrogen production and Hydrogen Allocation Round (HAR) funding mechanisms for development, transport infrastructure is critical to drive investment [3].

The LTS Futures Project was developed to demonstrate how the existing LTS could be safely, reliably, and cost effectively repurposed to transport hydrogen at scale. Achieving UK and Scottish net zero targets (2050 and 2045 respectively) requires a major transition away from natural gas, particularly for hard to electrify industrial and commercial users who rely on the existing high-capacity gas transmission network for supply.

The LTS is a critical national infrastructure asset, spanning over 11,000 km across Great Britain, and is uniquely positioned to form the backbone of a future hydrogen transmission network connecting large scale hydrogen production to industrial clusters, commercial users, and urban demand centres. UK strategy considered industrial clusters, focusing on the deployment of hydrogen production in proximity to or within industrial hubs linked to carbon capture, utilisation and storage (CCUS) and major oil and gas operations. With the LTS network already connected to towns, cities and industrial and commercial offtakers, repurposing offers the opportunity to serve cluster regions with low-carbon energy, without the need to duplicate existing infrastructure.

System transformation of the networks cannot proceed without robust evidence that LTS pipelines, assets, and operational practices are compatible with hydrogen service. The LTS Futures Project addresses this by developing a programme of works to establish a methodology and evidence base for repurposing and uprating LTS pipelines for hydrogen. The development of a methodology for repurposing allows SGN and wider GDN operators to secure the operation of existing assets, providing a continued reliable, cost-effective energy system for our consumers.

The LTS Futures Project is essential to any future scale rollout enabling the UK's hydrogen economy by proving that existing transmission infrastructure could deliver low carbon hydrogen safely and affordably to end-use sectors.

2.5 Overview of Project

The LTS Futures programme was designed to generate critical evidence on whether GB LTS could be safely and cost effectively repurposed at scale to convey 100% hydrogen. It addressed a key national net zero evidence gap by combining laboratory testing, full-scale testing and a first of a kind live trial, culminating in a repurposing and uprating Blueprint that can be applied across the GB LTS.

"Re-using and re-purposing existing assets and infrastructure dramatically lowers the timing and costs to access the energy transition. Only through bold initiatives like LTS Futures led by SGN will we be able to realise these benefits for society."

Colin Pritchard, Sustainability Director for INEOS Grangemouth

2.5.1 Delivery Overview

The programme was structured around six integrated elements:

Element 1
Enabling works and live trial design

This included all enabling works which provided evidence for the project to progress through Stage Gate 1, as well as the repurposing of the Grangemouth to Granton pipeline and the design which enabled the live trial.

Element 2
Laboratory material testing

A full suite of mechanical tests in air and in hydrogen on three different pipelines and associated welds. This included tensile, fatigue and fracture tests to provide an understanding of the effect of hydrogen on material properties. The data gathered is to be used in updates to industry standards and technical assessments.

Element 3
Full-scale testing

Five different workstreams including development and application of live welding and hot tapping procedures for hydrogen pipelines, data gathering for hydrogen venting and flaring, burst and fatigue tests on hydrogen pipeline defects, hydrogen fatigue tests on fittings and testing a Pressure Reduction Installation (PRI) with hydrogen. The testing informed development of live trial procedures and is to be used in updated industry standards and technical assessments.

Element 4
Construction and Live Trial

The live trial demonstrated uprating and repurposing of an existing LTS pipeline to convey hydrogen. Activities including live welding and flow stopping were completed, showing that the critical tasks required for operating and maintaining a hydrogen network could be carried out successfully.

Element 5
QRA and Case for Safety

QRAs were produced for both the hydrogen supply and Grangemouth to Granton pipelines taking account of the potential risks and consequences of conveying hydrogen. The project also developed a Case for Safety for the trial, demonstrating how it would be operated safely.

Element 6
Knowledge dissemination and skills development

Sharing the knowledge and learning from the project and trial are essential to ensure that the maximum value of the funding is realised. This sharing of learning across industries benefits the whole hydrogen system development and allows future projects to build on existing understanding.

Delivery followed a stepped approach with defined stage gates, ensuring costs and risks were controlled and learning was captured even where uncertainties remained. Stage Gate 1 presented the information needed to inform a recommendation on whether to progress with modifications to the Grangemouth to Granton pipeline and construct the hydrogen supply pipeline. This stage gate was passed in May 2023. The Stage Gate 2 decision on whether to progress to the live trial was based on a review of the evidence, which demonstrated that the trial could be carried out safely and that key learning outcomes would be achieved. The project progressed through Stage Gate 2 in December 2024.

2.5.2 Key Outputs and Outcomes

The project delivered a number of key outcomes in line with the project direction including:

- Technical evidence demonstrating that representative LTS pipelines can be repurposed for hydrogen service, subject to defined conditions, inspection regimes, and mitigations.
- Development and validation of an uprating and repurposing Blueprint, providing a repeatable methodology for the ~11,000 km GB LTS network.
- Evidence on hydrogen integrity, defect tolerance, fatigue life, hot works, venting, and PRS operability, closing multiple gaps identified in the Health and Safety Executive (HSE) hydrogen gap analysis.
- Case study analysis on linepack behaviour and uprating potential. This shows how increased pressure and flow could materially reduce the volume of new pipelines required in a future hydrogen system.
- Completed pipeline specific and GB wide QRA's for hydrogen LTS operation to inform future regulatory and safety cases.

2.5.3 Value for Money and Consumer Impact

Value for money for customers was at the forefront of decision-making for the project. Key project outputs on financial spend, repurposing spend estimates, and robust commercial approach are listed below:

- Total approved funding request: ~£28.1 million, split between Regulatory Asset Value (RAV) and research and development (R&D) in line with regulatory guidance. SGN and GDNs provided funds of £2.99 million as benefit in kind (BIK).
- Independent quantity surveyor review, competitive procurement, and staged delivery ensured efficient cost control.
- Whole system analysis shows that repurposing LTS assets costs 1.5 – 9.7% of full replacement, with significant Net Present Value (NPV) benefits to consumers compared to decommissioning and rebuild.

2.5.4 Wider Benefits and Learning

The LTS Futures Project provides significant evidence and learning that can be applied to future projects assessing asset repurposing in the UK. Some key wider benefits of the project included:

- Reduced need for new steel pipelines supports lower embedded carbon and faster delivery of net zero outcomes.
- Strong collaboration with HSE, Department for Energy Security and Net Zero (DESNZ), Ofgem, the Institution of Gas Engineers and Managers (IGEM), National Grid, all GDNs, and industry bodies, ensuring learning is transferable and nationally consistent.
- Creation of new hydrogen operational procedures, training materials, and competence frameworks, improving industry readiness.
- Evidence directly informs future heat policy, industrial cluster decarbonisation, and hydrogen transmission planning.

2.5.5 Overall Conclusion

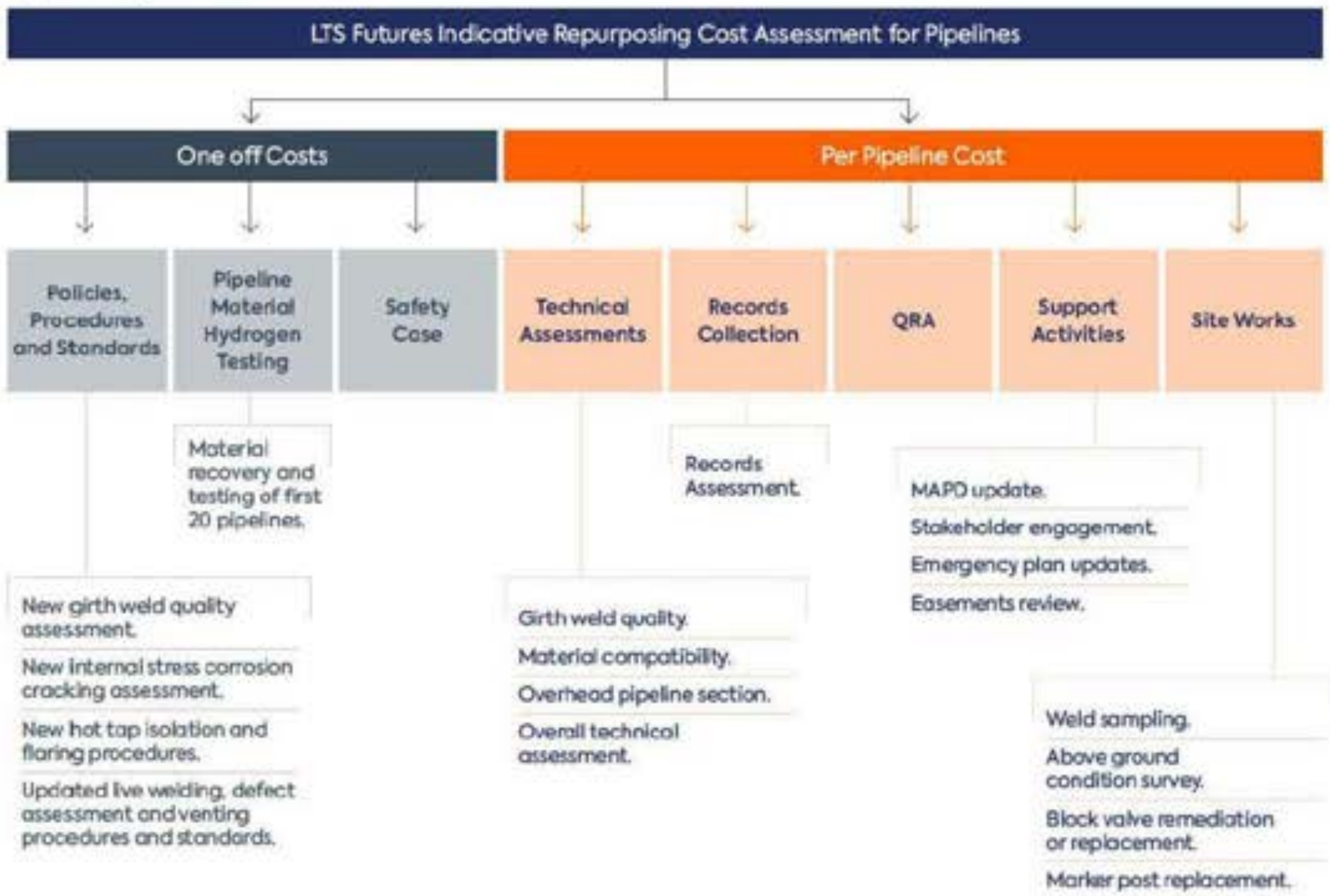
LTS Futures has successfully met its Net Zero Pre construction Work and Small Net Zero Projects Re-opener (NZASP) objectives, providing robust technical, safety, commercial, and regulatory evidence that materially reduces uncertainty around hydrogen use in the LTS. The programme represents good value for money, delivers strategic optionality for GB net zero pathways, and significantly de-risks future investment decisions.

2.6 Cost Assessment

As part of the LTS Futures NZASP submission to Ofgem [4], it was estimated that the repurposing of existing LTS pipelines and associated infrastructure will cost 15–30% of the total cost to replace all these assets with new infrastructure. To evaluate this estimation, an indicative cost assessment for repurposing LTS pipelines to hydrogen was produced based on the work undertaken within the LTS Futures Project. A similar assessment for repurposing PRIs will be produced once the Element 3 Work Package 5 test programme has been completed.

The cost assessment is detailed in the LTS Futures Blueprint [5]. As the future supply and demand for hydrogen has not been defined, some cost exclusions have been applied. Costs associated with outcomes from the repurposing assessments, including diversions, increased site outlay, land renegotiation and compensation, and works to bring a pipeline into compliance with IGEM/TD/1 Edition 6 [6], were excluded. For repurposing pipelines, costs were split into two sections, as shown in Figure 1, with a series of 'one-off' upfront costs in addition to 'per-pipeline' costs. A 'low', 'medium' and 'high' scenario for each 'per-pipeline' cost was produced with guidance as to how to apply each scenario. An example application of the methodology was completed for a SGN pipeline to demonstrate the process. Costs for these different elements were generated based on real values incurred during the LTS Futures Live Trial.

Figure 1: Blueprint cost assessment.



Within the NZASP submission [4], the cost of constructing a new LTS pipeline network was estimated for comparison purposes. The estimated cost of building a new 11,000 km LTS network was £11.889 billion, equating to an average construction cost of £1.081 million per km. Decommissioning costs for the current LTS were also calculated and assumed to be equivalent to the main contractor construction costs, reflecting the comparable activities involved (principally excavation, pipe removal, and land reinstatement). On this basis, the estimated cost of decommissioning the existing LTS network was £7.73 billion, equivalent to £0.703 million per km. The total estimated cost of the base scenario to customers, comprising new build construction and decommissioning of the existing network, was £19.619 billion, equating to an average cost of £1.784 million per km.

Since the NZASP submission in 2021 [4], the external cost environment has changed with increased geopolitical volatility heightening focus on energy security and creating sustained inflationary pressure on the UK economy. There have been significant increases in construction, labour, and materials costs, which directly impact both new build and repurposing pipeline cost assumptions. As a result, cost estimates developed at the time of the original bid are no longer fully reflective of the current market environment, consistent with trends observed across Ofgem regulated infrastructure projects. Within the cost assessment, an inflation adjustment calculation was completed with costs increasing from £1.34 million per km to £3.78 million per km. This does not include the costs for decommissioning and is for building new only.

Based on the inflation adjusted LTS Futures new build cost estimate and the observed costs from the 3" hydrogen supply pipeline constructed during the Live Trial, it is estimated that new hydrogen pipeline construction costs are likely to fall within a range of approximately £1.34 million to £3.78 million per km, depending on route complexity, diameter, and site specific constraints. Using evidence from repurposing the 18" Grangemouth to Granton pipeline and the wider GDN cost model, repurposing existing LTS pipelines for hydrogen was estimated to cost in the range of £20,500 to £129,500 per km, which is materially lower (1.5% – 9.7%) than the estimated new build costs.

2.7 Project Governance/Project Management Plan (PMP)

2.7.1 Governance Framework

The LTS Futures Project was delivered under a robust, multi layered governance framework designed to ensure regulatory compliance, independent assurance, effective decision making and strong financial control throughout the project lifecycle. Governance arrangements were aligned with SGN's Future of Energy (FoE) governance model, Ofgem's Schedule 1 Direction [7], and wider regulatory and safety obligations.

Clear separation was maintained between delivery, assurance, and approval, providing transparency and objectivity across technical, safety, and financial decisions.

2.7.2 Roles, Accountability and Delegated Authority

Overall accountability for delivery was retained by the LTS Futures Project Director, supported by a dedicated Project Management Office (PMO). Clear role definition was established through a Responsibility Assignment Matrix (RAM), ensuring that accountability, responsibility, consultation, and information flows were explicit across all project elements.

Financial and change approval limits were governed through SGN's Delegated Levels of Authority, with escalation routes through:

- Project Manager.
- Project Director.
- Project Sponsor.
- Chief Strategy and Regulation Officer.
- SGN Executive / Board (where required).

This ensured that all cost, scope and schedule changes were authorised at the appropriate level and remained within the Ofgem approved NZASP framework.

2.7.2.1 Steering and Decision Making Forums

Strategic oversight was provided through a formal Steering Committee, chaired at Chief Strategy and Regulation Officer level, which met monthly. The Steering Committee:

- Reviewed project performance against baseline (schedule, cost, risk, and benefits).
- Considered escalated risks, issues, and regulatory matters.
- Oversaw readiness for key milestones, including live trial operations and operational readiness activities.
- Provided assurance that the project remained compliant with Ofgem, HSE, and SGN governance expectations.

In addition, monthly Project Performance Reviews provided structured scrutiny of delivery performance, supported by integrated cost, schedule, risk, and change reporting.

2.7.2.2 Regulatory Governance and Ofgem Oversight

Ofgem acted as the formal customer for the project through the Schedule 1 Direction, with governance supported via:

- Defined outcomes and milestones set out in Annex 2 of the Project Direction [7].
- Regular engagement meetings to review progress, evidence requirements and clarifications.
- Formal Stage Gate reviews.

The project successfully passed Stage Gate 1 and subsequently progressed through Stage Gate 2, supported by no objections from the HSE on the LTS Futures Case for Safety for the live trial. Evidence evolution and regulatory alignment were formally recorded through meeting minutes and controlled submission packs.

Figure 2: Ofgem project governance.

SG1	SG2		
Stage Gate One Decision on whether to progress modifications of Grangemouth to Granton pipeline and construct H2 supply infrastructure, including supporting evidence for Ofgem decision.	**Stage Gate Two** Recommendation on whether to progress to live trial, including supporting evidence, for Ofgem decision.	LIVE trial	Project completion and blueprint delivery.

2.7.2.3 Safety and Technical Assurance Governance

Given the first of a kind nature of the live hydrogen trial, enhanced safety and technical governance arrangements were embedded:

- A structured HSE Evidence Pathway and Comprehensive Formal Assessment (CFA) submission process was used to track regulatory evidence against defined gaps and submission requirements.
- Independent technical appraisal was provided by DNV and Premtech for designs, and ROSEN provided an independent review of welding procedures and qualification reports.
- Pipeline Integrity Engineers (PIE) provided independent technical assurance across all major deliverables.
- A formal Independent Verification of Readiness (IVoR) process was implemented by SGN prior to commissioning, providing senior level confidence that assets, people and procedures were ready for live hydrogen operation.
- Operational readiness was a critical verification to ensure transition to business readiness for operation, with full alignment to SGN's core business (Operations, Maintenance, Operational Control Centre (OCC), Asset and Gas Control). Illustrating readiness would lead to SGN Executive and CEO sign-off to proceed with the live trial. Sign-off was based on a future operational state via a transition framework and sequence of review and assurance events. Within the transition phase of operational readiness, its people, processes, equipment, and systems are fully prepared to accept and move into the operational phase of the project. This ensures the readiness and assurance for the SGN business to be able to go live and commence the trial.
- Adherence to INEOS assurance processes through completion of Project Health Safety Environmental Review (PHSER) and Pre-Start Up Safety Review (PSSR) prior to going live. The project also contracted an independent process safety review of the designs through Costain Group.
- Submission of two stage gate reports to Ofgem detailing the viability of the Grangemouth to Granton pipeline for repurposing and for progression to the live trial. All reports included all evidence illustrating suitability of the project to move through stage gates and for completion of the live trial.

Technical approvals for hydrogen specific procedures and adaptations to SGN standards were governed through the Hydrogen Governance Group (HGG) and Technical Authority Level (TAL) processes.

2.7.2.4 Change Control and Baseline Management

The project operated a robust Baseline Change Control process to maintain integrity of the Performance Measurement Baseline (PMB). All changes affecting scope, cost, or schedule were:

- Captured through a formal Baseline Change Request (BCR) process.
- Assessed for impact and funding source (including contingency and risk drawdown).
- Reviewed and approved via a Baseline Change Board (BCB).

This ensured transparency of decision making, prevented scope or cost drift, and maintained alignment with Ofgem approved assumptions.

2.7.2.5 Financial Governance and Assurance

Financial governance was underpinned by:

- Monthly cost forecasting and accrual reviews.
- Independent finance and business partner challenge.
- Clear separation between cost estimation, approval, and reporting.

Performance was tracked against both budget and baseline, with Estimate at Completion (EAC), contingency use and variance explanations formally reviewed and reported through directorate and executive dashboards.

2.7.2.6 Risk and Issue Governance

Risk management was integrated into governance through a modified project specific risk framework, with:

- Monthly risk and issue review meetings.
- Explicit ownership of strategic, regulatory, safety, and delivery risks.
- Steering Committee visibility of high and emerging risks and issues.

Opportunities were also actively managed alongside threats, ensuring governance focused not only on risk mitigation but also on value optimisation and learning for future deployment. Issues were managed alongside risks minimising their impact on scope, cost and time.

2.7.2.7 Stakeholder Governance and External Interface

Governance extended to structured engagement with key external stakeholders, including:

- HSE (Pressure System Regulations (PSR), Gas Act notifications and evidence review).
- Environmental regulators and LAs through Environmental Impact Assessment (EIA) / Environmental Consents Unit (ECU) processes.
- Industry partners and landowners related to the live trial.

These interfaces were governed through formal logs, agreed communication plans and escalation routes, ensuring transparency and regulatory confidence.

2.7.2.8 Governance at Project Close

As part of project closure:

- Governance records, decisions and approvals are being formally archived.
- Lessons learned were captured through structured reviews and workshops.
- This formal project closedown report has been submitted to Ofgem in line with NZASP requirements.

Governance arrangements ensured that the project concluded with a clear audit trial, regulatory compliance, and a robust evidence legacy.

2.7.2.9 Overall Governance Assessment

The LTS Futures Project was delivered within a strong, proportionate, and transparent governance framework, appropriate for a complex, high risk, first of a kind hydrogen project. The arrangements provided Ofgem, HSE, and SGN senior leadership with sustained assurance that the project was:

- Controlled and compliant.
- Technically and operationally safe.
- Financially disciplined.
- Delivering learning and value for future hydrogen system decisions.

2.8 LTS Futures supporting projects

Several Network Innovation Allowance (NIA) projects were carried out to support the development of LTS Futures, both prior to the project and during. These encompassed initial surveys and feasibility studies completed to enable the project bid submission, gain further learnings from testing or material from LTS Futures and the delivery of additional scope during the live trial.

2.8.1 NIA enabling works

These projects were developed to provide initial research which directly fed into the development of the LTS Futures Programme or established to undertake preparatory works to progress to the LTS Futures Live Trial.

2.8.1.1 NIA_SGN0166 - The Future of LTS: Evaluation of Vintage Pipeline Materials in Hydrogen Environments

Prior to LTS Futures, initial research was carried out to investigate the effect of hydrogen on vintage pipe material using electrochemical charging as a method of creating a hydrogen environment.

The project findings were consistent with the published literature on hydrogen embrittlement of carbon-manganese pipeline steels. In line with established research, the study confirmed that hydrogen exposure has a limited effect on yield and ultimate tensile strength (UTS) but causes significant reductions in ductility and fracture toughness, with susceptibility increasing as material strength rises. The project aligned with literature and international guidance in identifying cold worked and high strain regions (e.g. dents and cold bends) as presenting the greatest risk, and it highlighted weld quality as a key vulnerability in older pipelines. Consistent with standards such as ASME B31.12 [8], the results supported the need for conservative stress limits and targeted inspection. This highlighted the need to carry out testing in more realistic hydrogen environments to determine if the outcomes were the same or potentially less detrimental to the material properties. Further work was carried out in the LTS Futures materials testing program which is detailed in Section 3.7.

2.8.1.2 NIA2_SGN0001 - Grangemouth to Granton LTS Futures

This project was developed to undertake preparatory works for development of the LTS Futures Live Trial. This included:

- An optioneering study for the hydrogen supply line including a feasibility study.
- Initial development of the repurposing strategy.
- Consideration of how statistically representative the Grangemouth to Granton pipeline is of the LTS.
- Development of understanding of land referencing requirements and impact of the live trial on the landowners.

Hydrogen supply optioneering identified a refinery fed pipeline connection as the preferred solution compared to the tanker supply, as it enabled the opportunity to run multiple operations. For further details of the hydrogen supply feasibility study, see Section 3.2.1.

It was concluded that repurposing the Grangemouth to Granton LTS pipeline for 100% hydrogen was technically feasible and provided an upper bound, statistically representative case for the GB LTS. This was concluded by assessing the pipeline parameters such as wall thickness (WT), coatings, material grade and pipeline route features, such as airport proximity, road crossings, infringements and sleeves against the national LTS. These parameters and features would be fed into the overarching QRA and blueprint. It was also highlighted that use of a non-operational, nitrogen filled asset eliminates security of supply risks.

A full landowner reference map was created of the Grangemouth to Granton pipeline route and included within the stakeholder engagement plan.

2.8.1.3 NIA2_SGN0012 - Recommissioning Grangemouth to Granton

This project was created to research difference aspects of recommissioning strategy for the LTS Futures Grangemouth to Granton pipeline. This included:

- Review different mediums for inline inspection (ILI), considering potential design and construction records which can cause limitations.
- Define potential ILI requirements.
- Cost benefit analysis of ILI from preliminary research.
- Understand the potential risk of infringements along the pipeline route.
- High level assessment of potential uprating to minimise linepack capacity losses.

The project concluded that technically and economically viable options exist to internally inspect the pipeline despite its low pressure, low flow operating constraints. A range of ILI delivery mediums such as compressed air, nitrogen, water, and hybrid options were assessed, concluding that suitable inspection solutions are achievable and could be progressed further. ILI was not carried out as apart of the LTS Futures project and a hydrotest was undertaken to prove pipeline integrity. Further details of this can be found in Section 3.1.2.3. Close Interval Potential Survey (CIPS) and Direct Current Voltage Gradient (DCVG) surveys were also conducted, which did not identify any problems which would have prohibited the development of the Live Trial.

Possible infringements along the pipeline route were preliminarily risk assessed based on natural gas, as a QRA would be completed once the models were updated to include findings of hydrogen rupture tests, further information can be found in Section 3.5.2. Three sections of the route with nearby residential development were identified as requiring further societal risk assessment and mitigation consideration.

An assessment showed that uprating could increase capacity across all networks at design factors of 0.3 and 0.5, but the achievable increase is dependent on local network configuration and by identifying the lowest design pressure along the pipeline route.

[redacted]

[redacted]

2.8.2 Projects which have supported research and development

2.8.2.1 NIA_CAD0111 Asset Records Readiness for Hydrogen

The project was developed to investigate and understand the current condition and management of records. The project included a targeted review to improve the completeness of gas network asset records for net zero planning purposes, without duplicating existing initiatives to improve general record completeness. It has been ensured throughout this process that there is enough detail to support decommissioning of network sections as customers may potentially move to alternative heating initiatives. It has been recommended targeted actions at postcode level to improve the accuracy of the records and explored the use of artificial intelligence (AI) and other technologies to improve processes.

2.8.2.2 NIA2_SGN0065 NDT Fatigue Crack Growth Rate of Hydrogen Pipelines

As part of the LTS Futures testing programme, a full scale fatigue test was carried out on a vessel with a range of defects on a section of vintage pipe. This project allowed the use of Non-destructive Testing (NDT) to measure Fatigue Crack Growth Rate (FCGR) via Time of Flight Diffraction. This technique has several advantages including recordable data generation, immediate results and no requirement for shutdown. Further information can be found in Section 3.8.2.

2.8.2.3 NIA2_SGN0070 Full Scale Burst Testing of Internal Cracks in Hydrogen

Within LTS Futures, nine burst tests on different defects in vintage pipeline material were conducted at DNV Spadeadam. Comparative testing via hydrostatic and pneumatic (gaseous hydrogen) methods was performed. The testing noted no significant difference in the burst pressure of external pipeline defects however an internal crack failed at a significantly lower pressure than would be expected with natural gas, highlighting a potential effect of hydrogen. This NIA project was developed to carry out further burst tests with an internal crack defect. Further information on burst test within LTS Futures and this NIA project can be found in Section 3.8.1.

2.8.2.4 NIA2_SGN0077 Hydrogen Asset Compatibility Tool (ACT) for Transmission

An assessment methodology called the Asset Compatibility Tool (ACT) has been developed, consisting of an Excel-based tool and user guide, to evaluate the suitability of existing natural gas transmission assets for conversion to 100% hydrogen service at pressures from 7 bar to 94 bar. The method supports the management of change from natural gas to hydrogen by assessing asset compatibility and relative risk.

Both above and below ground assets are covered in the scope of the tool, including bends, valves, regulators, slam shuts, relief valves, and pig traps. Assets excluded include pipelines, compressors and cast-iron components.

The assessment tool has been incorporated into the LTS Futures blueprint methodology for repurposing existing natural gas transmission assets to hydrogen.

2.8.2.5 NIA2_SGN0078 and 96 Hydrogen Permeation through the Oxide Layer - Phase 1 and 2

This project focused on researching hydrogen permeability rate through different American Petroleum Institute (API) grades of steel. It conducted an initial literature review of the international scientific and industry knowledge base. Hydrogen permeation is highly dependent on the microstructure which can significantly differ with grades of material. There is limited knowledge of the microstructures present across the transmission pipelines.

2.8.2.6 NIA2_SGN0084 Hydrogen Fracture Surfaces Assessment

During LTS Futures, full scale burst testing of pipeline defects and fatigue testing of small-bore connections which had been exposed to hydrogen was conducted to inform further standards, pipeline design and operational procedures. This NIA project is undertaking additional analysis of the fracture surfaces to provide a visual confirmation of hydrogen diffusion into the material microstructure and if this contributed to failure in the case of the burst tests. For the small-bore connections, the testing will determine if there was any effect on welds which were exposed to hydrogen. This is being completed by a range of methods such as macro photography, Optical Microscopy (OM) and Scanning Electron Microscope (SEM) fractography.

2.8.2.7 NIA2_SGN0110 HCATE Hydrogen Condition & Test Affects

As a part of LTS Futures, full scale fatigue testing has been conducted. The test was conducted by pumping water in and out the vessel to pressurise an outer annulus of hydrogen in contact with the with the inner pipe wall. Due to this test rig configuration, hydrogen gas was saturated with water and small quantities of oxygen. This NIA project has been developed to carry out tests to help understand how this saturated hydrogen gas may have differing effects on fatigue test results. The effect of oxygen as an absorption inhibitor is also being tested. The fracture surfaces will also be analysed by SEM.

The project will also investigate the effect of loading rate on fracture toughness. This is to provide an understanding of the potential effect of loading rate on the burst test results from the original material (LTS Futures and NIA2_SGN0070) and the new suite of burst tests from NIA_SGN0111. This testing programme is still ongoing

2.8.2.8 NIA2_SGN0111 Burst testing of internal sharp defect in hydrogen – conditioning investigation

Continuing from LTS Futures, this NIA project is conducting four additional burst tests on different pipeline material to LTS Futures, to study the effect of hydrogen on internal sharp defects and the effect of the post soaking duration on the failure pressure. The pneumatically tested vessels will be condition with pressurised hydrogen and soaked up to three months. After soaking, the burst tests will be undertaken:

- Immediately after conditioning.
- 8 days post after conditioning.
- 128 days post conditioning.

These tests will support any conclusions which have been made from the previous burst tests carried out by LTS Futures and NIA2_SGN0070. Further information on these tests can be found in Section 3.8.1.

2.8.2.9 SIF 10068217 Velocity Design with Hydrogen Beta

Hydrogen has different energy density by volume to natural gas, and to meet downstream demand, there will need to be an increase in pressure, volume or velocity for a hydrogen gas network. Previous phases of this project identified that an increase to velocity limits would be the most practical solution, allowing for avoidance of costly network reinforcement. The impact to erosion rates, particle transport, noise and vibration were the main factors to consider in order to ensure safe and reliable operation of a future hydrogen network. This project seeks to evaluate the impact of increased velocity on erosion, vibration, noise, and particle transport under hydrogen flow conditions. To achieve this a full-scale test rig will be built to provide empirical evidence to validate industry models and establish updated velocity limits for hydrogen service.

2.8.3 Projects which supported additional scope delivery during the live trial:

A number of additional projects were carried out in tandem with LTS Futures and ultimately resulting in increasing the learning from the live trial. These projects enabled flow stopping for two technologies, the stopple train and BISEP, to be included in the live trial plans. The project details can be found in their corresponding NIA projects detailed below and are also included in Section 3.6.3.

- NIA2_SGN0036 and 52 BISEP hydrogen testing and live field trial.
- NIA2_SGN0076 Stopple Live trial (Phase 2).

3. Outcomes and Achievements

3.1 Repurposed Pipeline and Block Valve

The project successfully demonstrated that existing assets are suitable for and can be repurposed to hydrogen service. For the LTS Futures project, this included repurposing 30 km of existing high-pressure pipeline and its associated block valve to hydrogen and the completion of a live trial on these assets. The process developed by the project is detailed in the LTS Futures Repurposing Blueprint.

The following sections detail the modifications, assessments and evidence that was compiled to support this decision and allow the project to progress through its first stage gate and on to the live trial.

3.1.1 Repurposing Modifications

The Grangemouth to Granton pipeline originally operated between Granton Transmission Reduction Station (TRS) and the INEOS Forties Pipeline System site. To enable the trial, the pipeline was diverted from West Shore Road into the grounds of the SGN Granton training centre. This abandoned the section leading into the PRS, which was 7 barg rated and therefore not suitable for the trial. The diversion into the training centre was terminated with an 18" full bore ball valve and swan neck bringing the pipeline above ground. This allowed for the installation of a temporary pig trap for the hydrotest and drying.

At Newton, a 50 m section of the existing Grangemouth to Granton pipeline was cut out adjacent to the Newton Block Valve (NBV) compound. This section of pipe was removed for materials and full scale testing programmes being carried out as part of the project and replaced with X52, 9.52 mm WT, seamless pipe, designed in compliance with IGEM/TD/1 [6]. Within the compound, the existing bypass was removed prior to the hydrotest, leaving the mainline block valve and 2 x 6" offtake valves. A replacement, project-specific bypass was designed and installed in compliance with IGEM/TD/13 supplement 1 [9]. This enabled control of downstream pressure for the hotworks during the live trial.

At Grangemouth, the pipeline terminated at a pig trap installation within INEOS FPS. This pig trap and associated pipework was removed prior to hydrotest, and a new Class 600 weld-neck flange was installed.

This formed the connection for the temporary pig trap which was utilised for the hydrotest and drying operations. A second Class 600 weld neck flange was installed to remove air-gapped pipework.

3.1.2 Grangemouth to Granton Pipeline

3.1.2.1 Grangemouth to Granton Pipeline – TD/1 Compliance Study

A study was carried out to assess the pipeline's compliance with IGEM/TD/1 Edition 6 [6]. The report concluded that the pipeline should be declared as satisfying IGEM/TD/1 Edition 6 [6], with a maximum operating pressure (MOP) of 26 barg, following the close-out of a series of recommendations. The recommendations and remedial actions are detailed in Table 1 on the following page. These were all resolved with the actions detailed prior to commissioning.

3.1.2.2 Grangemouth to Granton Pipeline Repurposing Study

Having established the compliance of the Grangemouth to Granton pipeline with IGEM/TD/1 Edition 6 [6], the next step towards hydrogen service was to complete a repurposing study to determine compliance with IGEM/TD/1 Edition 6 Supplement 2 [10]. The resulting report confirmed that the Grangemouth to Granton pipeline was suitable for hydrogen service with the following recommendations to be closed out prior to the live trial. Table 2, outlines the recommendations and the actions taken prior to the trial.

Table 1: TD/1 compliance recommendations.

Area	Description of recommendation	Response and progress of actions
MOP	MOP to be declared at 26 bar.	PSR Regulation 22 [11] notification was submitted to HSE.
Line Walk	Pipeline line walk to be repeated prior to the live trial.	Repeat line walk completed in 2024.
Daily pressure cycle	The pipeline to not be subject to daily pressure cycling during the live trial.	Fatigue life assessment concluded that the remaining fatigue life is sufficient for the live trial.
Road Crossing	M90 and A904 road crossings to be investigated and risk assessed.	QRA completed to cover all road crossings with non-compliant sleeves.
	Country road between A904 and Abercorn and A706 road crossings to be subject to risk assessment.	QRA completed to cover all road crossings with non-compliant sleeves.
River Crossings	Four watercourse crossings to be risk assessed.	2024 underwater crossing surveys were completed. Analysis of the results showed compliance the original IGE/TD/1 [12], with no notable reductions in depth of cover (DoC) over time.
Nitrogen Sleeves	Sleeves to be maintained in accordance with MAINT/5.	Monthly pressure readings of sleeves were recorded and reviewed.
Corrosion Protection	Investigate why the instant OFF potential readings are more negative than -1200 mV.	Five investigative digs to confirm the pipeline condition were carried out. The pipeline is electrically bonded to others in the pipeline corridor. Changes to the CP system on the Grangemouth to Granton pipeline could adversely affect the CP systems of the other pipelines, therefore rebalancing was not carried out due to the short duration of the trial.
	Re-balance the cathodic protection (CP) system to obtain acceptable CP readings along the pipeline.	The pipeline is electrically bonded to others in the pipeline corridor including pipelines belonging to other operators. Changes to the CP system on the Grangemouth to Granton pipeline could adversely affect the CP systems of the other pipelines, therefore rebalancing was not carried out due to the short duration of the trial.
	CIPS and DCVG results to be assessed to determine requirement for further coating defect validation digs.	The surveys carried out were overlaid on a map to create a unified view of the results, to help identify locations for dig verifications to be carried out.
	Further investigation of identified under-protected coating defects.	Five dig verifications were completed, and one excavation uncovered disbonded coating on a sleeve end seal, which was repaired and reinstated.
Compliance	Put in place the appropriate Written Scheme of Examination (WSoE) and register the pipeline under the Pressure Systems Safety Regulations.	WSoE developed and reviewed. PSR Regulation 22 [11] notification submitted to HSE.
	The pipeline to be operated and maintained to IGEM/TD/1 Edition 6 Supplement 2 [10].	This will be required throughout the project including the live trial.
Valve Maintenance	Valve maintenance to be completed in accordance with MAINT/5.	Newton block valve (NBV) was moved prior to the live trial, and as part of the pressurisation steps, sealing capability was confirmed. WSoE was developed and approved prior to commissioning.
Modifications for Repurposing	Any modifications for repurposing to be done in accordance with SGN/PM/PS/5 [13].	All modifications were reviewed and signed off as per SGN/PM/PS/5 [13].
Local Authorities	Contact the relevant LAs prior to the live trial.	The three LAs were contacted and engaged in emergency response planning.

Table 2: Pipeline repurposing recommendations.

Area	Description of recommendation	Response and progress of actions
Corrosion Protection	In accordance with the CIPS and DCVG Survey report, SGN should rebalance the Impressed Current Cathodic Protection System (ICCPS) to ensure the maximum permissible "instantaneous Off" criterion of between -850 mV to 1200 mV relative to a $Cu/CuSO_4$ reference cell and carry out a CIPS on areas along the pipeline route where uncleared scrub exists. The CP system should continue to be maintained for the duration of the live trial.	Five investigative digs to confirm the pipeline condition had been carried out. The pipeline is electrically bonded to others in the pipeline corridor. Changes to the CP system on the Grangemouth to Granton pipeline could adversely affect the CP systems of the other pipelines, therefore rebalancing was not carried out due to the short duration of the trial.
Proximity to other Pipelines	SGN should confirm the proximity of the pipeline to all parallel pipelines along the pipeline route.	A proximity assessment was carried out prior to the live trial.
Depth of Cover	The 66 regions of depth of cover identified as being below 1.1 m in the line walk survey and the 7 regions of depth of cover identified as being below 1.2 m in the river, burn, and ditch crossing surveys should be reviewed and assessed to determine if they are acceptable for hydrogen service during the live trial.	The surveys carried out were overlaid on a map to create a unified view of the results, to help identify depth of cover trends at locations. There were no areas of concern for the duration of the trial.
Ground Movement	Given the issues with ground movement indicated in the IGEM/TD/1 report from 1986 [14], the pipeline route should be reviewed and assessed to determine the potential for ground movement during the live trial and the effect this would have on the pipeline. Depending upon the outcome of this assessment, appropriate protective measures may be required for the live trial.	A landslide susceptibility study for the pipeline route indicated that most of the route had a 'low to nil' landslide risk, with certain sections classified as having 'moderate' landslide potential. Outputs were used in the QRA.
Maintenance	As the asset must be treated as a live pipeline following the revalidation hydrotest, a maintenance regime should be developed and applied for the intervening period between completion of the revalidation hydrotest and commencement of the live trial.	A Post-Hydrotest Integrity Management Plan was developed and followed until the commencement of the live trial. Following this, maintenance requirements were included in the pipeline operation and maintenance work instruction (WI).
	Inspection procedures, frequencies, results, and techniques to be applied during the trial should be developed for hydrogen service.	Operation and maintenance WIs were developed, see Section 3.5.3, and an audit and inspection plan was put in place.
Maintenance Instructions and Procedures	Existing maintenance instructions and procedures to be applied during the trial should be updated to account for the operational conditions during the live trial.	Operation and maintenance WIs were developed for the trial. See Section 3.5.3.
Training	Personnel should have specific hydrogen hazard awareness training and should be familiar with the appropriate WIs and procedures prior to the commencement of the live trial.	A training and competency plan was developed, and training was completed prior to the live trial. See Section 3.5.4.
Knowledge Dissemination	Knowledge sharing should be emphasised during and after the live trial.	See Section 6.

3.1.2.3 Grangemouth to Granton Pipeline Gauge Pigging and Hydrotest

Prior to hydrotesting the pipeline, cleaning and gauging of the pipeline was completed in December 2022, firstly using a gauge plate pig and then for a second run using the ROSEN Ultimate Clean Pig (CLP).

The gauge plate from the first run had minimal damage and was consistent with what is typically observed during cleaning/gauging runs. This allowed the second run to be completed with the ROSEN tool without an unacceptable risk of damage. The CLP tool gauge plate had some wear and deformation when received at Grangemouth. Following analysis of the data, the peak differential pressure likely to have caused this was identified as occurring on the above-ground section within the Grangemouth site. This correlates approximately with the location of a barred tee. The output from the run confirmed that there were no other mechanical obstructions in the pipeline greater than 7.86% outer diameter (OD) in the 6.35 mm WT sections and 6.49% in the 9.52 mm WT sections. This concluded that no excavations or further assessments were required in advance of the hydrotest.

A hydrotest of the 30 km Grangemouth to Granton pipeline was completed to re-validate the integrity of the pipeline in accordance with IGEM/TD/1 Edition 6 [6]. Typically, revalidation would be carried out using ILI; however, this was not considered practical in the case due to:

- The complexity of generating the flow conditions to provide consistent velocity for the ILI tool which would be required to generate acceptable data. The Grangemouth to Granton pipeline was out of service and isolated from the gas network.
- Significant estimated costs of ILI with the hydrotest providing greater value for money to the project in terms of revalidating the pipeline.

The pipeline was successfully uprated and hydrotested in January 2023 to 39 barg (1.5 x the proposed 26 barg MOP) and held for 24 hours (exceeding the code requirements). Following the hydrotest, the pipeline was emptied, dried and pressurised with nitrogen to 2 barg for preservation until the trial. No further pigging operations were planned, and the temporary pig traps were removed.

3.1.2.4 Interim Maintenance Plan

Following the hydrotest, it was acknowledged that there would be a period of time before the pipeline would be repurposed for the live trial. The project developed an interim maintenance plan to ensure that the pipeline's integrity, which was proven by the hydrotest, was preserved until the live trial. Many of these maintenance requirements would be standard for any high-pressure pipeline, and although the Grangemouth to Granton pipeline was only at 2 barg with nitrogen, these measures were implemented to ensure the integrity was not compromised prior to the trial.

Table 3: Interim maintenance measures.

Area	Description of recommendation	Response and progress of actions
Mapping	Confirmation that SGN's mapping of the route aligns with the updated pipeline route.	Pipeline route was updated in SGN's mapping system.
Compliance	The standard frequency to update an MOP Affirmation Report is 4 years.	A new report is planned for 2025, prior to the live trial.
Pressure Monitoring	Installation of an internal pipeline pressure monitoring system during the nitrogen-filled period will allow any loss of pressure to be investigated and addressed prior to the hydrogen trial.	Pressure monitoring system has been installed. Pipeline nitrogen pressure is being monitored and regularly reviewed.
Aerial Survey	Grangemouth to Granton pipeline is captured in RAPTOR system and treated as an operational pipeline.	An internal audit of aerial sightings in the vicinity of the pipeline route was completed.
Vantage Point Survey	Only required if pipeline cannot be aerially surveyed.	Documented vantage point surveys will be provided, if necessary, to address gaps in aerial surveys.
Corrosion Prevention	T/R monitoring and test post surveys (functional, interim, and major) as per ECP/2 [15].	CP monitoring is an ongoing activity conducted up to and during the live trial. The CP system has been maintained prior to the LTS Futures project and will continue to be operated and maintained after the live trial.
CIPS / DCVG Survey	One coating defect validated and remediated prior to hydrotest. Ongoing analysis of CIPS / DCVG outputs to identify validation digs. Any coating defects will be remediated as appropriate. Another CIPS / DCVG is not required prior to the live trial.	Complete CIPS and DCVG surveys were carried out and overlaid on a map to create a unified view of the results, to help identify locations for dig verifications to be carried out. Five dig verifications were completed, and one excavation uncovered disbonded coating on a sleeve end seal, which was repaired and reinstated.
Underwater Crossing Survey	The River Almond is tidal with depth of cover (DoC) recorded as 0.7 metres in February 2022. Confirm no unacceptable reduction in DoC.	2024 underwater crossing surveys complete. A comparison between the strip map, 2022 and 2024 DoC readings has been made, and the results indicate no significant change in the DoC. There is no evidence to suggest that the probability of external interference at the crossing has significantly changed since installation.
Line Walking	Check for signs of third-party damage, or activity that could negatively affect pipeline integrity.	2024 line walk complete with data available. Outputs have fed into DoC analysis.
Owner / Occupier Liaison	Landowners are to be captured in Landowner Database or temporary database for trial period to be set up. Meeting with landowners planned for 2023.	A specific landowner database was developed for the project detailing all contact with landowners over the project. A town hall meeting to introduce the project was carried out in 2023. Landowner liaison has been conducted prior to above ground surveys and works, with ongoing liaison throughout the project as per the Stakeholder Engagement Plan.

Table 3: Interim maintenance measures (continued).

Area	Description of recommendation	Response and progress of actions
Local Authority (LA) Planning Departments	Planning Departments of City of Edinburgh, West Lothian and Falkirk to be informed of pipeline route and live trial. Submission of Regulation 22 notification to the HSE will initiate process to capture the pipeline on the Land Use Planning (LUP) system and allow the Consultation Distance to be established and provided by the HSE to the LAs.	PSR Regulation 22 [11] notification submitted to the HSE. Communications with LA Planning Departments outlined in the LTS Futures Stakeholder Engagement plan.
LA Emergency Planning	LAs will need sufficient time and support to capture the Grangemouth to Granton pipeline hydrogen live trial in their emergency plans.	Project-specific appendix for LA Emergency Plans was issued to the LAs.
Emergency Exercise	A desktop emergency exercise will be planned to test and adjust the arrangements in advance of the hydrogen trial. This will be followed up with a live emergency exercise.	A desktop emergency response exercise was carried out prior to commissioning. This included all LAs, HSE and emergency services.
Linesearch Before U Dig (LSBUD)	LSBUD has accurate pipeline route details.	SGN have confirmed that the Grangemouth to Granton pipeline is in the LSBUD system.
Third Parties	Identify all relevant third parties and initiate communications.	A project-specific landowner database was developed and regular communication with landowners was ongoing throughout the project. There was regular communication with the LAs. Normal SGN procedures include contact with statutory bodies and other pipeline operators.
Nitrogen Sleeves	Pressure monitoring data loggers which are read monthly. Investigate, assess and remediate as appropriate any sleeves losing pressure.	Pressure monitoring data loggers were read monthly. Six sleeves were identified as losing pressure due to connection hoses or fittings, and these were remediated prior to commissioning.
Marker Posts	Marker post condition identified from 2022 line walk report and remedial activities ongoing. Marker post condition updated during aerial / vantage point survey.	Damaged / missing marker posts were identified in the 2022 line walk with remedials completed. Further damaged / missing marker posts will be identified from the 2024 line walk with remedials work completed prior to commissioning.
Valves and Actuators	Main line valve at NBV site should be treated as a Safety Critical valve and bypass valves as Network Critical. They should be tested in advance of the live trial to demonstrate leak tightness for hydrogen service by closing valve and pressurising cavity with helium to confirm sealing capability of double block and bleed valve seals and other mechanical connections. Adequate time should be planned for any remedial actions required.	Activity stated is not appropriate due to the level of pressure in the line prior to commissioning. The valves were moved prior to commissioning, and during the pressurisation steps, the sealing capability of the mainline block valve was confirmed. The new bypass arrangement included specific hydrogen-rated isolation valves.

3.1.3 Newton Block Valve (NBV)

The NBV is located approximately halfway between Grangemouth and Granton. The bypass around the block valve was removed and replaced with a new purpose-built bypass to support the needs of the trial. This allowed control of pressure downstream of the block valve for the live trial hot works operations.

The block valve site was excavated in 2023, and a full inspection was completed. All remedial works identified were completed including replacement pipe supports and maintenance on the existing valves. Following these works, the 2 x 6" offtake valves and the mainline block valves were chambered to allow for monitoring during the live trial. The pipework was hydrotested as part of the pipeline hydrotest in January 2023, and the bypass was hydrotested separately prior to installation.

A repurposing assessment of Newton Block Valve was carried out in accordance with IGEM/TD/13 Edition 2 Supplement 1 [9] and was confirmed to be suitable for hydrogen service provided the following recommendations were closed out.

Table 4: Repurposing recommendations for NBV site.

Area	Description of recommendation	Response and progress of actions
Location and Layout	The reinstatement of the bypass and vent pipework should be in accordance with IGEM/TD/13 Edition 3 [16] and its Supplement 1 [9] and consider the hazardous area assessment.	The new bypass was designed in accordance with IGEM/TD/13 Edition 3 and Supplement 1 [17] [18]. Hazardous area drawings were produced for the site, and an independent approval and appraisal process was followed.
Hazardous Area Assessment	It is recommended that a hazardous area should be calculated and drawings produced prior to the live trial, noting the requirements of IGEM/SR/25 Edition 2 with amendment 2013 Hydrogen Supplement 1 [19]. If the hazardous area extends beyond the site, then a Quantified Risk Assessment (QRA) shall be performed to determine the level of risk posed to the general public in the vicinity of the installation.	A hazardous area was calculated, and drawings were produced for the site. The hazardous areas did not extend beyond the site boundary, therefore no QRA was required.
Housings, Kiosks, Buildings	There are no housings, kiosks or buildings at NBV site and therefore no recommendations.	Not applicable as there will be no buildings on site, and kiosks were positioned out with the hazardous areas.
Installation Design	The reinstatement of the bypass and vent pipework should be in accordance with IGEM/TD/13 Edition 2 and its Supplement 1 [16] [9].	An independent process for approval and appraisal was used prior to design acceptance and proceeding to construction.
Flowrate and Velocity	An assessment of flow velocities should be completed to ensure that the gas velocities are in accordance with IGEM/TD/13 Edition 2 and its Supplement 1 [16] [9].	An independent process for approval and appraisal was used prior to design acceptance and proceeding to construction.
Pipework Material and Sizing	The reinstatement of the bypass and vent pipework should be in accordance with IGEM/TD/13 Edition 2 and its Supplement 1 [16] [9].	An independent process for approval and appraisal was used prior to design acceptance and proceeding to construction.
Pressure Boundaries	Not applicable to the NBV installation.	Not applicable to NBV in its planned configuration.
Isolation Valves	That leak detection is incorporated into the commissioning procedure with adequate time planned for any remedial actions required.	NBV was moved prior to the live trial, and as part of the pressurisation steps Non-routine operations (NRO), sealing capability was confirmed. WSoE was developed and approved prior to commissioning.
Gas Cleaning / Filters	Filters incorporated into the new works for the live trial should be designed in accordance with IGEM/TD/13 Edition 2 and its Supplement 1.	An independent process for approval and appraisal was used prior to design acceptance and proceeding to construction.
Regulators	Regulators incorporated into the new works for the live trial should be designed in accordance with IGEM/TD/13 Edition 2 and its Supplement 1 [16] [9].	An independent process for approval and appraisal was used prior to design acceptance and proceeding to construction. New regulators installed were specified for hydrogen service.
Protective Devices	Not applicable to the Newton Block Valve installation.	Not applicable to NBV in its planned configuration.
Vibration and Noise	Perform a screening assessment noting sources of excitation and features susceptible to vibration. If the risk of failure from vibration is deemed credible, appropriate inspection is recommended to identify potential cracking and any indications assessed. Vibration and noise monitoring should be carried out during the live trial.	Site was manned during all flowing gas operations and monitored for excess vibration and noise by onsite personnel.
Auxiliary Pipework, Fittings and Bolts	Not applicable to the NBV installation.	Not applicable to NBV in its planned configuration.
Vents / Breathers	The venting pipework and valves should be re-instated ensuring the sizing of the vents allows either pipeline section to be depressurised as rapidly as practicable.	Not applicable to NBV in its planned configuration.
Metering	Not applicable to the NBV installation.	Not applicable to NBV in its planned configuration.
Corrosion Protection	Carry out a detailed visual inspection of pipework in accordance with clause S16.6.6 of IGEM/TD/13 Edition 2 Supplement 1 [9] and T/PR/NDT/1 [20]. Particular attention should be made to the soil-air interface and pipework-support interface.	Detailed inspection of the site was carried out as part of the remedial works. Coating was re-instated and pipe supports replaced prior to chambering of the valve and reinstatement of the site.
Electrical and Instrumentation	Leak and flame detection devices are installed at appropriate locations in accordance with IGEM/TD/13 Edition 2 Supplement 1 [9].	Flame and leak detection instrumentation was installed onsite covering all potential leak locations.
Signage and Demarcation	Signage at the NBV installation should reflect the change to hydrogen operation prior to the live trial.	Appropriate signage was in place in advance of the live trial.
DSEAR [21]	A dangerous substance and explosive atmosphere risk assessment should be carried out for the installation.	Dangerous Substances And Explosive Atmospheres Regulations (DSEAR) assessment completed before commissioning.

3.2 Designed and Constructed a New Hydrogen Supply Pipeline and Entry Unit

The design and construction of the supply pipeline, entry unit and block valve bypass were primarily intended to facilitate the live trial. However, each of these tasks also demonstrated the usability of existing hydrogen supplements to design codes to produce safe and functional assets. These activities also provided an opportunity to consider how existing facilities could be repurposed and the potential challenges with this, including equipment selection, procurement and costs.

3.2.1 Feasibility Study

In preparation for the project, a feasibility study was carried out along the Grangemouth to Granton pipeline route and considered the routing of the hydrogen supply pipeline. This included potential options for connection points to the INEOS hydrogen supply, entry unit locations, and a diversion at Hopetoun Garden Centre with the pipeline terminating at Granton. The study concluded with recommendations for progressing with a connection point with INEOS Olefins and Polymers (O&P) proximal to Bo'ness Road, and routing the supply line through the grass verge to the entry unit. At this stage, an entry unit location external to the FPS site was the primary option. This was later reconsidered, and siting of the entry unit within INEOS FPS became feasible. The study recommended further assessment of the pipeline at Hopetoun Garden Centre to determine if a diversion was required. A subsequent site specific QRA deemed the risk at this location to be broadly acceptable and no mitigation measures were required.

A separate study was completed by INEOS to review potential connection points within O&P and routing to the boundary fence at Bo'ness Road. This concluded that the timing of the works would play an important role in determining the most appropriate option, due to some connection points requiring a site shutdown.

[redacted]

[redacted]

3.2.2 Detailed Design

A detailed design was completed for each of the new installations, including:

- Hydrogen connection point within INEOS O&P and pipework to the boundary fence.
- 3" hydrogen supply pipeline (1.2 km) and Bo'ness Road compound.
- Hydrogen entry unit.
- NBV bypass.

The designs utilised existing SGN procedures and industry design standards including:

- IGEM/TD/1 Edition 6 – Steel Pipelines and Associated Installations for High Pressure Gas Transmission [6].
- IGEM/TD/1 Edition 6 Supplement 2 – High Pressure Hydrogen Pipelines [10].
- IGEM/TD/13 Edition 3 – Pressure Regulating Installations for Natural Gas, Liquefied Petroleum Gas and Liquefied Petroleum Gas/Air [17].
- IGEM/TD/13 Edition 3 Supplement 1 – Pressure Regulating Installations for Hydrogen at Pressures Exceeding 7 bar [18].
- IGEM/SR/25 – Hazardous Area Classification of Natural Gas Installations [22].
- IGEM/SR/25 Edition 2, with amendments 2013, Hydrogen Supplement 1 – Hazardous Area Classification of Installations Using Hydrogen or Blends of up to and Including 20% by Volume Hydrogen in Natural Gas [19].

During this process, there were regular design co-ordination meetings between all relevant internal and external parties to ensure the developing design continued to meet the needs of the project and ensuring that the connection points between designs aligned in terms of design standards.

Designs from each of these disciplines were included for each site:

- Mechanical design for pipework and equipment to be installed.
- Civil design for support structures and bases.
- Electrical design for instrumentation and data logging, control systems and onsite power.
- Hazardous area assessments.

The design process was controlled and co-ordinated through technical queries and a deviation process was followed for any adaptation where the specified design code could not be met. A design decisions and assumptions register was developed and maintained throughout the process as a record of the design choices made.

With the finalised design in place, a Hazard and Operability Study (HAZOP) was carried out. These were conducted in accordance with the requirements of BS EN 61882:2016 [23] with supplementary guidance from "HAZOP Guide to best practice" [24]. HAZOPs were attended by representatives from each discipline and connected party to ensure a comprehensive study was completed. Actions were issued to attendees and follow-up close-out meetings were held to agree completion of these.

The final stage was the approval and appraisal of designs. This was carried out through the established processes detailed in:

- SGN/PM/PS/5 – The Management of New Works, Modifications and Repairs [13].
- SGN/WI/PS/6 – Work Instruction for Managing High Risk New Works, Modifications and Repairs [25].

Due to the novel nature of the project, a detailed independent review process was carried out for the selected equipment items to ensure the items procured were suitable for use in hydrogen service and had been tested to demonstrate this. In most instances, the need for equipment testing in hydrogen was defined in the procurement specification. However, for some items, such as plug valves, additional testing was carried out and verified by a third party for the project, as testing with the manufacturer was not available. In selecting equipment, input was taken from existing facilities handling hydrogen, and the items they used to ensure the most appropriate choices were made.

3.2.2.1 Connection point with INEOS O&P to Fence Boundary

A feasibility study was carried out to determine the most suitable option for the tie-in point within INEOS O&P. Initially, this would have involved approximately 440 m of onsite pipework; however, due to a delay with the project, it was possible to utilise a connection point closer to Bo'ness Road, requiring 80 m of pipework, as the trial would be taking place after the 2024 turnaround.

Onsite pipework was designed and constructed to ASME B31.3 using INEOS-approved designers and contractors. There was consistent communication between INEOS and SGN designers to ensure the designs were compatible and met the required standards, with clear delineation points between sections. The route consisted of above-ground pipework and valves to the fence boundary, followed by a buried section under the boundary fence and into the Bo'ness Road compound. Construction of the connecting pipework with INEOS O&P was completed in April 2025, with isolation spades remaining in place until final preparations for commissioning.

3.2.2.2 Supply Pipeline – Design and Construction

The hydrogen supply pipeline was the first pipeline designed and constructed in line with IGEM/TD/1 Supplement 2 [10]. Following on from the feasibility study, the design firstly confirmed that the suggested 3" diameter would meet the supply needs of the project. At this stage, the final flow rate of hydrogen available was still to be finalised, but a broad agreement of 250 kg/hr had been reached. This was agreed with INEOS and met the trial requirements. The design process then considered the route from the connection point with INEOS O&P at the fence boundary on Bo'ness Road to the connection with the entry unit to be located within INEOS FPS. There were several challenges to be considered along the route including:

- Heavily congested verges and footpaths with several other buried services.
- Narrow road sections and a bridge requiring traffic management.
- Gateway crossings to the INEOS site, which were critical for its emergency response.
- A culvert crossing.
- An above-ground crossing (river), which utilised a listed bridge.
- Routing of the pipeline into INEOS FPS and negotiation of existing infrastructure.
- Lack of a permanent power supply for the required instrumentation/monitoring.

A decommissioned/abandoned 6" and 16" mains at the culvert and on the side of the bridge respectively were used as sleeves for the new hydrogen supply pipeline.

Figure 5: Bo'ness Road compound – hydrogen isolation point.

Prior to commencement of the construction works, a Hazards in Construction Study (HAZCON) was carried out to ensure that all potential hazards had been considered and mitigated in relation to the build, specifically the challenging culvert and river crossing sections.

The finalised route started from an isolation compound on the Bo'ness Road following which the pipeline was buried below ground in the grass verge. The 3" pipeline was installed across three gateways/access points along the route using a moling technique to minimise disruption. Following this, the pipeline route reached the INEOS culvert. At this point, there was significantly reduced depth of cover for the existing abandoned 6" main which was to be used as a sleeve. This reduced depth of cover and sleeving required engineering policy deviations to be approved, as this was not code compliant. Impact protection was installed in the culvert during the construction of this section to protect INEOS assets.

The pipeline continued in the grass verge until it reached the River Avon crossing, where it was routed above ground and was sleeved in an existing 16" abandoned main. This deviation from code also required approval. Due to the condition of the supports and congestion with other services on the bridge, significant remediation works were required. As the bridge was a listed structure, there were also constraints with access, and a number of surveys were required to ensure structural stability for the pipeline. Ecological surveys were also carried out prior to works commencing.

After the bridge crossing, the pipeline crossed Bo'ness Road and continued in the grass verge on the north side towards INEOS FPS. For the final section of pipeline to enter the FPS site and the area for the hydrogen entry unit, it would cross a gateway, security fences and the fire main for the INEOS FPS site. Horizontal Directional Drilling (HDD) was used to install this section of pipeline, minimising the disruption to INEOS facilities. This was a significant challenge, as INEOS were unfamiliar with this process, with some concerns regarding potential unmarked services within the FPS site. This required significant engagement and planning, taking almost 12 months to gain approval.

Figure 6: Gateway 7 moling pit.

Figure 7: River Avon bridge crossing construction.

Figure 8: HDD exit INEOS FPS site.

Figure 9: Pipe string on exit.

Other considerations along the pipeline route included the need for a rolling traffic management system. During the construction period, a lane closure was required to provide a safe working area for onsite contractors. Engagement with INEOS was on-going and, although operations were mostly outside of their site boundary, construction work was taking place in and around their assets. Substantial engagement with LAs and the public regarding road closures was undertaken to improve awareness and minimise disruption.

Civil works were completed at the fence boundary with INEOS O&P on Bo'ness Road to create a small compound for isolation valves and monitoring equipment. This consisted of a security fence, concrete base to support pipework and an instrument cabin. Vehicle impact protection was also installed at the roadside.

In addition to the logistical issues, there were technical difficulties to be overcome. The development and qualification of suitable welding procedures were required, as initial Shielded Metal Arc Welding (SMAW) procedures were not suitable. A new Tungsten Inert Gas (TIG) procedure was developed and qualified, allowing construction to proceed. Due to the novel nature of the project, there were additional quality and assurance monitoring, both in regard to the materials used and onsite operations. There were also challenges regarding carrying out radiography on 100% of the welds on the pipeline due to the congested nature of the installation area and its proximity to the general public.

Following completion of the mechanical works, electrical and instrumentation installation commenced. This provided the required monitoring system for the hydrogen supply pipeline, allowing the pressure and temperature to be monitored, as well as the flame and leak detection sensors at the Bo'ness Road compound. Data was monitored via a Watchlog system, which could be viewed remotely and accessed by the project team and Gas control centre (GCC). As there was no permanent power supply to the compound, all equipment was battery powered, and regular onsite maintenance ensured that batteries were swapped at required intervals. Connection to the Watchlog system was via the mobile phone network, and multi-network SIMs were used to minimise connection issues. In the event of a network failure, the Watchlog system would notify GCC that communications had been lost, and the onboard memory capacity within the unit could retain several days of data.

When all construction and testing onsite were completed, a commissioning certificate was issued in preparation for commissioning. See Section 3.6.1.

3.2.2.3 Hydrogen Entry Unit

The design for the hydrogen entry unit utilised the specifications provided in IGEM/TD/13 [17]. While designed in a similar way to a natural gas entry unit, there were significant differences. Some of these adjustments were due to the operational requirements and others in relation to the bespoke nature of the trial.

The following equipment was included within the entry unit:

- Isolation valves.
- Filtration.
- Coriolis flow meter.
- Safety shut-off valve.
- Pressure control valve.
- Flow control valve.
- Odorisation unit.
- Gas sampling.
- Flame and leak detection.
- Pressure monitoring.
- Temperature monitoring.

The entry unit design had to overcome both operational and logistical challenges including:

- A lack of permanent power supply onsite.
- Varying gas composition.
- Prohibition of fugitive emissions from any equipment item.

These challenges were addressed as the design was developed ensuring that the needs of the project continued to be met. The entry unit operated as a single stream as there were no end users and no criticality of supply concerns, therefore the redundancy provided by a twin-stream unit was not required. Pressure and flow control was provided with electrically actuated valves, and while these are not typical, there were no fugitive emissions from normal operation. A Coriolis flow meter was selected, as this could accommodate changes in gas composition while still maintaining the accuracy required for flow measurement. In line with IGEM/TD/13 Supplement 1 [18], the site had flame and leak detection equipment fitted. This was positioned to cover all onsite equipment and, coupled with pressure and temperature instrumentation, allowed the site to be remotely monitored outside of operating periods. Pressure monitoring through the Watchlog system provided an alert if the pressure in the isolated section decreased by 0.5 barg in 30 minutes.

The design also considered the potential need for onsite maintenance and recognised that live working on a hydrogen system would not be allowed. It included provision for isolating and purging individual sections of the entry unit using a fixed onsite vent stack with a considered hazardous area, should venting of a small, isolated section be required.

Following completion of the design, a HAZOP was carried out with input from all disciplines. INEOS personnel were involved in this process, as the entry unit was located inside the FPS site and would be used to control and measure the flow of hydrogen for the trial. It was important that the design and operation of the entry unit did not pose any unnecessary or unmanaged risk to the remainder of the facility.

Figure 10: Hydrogen entry unit piping and instrumentation diagram.

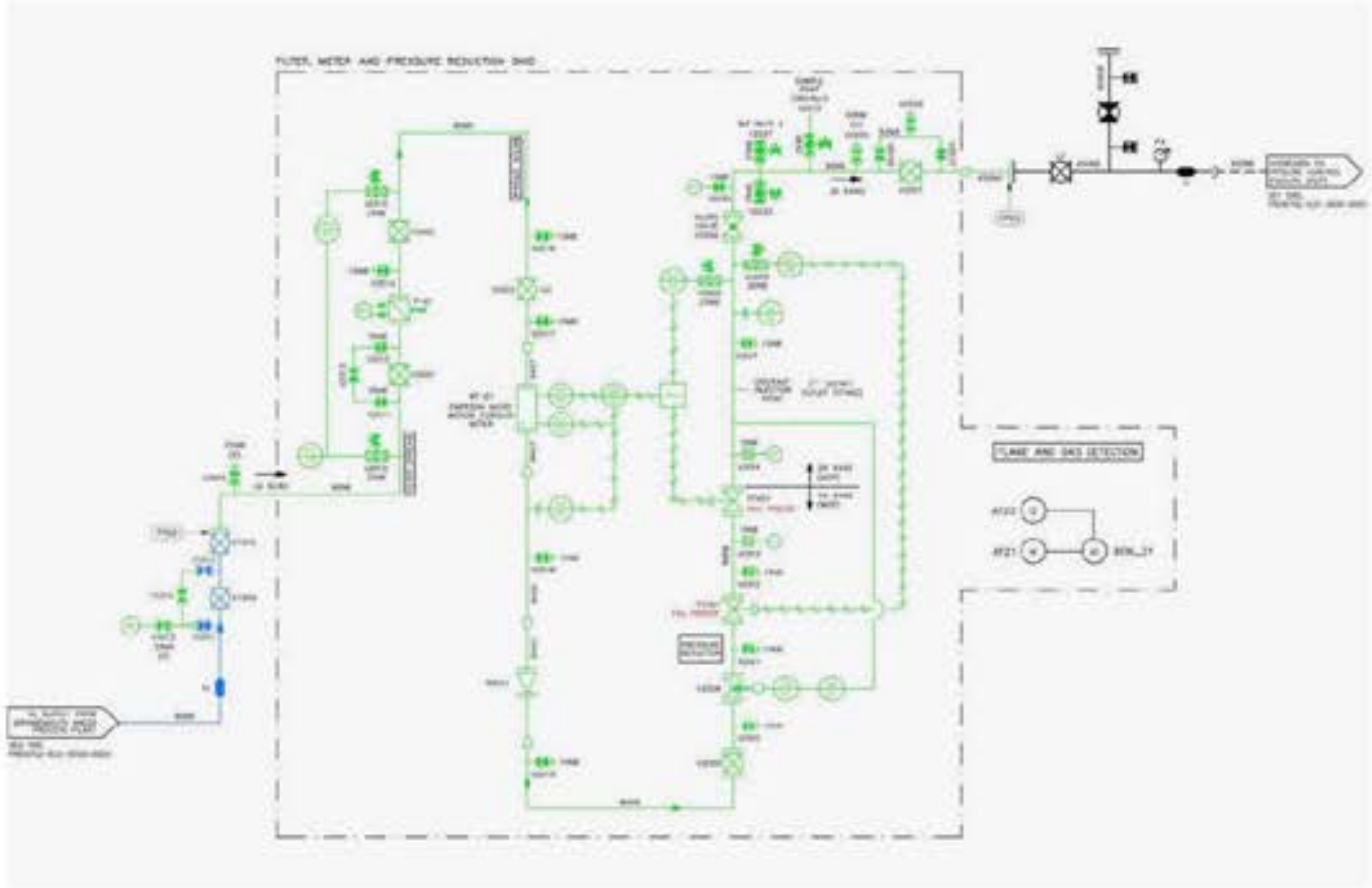


Figure 11: Hydrogen entry unit.

The following table details the required actions identified by the HAZOP and the work completed to close these prior to commissioning.

Table 5: HAZOP actions summary.

HAZOP action	Close out task
Use of nitrogen for purging	
Overpressure protection for the nitrogen inlet/purging system was required to protect the entry unit and pipeline from over pressurisation (40 barg for the entry unit and 26 barg for the pipeline).	Specification to the supplier for this system included the requirement for overpressure protection. The design of the system was reviewed to ensure pressure relief was included.
Nitrogen inlet/purging system to be designed to ensure the pipeline is protected from under-temperature.	Specification to the supplier for this system included the requirement to ensure liquid carry-over is not possible. Design of the system reviewed to ensure this is covered.
Gas odorisation and sampling	
WI, risk assessment, and training for the odorant system required.	Included in site Operations and Maintenance WI. Training provided for all personnel using the odorisation unit.
Review of positioning of the sample point to prevent the release of pipeline contents following the failure of a valve.	Sample point relocated upstream of the isolation point.
HAZOP of odorisation system from the vendor to ensure over-pressurisation of the system has been reviewed and to determine critical valves.	To prevent overpressure, the odorant injection system has three forms of protection, consisting of two non-return valves (NRVs) – one in the connection quill and one in the odorant cabinet – and a solenoid valve that opens on pump stroke and automatically closes. All valves and the pump are rated for the Network Entry Point (NEP) design pressure of 40 barg.
Confirm the heater system in the odorant cabinet and any protection system.	Self-controlled heater system in the odorant cabinet adjustable by thermostat has a maximum heating output of 300W. EEx protection : II 2G Ex db IIC.
Confirm the design and protection measures of the odorant blanket gas pressure relief and position of the carbon filter. Confirm required maintenance for the carbon filter.	The nitrogen system is protected from overpressure by a pressure regulator located at the bottle connection and a relief valve. The vessel is designed for full vacuum pressure. Maintenance frequency for the carbon filter is recommended to be annual, therefore it will not require replacement during the trial.
Review suitability of sample bags for use with hydrogen.	Bags not suitable. Grab sample panel specified for gas sampling.
Confirm pressure breakdown for sampling point.	Detailed design for pressure sampling system was produced.
Instrumentation and other equipment	
Review location of second flame and leak detection sensor to ensure coverage of whole site.	Location of sensor reviewed at this stage; however, a further decision was made that full redundancy of sensors was not required and specification was reduced to one sensor.
Review battery life for fire and gas detection and consider installation of solar panels.	Battery life reviewed and increased to 14 days. Due to short duration of project, no solar panels were installed.
Confirm fire/gas/pressure monitoring system has a suitable alarm for loss of comms.	Watchlog system notifies contacts in the event of comms failure including OCC.
Review of the need for a relief valve on the entry unit – potential for solar gain to increase the pressure in a locked-in section.	Calculations completed, demonstrating that an ambient temperature rise of 50°C would not require a relief valve on the system.
Confirm that the design of the vent stack has considered the asphyxiation risk and noise.	Vent designed in line with IGEM/SR/25 [22].
Phased drawings for operational and non-operational phases.	Phased drawings were produced and included in NROs.
INEOS to confirm arrangements and willingness to continue operation in the event of a failure of the digital angel System.	Loss of radio communications onsite would be classed as an emergency. Back-up intrinsically safe (IS) phones and landlines will be used by INEOS for core operations to be maintained. All other onsite work would be stopped and brought to a safe state.
Conducted an occupational assessment for the maintenance procedures, including Personal Protective Equipment (PPE).	SGN carried out an internal review of the suitability of existing PPE for use with hydrogen, and all personnel working on the trial will have suitable PPE for their role. WIs included the required PPE for any task being undertaken and risk assessments addressed occupational health issues.

Civil works were carried out onsite to install temporary fencing, which defined the boundary of SGN-controlled operations on the site. Concrete bases were installed to support pipework and instrumentation kiosks, with additional works to provide vehicle access and vehicle impact protection. Fabrication and hydrotesting of the entry unit pipework sections were completed offsite. The pipework sections and equipment items were then constructed onsite and leak tested prior to commissioning. It was acknowledged that testing of the final connection to the Grangemouth to Granton pipeline would not be possible, and therefore a sentry gasket was used, allowing the integrity of this connection to be proved.

The construction of the entry unit within the FPS site required significant engagement with INEOS to ensure personnel were inducted and could access the site. Risk Assessment Method Statements (RAMS) for the work had to be submitted six weeks in advance of works for INEOS approval and required operations to be scheduled to prevent delays. As part of the training and offsite testing process, the entry unit had been previously constructed, tested and operated using hydrogen in a pseudo-SAT (site acceptance test), and this provided confidence and reduced the number of minor onsite issues to be resolved during construction and electrical and instrumentation setup.

Following the completion of mechanical installation, there was a significant amount of Electrical and Instrumentation (E&I) equipment installation and testing to ensure all control valves and monitoring systems were operational with setpoints as required. Onsite power was supplied by a generator when the site was manned, and outside of these times, battery systems powered critical instruments and the Watchlog system. Critical instruments were used for monitoring the entry unit and site for potential leakage and included flame detection, leak detection, pressure and temperature monitoring. An onsite remote telemetry unit (RTU) was used to input valve positions and setpoints for the pressure and flow control valves, monitor additional onsite instrumentation and communicated with the odorisation unit controller. Data from the RTU was captured on the Watchlog system and could be viewed remotely. The odorisation system, which was initially commissioned by the vendor onsite using ethanol, was primed with NB (new blend) odorant prior to hydrogen commissioning.

The mechanical and electrical build phase of the entry unit took approximately 12 weeks. On completion of the works, a commissioning certificate was issued in preparation for the start of the trial.

3.2.2.4 Newton Block Valve Bypass – Design and Construction

Figure 12: Newton block valve by-pass.

A bypass to the NBV was not required as part of the original feasibility study; however, the need for this became apparent as the detailed scope for the live trial operations developed and expanded. It was recognised that the hydrogen supply from INEOS alone would not sustain the required velocity in the pipeline for the welding operations to be carried out, and an operating philosophy was developed to identify when and how flow would be controlled. For the welding operation, this involved using the pipeline section upstream of NBV as a reservoir to feed the downstream section where the welding would be carried out. The facility at Newton was used to manage the downstream pressure while the flow to the flare at Granton was adjusted to maintain the required velocity in the pipeline. See Section 3.6.2.

The repurposing works detailed in Section 3.1 allowed for the mainline block valve and existing offtake points to be utilised as the connection points for the new equipment to be installed.

The bypass was designed in accordance with IGEM/TD/13 Supplement 1 [18] and included equipment and instrumentation required for conducting the live trial, see Figure 12, such as:

- Pressure control and monitoring.
- Temperature monitoring.
- Gas sampling capability.
- Inline hydrogen monitoring for during the purge.
- Isolation points.
- Flaring (emergency use only).
- Onsite flame and leak detection.

A HAZOP was carried out on the finalised design, with input from all disciplines, to ensure that the site would operate safely and meet the requirements of the project. Actions from the HAZOP were closed out and actioned during the finalisation of the design and construction. These included:

- Installation of a fixed vent stack.
- Confirmation of alarm settings for low pressure.
- Inclusion of an additional escape gate in the boundary fence.

Civil works were completed onsite to install concrete bases to support the bypass pipework, instrumentation kiosks and the vent stack. A temporary base was installed for the emergency flare. An additional escape gate was also added to the boundary fence. Fabrication and hydrotesting of the bypass pipework sections were completed offsite. The pipework sections and equipment items were then constructed onsite and leak tested prior to commissioning.

The bypass site included instrumentation and electrically actuated pressure regulators used for the control of live trial operations. These were controlled and monitored using the onsite RTU. The site had no permanent power supply and therefore all equipment was powered by a site generator or battery system. During flowing operations, the site was manned and the onsite generator utilised for power. The batteries maintained power to critical instruments and alarms at all other times. These recharged when the generator was operating, removing the need for additional maintenance visits. Critical instruments included flame detection, leak detection, and pressure and temperature monitoring for the pipeline sections, each side of the block valve, and the above-ground bypass section. These instruments were monitored via the Watchlog system, which provided notifications when parameters were outside acceptable ranges, and could be accessed remotely. The emergency flare had a standalone control panel, battery and solar panel arrangement for its operation.

Following the completion of all onsite construction and end-to-end testing, a commissioning certificate for the site was issued.

3.2.2.5 DSEAR (Dangerous Substances and Explosive Atmospheres Regulations 2002) [21]

DSEAR requires employers to control the risks to safety from fire, explosions and substances corrosive to metals and puts duties on employers and the self-employed to protect people from these risks to their safety in the workplace, and to members of the public who may be put at risk by work activity. For the LTS Futures Project, DSEAR assessments were carried out for each of the sites:

- Bo'ness Road Connection Compound.
- Kinneil Entry Point.
- Newton Block Valve.
- Granton Flaring Facility.

The following table includes the hazards that were identified and the actions taken to mitigate against these.

Table 6: DSEAR risk assessment summary.

DSEAR action	Response
Hydrogen Gas (Unodorised and Odorised)	Control of ignition sources and all equipment on site, including portable equipment was appropriately ATEX rated to their hazardous areas zoning. For all sites, there was flame and leak detectors which covered all equipment.
Diesel	Control of ignition sources and all equipment on site, including portable equipment was appropriately ATEX rated to their hazardous areas zoning.
Odorant	An odorant system was specified to meet the needs of the project in terms of expected operating conditions including flows of hydrogen and MOP.
Hazardous Area Zoning (0-2)	Hazardous area drawings were located on site and part of the onsite induction, and a GS700H was located onsite. Control of ignition sources and all equipment on site, including portable equipment was appropriately ATEX rated to their hazardous areas zoning.

3.3 Emergency Response Planning

The project has demonstrated that a safe and successful response is possible when due consideration is taken for the different properties and behaviours of hydrogen. This section describes the actions taken by the project to ensure that the development of policies and procedures considered the physical properties of hydrogen as well as the required training and demonstration of competency of personnel involved. It is acknowledged that these plans and actions were suitable for the short duration and confined nature of the trial and that alternative arrangements would be required in some instances for a network repurposed to hydrogen. Nonetheless, it demonstrated that an effective and safe emergency response is achievable.

3.3.1 Major Accident Prevention Document (MAPD) Supplement

Following the introduction of hydrogen to the Grangemouth to Granton pipeline, it became a Major Accident Hazard (MAH) pipeline as defined in the PSR [11] and was therefore subject to regulatory requirements.

Regulation 23 of the PSR 1996 [11] requires that operators of pipelines transporting dangerous fluids must prepare an MAPD for their MAH pipelines. The guidance for the regulations states that MAPD is a management tool used to ensure that the duty holder has assessed the risks from major accidents and has introduced an appropriate safety management system to control these risks.

For the LTS Futures Project, a supplement to the existing plan was developed allowing due consideration, control, management, and mitigation of the hazards associated with hydrogen, including:

- Policies and procedures. See Section 3.5.3.
- Design standards (IGEM/TD/1 Ed 6 Supplement 2 and IGEM/TD/13 Edition 3 supplement 1) [10] [18].
- Organisational control including emergency response competency.
- Identification and control of hydrogen hazards.
- Pipeline monitoring including WSoE.

3.3.2 Policy and Procedure

3.3.2.1 Emergency Response Procedure

The development of an emergency response procedure had to account for the trial taking place, as two high-pressure hydrogen pipelines, although isolated from the natural gas network, were in the same geographical area as natural gas assets. Therefore, any response had to first differentiate between a hydrogen or a natural gas leak.

The trial area was defined using analysis of the potential PRE (public reported escape) distances, which considered dispersion and tracking from a release. This allowed us to define a pipeline corridor within which reporting of a PRE would trigger a dual response. This dual response was made up of an first call operative (FCO) and a member of the Hydrogen Pipeline Response Team (HPRT) and was reflective of the nature of the trial, a singular route of high-pressure hydrogen pipelines and a short duration trial. It's acknowledged that for a network repurposed to hydrogen, there would be widespread upskilling for FCOs, who would become trained and competent to respond to these potential events, which is likely to make a dual response unnecessary.

The HPRT were a subset of the pipelines maintenance team who respond in the event of a high-pressure pipeline incident and perform the Pipeline Emergency Response Officer (PERO) role. Team members were selected according to geographical location and the target response time to a PRE in the trial corridor (1 hour). This team had in-depth project specific training including hydrogen awareness, emergency response, gas detection, entry unit operation and flaring operations in advance of the trial. Where appropriately trained, HPRT personnel also fulfilled the roles of Authorising Engineers (AE) and Competent Persons (CP) for trial operations.

The schematic above outlines the response to a PRE received via the gas emergency number.

Following the arrival of the FCO and HPRT at the PRE location, HPRT were responsible for assisting the FCO in the initial escape investigation, specifically in the search for hydrogen. If a PRE was positively identified to be hydrogen, the HRPT would lead the response and escalate the event as required. For the LTS Futures Project, as there were no end users or critical supply issues, the response for any positively identified leak would have triggered flaring of the pipeline inventory.

To support in the identification of a leak, the HPRT used the GS700H gas detector, which had a range of sensors within the instrument that could differentiate natural gas and hydrogen. In addition to this, the pipelines and above ground installations (AGIs) associated with the trial had a range of pressure, temperature, flame and leak detection instruments installed. The data output from these systems was viewable remotely and could provide additional information to determine the potential source of a leak.

During the trial, a total of eight PREs in the pipeline corridor were responded to, but none of these were confirmed to be hydrogen.

Although not required during the live trial, an NRO for flaring of the pipeline inventory in the event of an emergency was prepared and reviewed prior to the introduction of hydrogen.

3.3.2.2 LTS Futures Guidance Note for Escalation of an Incident

This note was developed to provide guidance to operatives and line managers on the appropriate reporting and escalation process for any incident during the live trial. This procedure acknowledged the novel nature of the trial and the need for immediate escalation of any confirmed incident, ensuring there was no delay in the response.

This procedure detailed the roles and required response of the onsite PERO, who would be a member of the HPRT, and the team manager. The procedure provided guidance on categorising the onsite event and outlined the escalation process to senior management for each incident category.

The procedure detailed the requirement to inform the team lead for the HPRT and the project operations manager to ensure emergency actions were implemented and additional support was made available, if required.

3.3.2.3 Responding to Alarm Notifications

A procedure was required for the response to alarms generated by the onsite instrumentation and data logging system (Watchlog). For standard, permanent installations on the gas network, these systems would be linked to Supervisory Control and Data Acquisition (SCADA) and monitored by the GCC. Given the short-term and bespoke nature of the LTS Futures Project, a standalone system was implemented, with instrumentation feeding back to a Watchlog, which enabled live online viewing of outputs. The Watchlog sent notifications to and could be access by the project team, HPRT and GCC for 24/7 monitoring ensuring prompt investigation of any alarm notification.

The system was customised to trigger alarms for the rate of pressure change or activation of the onsite flame or leak detection instruments. When in non-flowing operations, the pipelines were isolated into five sections:

- 3" line.
- Entry unit.
- 15 km Grangemouth to NBV.
- NBV bypass.
- 15 km NBV to Granton.

If the pressure in any section dropped by 0.5 barg in 30 minutes, an alarm would be triggered. Flame and leak detection instruments were installed at each site with above-ground pipework, and activation of either instrument would activate the alarm. Notifications were issued by the system in the form of text messages and emails to a pre-determined list of users.

Alarm notifications were monitored by GCC, who were responsible for ensuring that the HPRT were dispatched to respond. The HPRT were trained and competent to respond to any alarm, and extensive scenario training was completed prior to the introduction of hydrogen. No alarm could be attended by a lone worker. On arrival at site, the procedure guided the attending team to quantify, categorise and respond to the emergency according to the categories below:

Table 7: Emergency catergorisation.

Emergency categories	
A	Erroneous alarm – no signs of loss of containment must be proved with an onsite GS700H.
B	Controllable loss of containment – small leaks or ignition that can be safely isolated from the supply.
C	Uncontrollable loss of containment – small leaks or ignition that cannot be safely isolated from the supply due to location.
D	Failed or damaged equipment loss of containment without ignition.
E	Failed or damaged equipment loss of containment with ignition.

During the trial, there were no alarms for the rate of pressure change in any of the pipeline sections or AGIs. There were a small number of activations of the flame and leak detection sensors; however, none of these were due to a hydrogen release. One such example was the activation of the acoustic alarm following the activation of an onsite Perimeter Intrusion Detection (PID) intruder alarm, which had been triggered by deer outside the boundary fence. This example demonstrates that further refinements are needed to prevent spurious alarms.

3.3.3 Supplement to Local Authority Emergency Plans

LAs are required to prepare emergency plans for pipelines, which have the potential to cause major accidents under PSR 1996 [11]. Prior to the live trial, a supplement was developed for the LAs to help support their emergency planning. This included a description of the trial and key information including:

- Hydrogen supplier.
- Difference in properties between natural gas and hydrogen.
- Assets, including pipeline parameters and isolation valve locations.
- Expected depressurisation time.
- Operational activities and their locations.
- Hazard planning distances (initial cordon distances and credible hazard distances).

3.3.4 Local Authority and Resilience Partner Engagement

There was close engagement with the LAs throughout both the development phase of the project and the live trial. As the live trial approached, engagement was increased through the East of Scotland Regional Resilience Partnership Civil Contingencies Liaison. After initial discussions, it was determined that to maximise involvement and therefore the benefits for all agencies, a desktop exercise would be most appropriate. The attendance at this desktop exercise included:

- HSE.
- SGN Operations.
- Falkirk Council.
- City of Edinburgh Council.
- West Lothian Council.
- NHS Forth Valley.
- Police Scotland.
- Scottish Fire and Rescue.
- Scottish Ambulance Service.
- NHS Lothian.

The exercise focused on interoperability between all services. There was a scenario for each LA catchment, which allowed the LA emergency plan to be applied, identifying possible gaps for a hydrogen pipeline. There were injects throughout these scenarios, as there would be in a real developing incident, to ensure that discussion revolved around the initial incident and multiple hours after it occurred.

After the event, feedback was collected, and 84% of the participants thought that the event was useful and informative including positive feedback from the HSE.

3.3.5 INEOS Integrated Emergency Response

An integrated emergency response was required between the INEOS facilities and SGN for the successful operation of the trial. INEOS facilities at Grangemouth are Control of Major Accident Hazards (COMAH) [26] sites and therefore any changes or new operations must be carefully managed to consider any potential wider impact.

INEOS O&P was the hydrogen supplier for the trial, and the hydrogen supply pipeline was in proximity to the boundary fence of the facility, traversing a number of gateways and a culvert. The entry point and entry unit for the Grangemouth to Granton pipeline was located within the INEOS FPS site. This meant that an integrated response in the event of an emergency was essential to ensure that any incident could be managed effectively and efficiently to prevent escalation.

Throughout the project there was a close working relationship with both entities at INEOS, and this collaboration increased in the run-up to and during the trial. INEOS developed their onsite emergency response with input from the project team, and a number of exercises were completed to train this out across all shifts onsite. The LTS Futures Emergency Response Procedure acknowledged the safety and security requirements for accessing the FPS site. In preparation for the trial, all personnel involved (in emergency response or routine operation) completed an induction for the FPS site. The emergency response procedure also required the HPRT attending in the event of a PRE or alarm response to call ahead of arrival to ensure there were no delays in accessing the site.

3.3.6 Training and Exercises

A range of training courses and scenarios were exercised to ensure that all personnel involved in the emergency response were equipped and competent to carry out their roles. The exercises allowed procedures to be tested and checks to be carried out to ensure that people and systems responded as required.

FCOs operating in the region of the pipeline corridor were briefed on the LTS Futures emergency response procedure and provided with new equipment (e.g. voltage testers and torches), and hydrogen-specific PPE as required. The main adjustment to their natural gas response was that a member of the HPRT would be attending with them as the hydrogen-competent person.

HPRT were fully trained in the emergency response procedure and as PEROs. They were responsible for assisting the FCO in the initial escape investigation, specifically in the search for hydrogen. If hydrogen was detected, they would lead the response and escalation and, where required, depressurise the LTS futures pipeline. The HPRT team carried gas detection equipment capable of differentiating between natural gas and hydrogen (GS700H) and were issued with hydrogen-specific PPE and equipment required for their role. In addition to providing the emergency response, HPRT had additional training on alarm response actions, and desktop exercises on a range of scenarios were completed.

OCC and GCC were briefed on the emergency response for the project and the updated procedures to be followed to dispatch the dual response (FCO and HPRT) to a PRE in the trial pipeline corridor.

Stress testing of the individual stages of the Emergency Response procedure was carried out as well as a full test of the whole process. This included:

- Confirmation that calls within the pipeline corridor were correctly identified by OCC for dual response.
- Ensuring the HPRT and FCO were dispatched and responded within one hour.
- Ensuing those responding had appropriate PPE and equipment to carry out their role.
- Ensuring that the procedure could be followed effectively to complete the identification and tracking of a gas leak.

This testing demonstrated that the procedure and training personnel had met the requirements for the trial.

Critical incident training was carried out for SGN senior management and included a full desktop exercise to test the procedures and processes to be used and ensure that all personnel were prepared for the trial. This exercise considered a developing incident with the actions to be taken at each stage. Team managers and incident controllers were also briefed on the project emergency response procedure.

3.3.6.1 Resourcing

Resourcing for the emergency response for the trial considered the natural gas assets within the pipeline corridor and the number of reported PREs over the previous 10 years as an indication of the potential required response. FCOs covering the region were trained in the emergency response procedure, and the HPRT were selected based on proximity to the pipeline and the ability to respond within one hour to a PRE. Members of this team were on an on-call rota to respond to any issue with the pipeline during the trial. They were not on standby for other emergencies but continued to carry out other aspects of their day-to-day roles.

Senior management currently operate on a standby rota for response to any incident, and this included the LTS Futures Project.

3.4 Regulatory Compliance and Commercial Contracts

The project encountered a number of regulatory and commercial requirements to ensure that the Grangemouth to Granton pipeline could convey hydrogen. Key partnerships, including the supply of hydrogen by INEOS, required clear commercial contracting to document the basis on which hydrogen would be delivered to, contained within, and removed from the LTS network. The regulatory and legal environment for hydrogen pipelines also needed to be understood in order to undertake the trial and comply with SGN's legal obligations as a gas transporter.

3.4.1 Legislative and Regulatory Framework

The list below details the regulatory environment applied for completion of the Grangemouth to Granton live trial and applicability for hydrogen:

- **Gas Act 1986 [27]**: Hydrogen falls within the statutory definition of "gas", meaning existing licensing requirements apply. The project confirmed that existing pipeline servitudes, which reference "gas", were suitable for hydrogen conveyance. Notifications required under the Gas Act were made to the HSE notifying it of the planned construction of the hydrogen supply pipeline.
- **Pipeline Safety Regulations (PSR) [11]**: Fully applicable to hydrogen. All required PSR notifications (Regulations 20, 21 and 22) were completed and submitted to the HSE.
- **Gas Safety (Management) Regulations (GS(M)R [28]**: As GS(M)R is specific to methane, the project operated outside its scope but worked in the spirit of it and developed a Case for Safety for the live trial. The CfS ensured the management of safe flows of hydrogen, planned for successful demonstration of live connections and flow-stopping technology, and ensured that risks arising from MAHs were as low as reasonably practicable (ALARP).
- **Health and Safety at Work Act [29]**: Provided the overarching safety framework for live operations.
- **Hazardous Substance Consent (HSC) [30]**: HSC is applicable to hydrogen, which is a named substance. The hydrogen system was assessed against the HSC requirements, and each site was below the 2-tonne threshold. However, as the Network Entry Facility is within the INEOS FPS top tier COMAH site, this was discussed with INEOS who liaised with their HSE inspector.

Overall, the project demonstrated that hydrogen pipelines can be regulated effectively using the existing statutory framework with appropriate adaptations.

3.4.2 Planning and Consenting

The LTS Futures hydrogen infrastructure was delivered under permitted development rights following extensive planning, regulatory, and environmental assessment. A new 3" hydrogen supply pipeline was constructed to connect INEOS' existing hydrogen supply to the Grangemouth to Granton pipeline, with works split between INEOS land and the public domain. Although the pipeline was below statutory EIA thresholds for length and diameter, its operating pressure exceeded 7 bar, triggering EIA screening under the Public Gas Transporter Pipeline EIA Regulations. Comprehensive environmental studies were undertaken, including ecological, archaeological, geotechnical, noise and environmental constraints assessments. Following consultation with statutory bodies, the Scottish Government's ECU confirmed that the development did not require a full EIA.

Planning considerations required detailed engagement with LAs to confirm the applicability of permitted development rights. SGN proceeded under Class 39 of the Town and Country Planning General Permitted Development Order (TCP GPDO) [31] as a public gas transporter, while INEOS relied on Class 24-permitted development rights following legal confirmation that its pipework was not a notifiable pipeline. Certificates of lawfulness were issued accordingly.

A wider EIA screening exercise was also completed for the remaining LTS Futures system assets, including network entry, pressure control, and flare facilities. Screening options and environmental determinations confirmed that these works did not constitute EIA development, allowing the project to proceed without express planning permission. The experience highlighted the complexity of applying existing planning and EIA legislation to hydrogen projects and reinforced the value of emerging national guidance to streamline hydrogen consenting in Scotland.

3.4.3 Commercial Contracting Approach

The LTS Futures live trial required a bespoke commercial and contractual framework for its operational phase. Although innovative in its use of hydrogen, the project was treated fundamentally as a gas transportation activity. To manage contractual and regulatory risk effectively, the framework closely replicated established methane market arrangements, adapted where necessary to reflect hydrogen, the project's short duration, and a derogation from the Uniform Network Code (UNC) [32].

The contracting structure defined clear roles for the Transporter (SGN), Producer (INEOS), and Shipper/Supplier (Ceres Energy Limited), ensuring compliance with the Gas Act 1986 [27]. Key agreements included:

- **Network Entry Agreement (NEA):** Adapted from SGN's standard methane NEA to cover hydrogen quality, measurement, operational coordination, and short-term trial requirements.
- **Scheduling and Nomination Agreement:** A bespoke mechanism replacing national gas balancing signals, defining delivery timing, volumes, pricing, and consequences of non-delivery.
- **Shipper Arrangements:** A simplified shipping services agreement between INEOS and Ceres to provide regulatory assurance through a licensed shipper.
- **Transportation Terms:** A concise analogue to the UNC governing network access, nominations, gas quality, liability, and termination.
- **Gas Sale Agreement:** A modified supply contract enabling compliant title transfer and simplified financial settlement.

Overall, the approach balanced innovation with regulatory certainty by leveraging proven contractual models. While highly project-specific, it provides useful precedent for future hydrogen trials assessed on a case-by-case basis.

3.4.4 Key Learnings

The live trial identified several important lessons for future hydrogen transportation, including:

- The importance of understanding existing servitude suitability for hydrogen repurposing with reference to specific gases or wider "gas", as defined within the Gas Act [27], which includes hydrogen.
- Clear and early engagement with planning authorities on hydrogen planning requests. EIA screening, knowledge and understanding of permitted development rights and notifiable pipelines under the TCP EIA and TCP GPDO is required by local planning authorities so that there is confidence that discussions can progress without resorting to external legal advice.
- The value of adapting existing gas commercial frameworks rather than creating entirely new models; however, this involves a resource intensive requirement for modification of complex legacy agreements such as NEAs.

The commercial and regulatory solutions developed provide a strong foundation for future hydrogen trials and wider network transition, while also highlighting areas where policy clarification and process improvement would accelerate deployment.

3.5 Safety Dossier

The safety dossier was developed in line to the ENA's Hydrogen Safety Case Framework [33] following direction from the HSE. This Framework details the required information from Production and Storage to the end user. For the purposes of LTS Futures, it consisted of a Case for Safety aligned to the requirements of the distribution section of the framework, and all its supporting documentation which demonstrated that the trial could proceed safely.

Figure 13: Safety dossier components

3.5.1 Case for Safety

The Case for Safety was split into the following sections:

Section 1	**Duty Holder**
Section 2	**Operation Undertaken**
Section 3	**Plant and Premises** • These sections provide a description of pipeline parameters and the works carried out prior to the live trial, for both the 3" pipeline and the existing 18" Grangemouth to Granton pipeline and associated AGIs. • Includes details of the activities that were carried out in the live trial, including welding, hot tapping and flow stopping demonstrations. • Includes details regarding the PPE, tools and equipment required for the trial.
Section 4	**Specifications and Procedures** • Section 4 explains the process of drafting hydrogen-specific WIs and NROs. These instructions were for Commissioning and Decommissioning, Operation and Maintenance, Venting and Flaring, and Emergency Response. These WIs were developed following completion of the detailed design and in conjunction with service providers where applicable.
Section 5	**Risk Assessment** • Section 5 provides a high-level overview of the QRAs for both the Grangemouth to Granton and 3" pipelines, as well as a network risk assessment for the LTS Futures trial.

Section 6	Safety Management Systems • This section outlined SGN's Safety Management Framework and explained how LTS Futures aligned with and fitted within that structure.
Section 7	Competency Arrangements • Details how personnel working on the trial will be competent operators on the natural gas network, who will be upskilled and trained for LTS Futures • This was further scoped and detailed in full within the training and competency plan which was submitted as a part of the safety dossier. See Section 3.5.4.
Section 8	Safety Management – Contractors and other Indirect Labour • Addressed the management of contractors in accordance with standard SGN practices, including verification that individuals were appropriately trained and competent to perform their designated roles. See Section 3.5.4.
Section 9	Health and Safety Information • Management of live trial operations under Safe Control of Operations and live trial agreement for communications.
Section 10	Health and Safety Communication • Provides a high-level review of LTS Futures Stakeholder Engagement and Communications Plan. • Interface with LAs, enforcing authorities, emergency responders and INEOS. • Knowledge sharing of safety critical information during the trial.
Section 11	Audit Arrangements • There was an Audit and Inspection Plan in line with SGN procedures.
Section 12	Cooperation • The live trial had no end users. This section details the requirement for a NEA to manage a supply of hydrogen for the trial and a communications document to describe the arrangements and processes for communication and cooperation between parties. It stated that SGN would support INEOS in developing their emergency response plan.
Section 13	Gas Escapes and Investigations • Section 13 details how a PRE from the pipeline will be dealt with and pre-trial testing of this response.
Section 14	Investigations • Investigations were managed using internal SGN procedures INV/1 [34].
Section 15	Content and Characteristics of Gas • Section 15 detailed the minimum hydrogen gas composition, which had been developed from the specs of the hydrogen produced from INEOS and the IGEM/H/1 [35] standard for low-pressure hydrogen utilisation. This section also includes requirements for compliance with this minimum standard and details of odorisation.

Due to the project having no end users, there were sections that were not relevant to the trial, and these were deemed not applicable:

Section 16	Continuity of Supply
Section 17	Adequate Pressure at the End of the Network
Section 18	Gas Supply Emergencies
Section 19	Gas Quality – Sole Conveyor Network
Section 20	Discontinuing Supply
Section 21	Restoration of Supply

3.5.2 Quantitative Risk Assessment (QRA)

QRAs were carried out for both the 3" hydrogen supply pipeline and the 18" Grangemouth to Granton pipeline. These considered a number of potential threats to the integrity of the pipelines. In line with guidance in IGEM/TD/2 [36], the following causes are included in the failure frequency analysis:

- External interference.
- Ground movement.
- Material and construction defects.
- External corrosion.

For hydrogen operation, the failure frequencies due to third-party interference and material and corrosion defects were increased by a factor of 5 and the failure frequency due to ground movement was increased by using the poor-quality girth weld curve as a proxy. These conservative assumptions accounted for the potential effects of hydrogen embrittlement and will be reviewed following completion of material and full-scale tests.

It should be noted that neither of the pipelines are considered to have poor quality girth welds, and this was a conservative and simplified way of increasing the failure frequency until the effect of hydrogen exposure was fully understood. For the Grangemouth to Granton pipeline, based on the date of construction (post 1972), 100% radiography would have been completed on all girth welds (as per 1969 Gas Council Instruction) [37], and therefore they are expected to be of high quality. For the 3" hydrogen supply pipeline, 100% radiography was completed during the construction.

Failure modes for the assessments included the potential of rupture and a range of possible puncture sizes for each pipeline (up to 25 mm for the 3" pipeline or 150 mm for the 18" pipeline). Due to the relatively low operating pressure of the pipeline and inclusion of overpressure hazards, it was considered that punctures could contribute significantly to the overall risk.

The ignition probability for hydrogen releases is expected to be higher than that for natural gas due to the lower minimum ignition energy and wider flammable range. In the assessment, ruptures have an ignition probability of 1.0 (all hydrogen ruptures were expected to ignite). For punctures, the HYEX model [38] was used to calculate ignition probability based on mass flowrate. For both punctures and ruptures, the split between immediate and delayed ignition was in the ratio ⅔:⅓ meaning the proportion of immediately ignited releases is assumed to be higher for hydrogen than for natural gas. This is in line with the wider flammability range and lower minimum ignition energy.

The consequences of ignition of a hydrogen release, either immediate or delayed, have the potential to result in both a thermal radiation and overpressure hazards. For the calculation of hazard distances, the following assumptions have been made:

- For the thermal radiation calculations, it was assumed that all ignitions are immediate.
- For overpressure calculations, two scenarios have been considered:
  - Immediate ignition (⅔ of the time) cases are treated as having a very short 100 ms ignition delay. For these cases, the overpressure is calculated for the total mass of released gas at 100 ms.
  - For delayed ignition (occurring ⅓ of the time), the overpressure is conservatively calculated for the time at which the hydrogen plume has fully established and is at its largest (this is calculated on a case-by-case basis and is typically between 5–15 seconds).

Harm criteria for thermal and overpressure hazards that were used for the assessment were:

- For thermal radiation, this is the distance to 1800 thermal dose units (TDU), referred to as Escape distance. This is the distance from the pipeline beyond which people are predicted to be able to escape in the event of a fire.
- For overpressure, the UK HSE use a value of 70 mbar to determine the outer zone boundary of the consultation zones for LUP [39] for overpressure consequences. This is the distance at which 1% lethality is expected for vulnerable population. For the QRA assessments, DNV have taken a conservative overpressure level of 40 mbar as resulting in fatality of the most vulnerable 1% of an average population when indoors.

Figure 14: Grangemouth to Granton pipeline route.

Table 8: Grangemouth to Granton pipeline parameters.

Nominal diameter (mm)	External diameter (mm)	Maximum operating pressure (barg)	Nominal wall thickness (mm)	Heavy wall pipe wall thickness (mm)	Material grade	Nominal depth of cover (m)	Seam type
450 (18")	457	26.0	6.35	9.52	X52	1.1	Spiral / seamless

3.5.2.1 Grangemouth to Granton

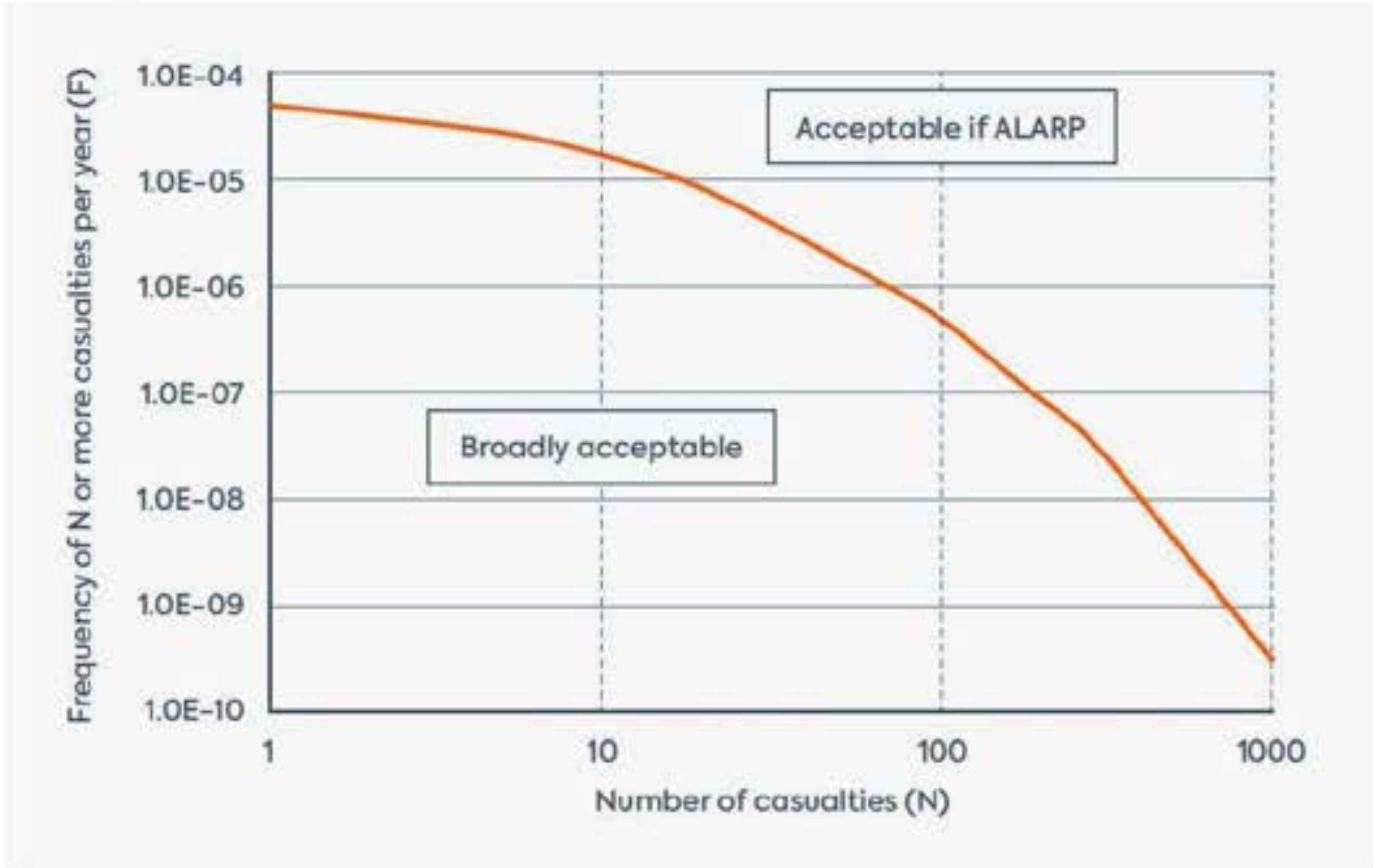
The Grangemouth to Granton Pipeline QRA was undertaken in two stages. Initially, a generic screening consequence assessment was conducted to identify areas along the pipeline route where the risk would likely be highest. This identified the following sites:

1. New Hopetoun Garden Centre.
2. Cramond Village.
3. Granton (including the Edinburgh Caravan and Motorhome campsite).
4. Pseudo M90 Road Crossing.

In the second stage, site-specific QRAs were undertaken at each of these higher-risk locations. The analysis included hazard identification, failure frequency analysis, consequence analysis and risk and ALARP assessment. For the Pseudo M90 Road Crossing, conservative assumptions were made for depth of cover (minimum according to IGEM/TD/1 Edition 1) [40] and sleeve length (only extending the width of the carriageway) to ensure the results of the assessment were the highest of all road crossings and therefore could be applied to others.

The risk assessment was undertaken assuming operation with both 100% natural gas and 100% hydrogen at the MOP of 26 barg.

Figure 15: TD/1 FN curve.



For both operation modes (natural gas or hydrogen), the specific parameters of the pipeline materials were used, including WT for heavy-walled sections and minimum actual depth of cover over the interaction length at each location.

The results show that the maximum individual risk level for the Granton assessment for both hydrogen and natural gas operation is below the 1.0×10^{-6} per year level that is considered to be 'broadly acceptable' at all occupied locations.

The results show that the maximum individual risk levels for the New Hopetoun Garden Centre, Cramond Village and pseudo M90 Road Crossing for natural gas operation are below the 1.0×10^{-6} per year level that is considered to be 'broadly acceptable'. For hydrogen operation, the maximum individual risk levels are above the 1.0×10^{-6} per year 'broadly acceptable' level.

Cost-benefit analysis was undertaken to demonstrate that the risk of all cases assessed is ALARP.

Societal risk was calculated and compared against the IGEM/TD/1 tolerability criteria [6]. The societal risk was within the broadly acceptable region for both natural gas and hydrogen operation for New Hopetoun Garden Centre, Cramond Village and Granton. For the representative M90 Road Crossing, the societal risk is within the broadly acceptable region for natural gas operation and just above the IGEM/TD/1 [6] broadly acceptable level in hydrogen operation. It should be noted that the criteria for the representative M90 road crossing differ (and are more conservative) from the actual crossing in the following ways:

- Depth of cover: the depth of cover at the road crossing exceeds the minimum depth stipulated in IGEM/TD/1 [6].
- Length of sleeve: the sleeve at the M90 exceeds the width of the carriageway and hard shoulder.

Figure 16: Assessment of pipeline route for geohazards.

Table 9: 3" Hydrogen supply pipeline parameters.

Nominal diameter (mm)	External diameter (mm)	Maximum operating pressure (barg)	Nominal wall thickness (mm)	Material grade	Depth of cover (m)	⅔ Charpy energy (J)	Design factor
80	88.9	40.0	5.5	L245NE (B)	1.21	20	0.16

3.5.2.2 Hydrogen Supply Pipeline

An assessment was undertaken of the supply pipeline route from the Bo'ness Road Compound to the INEOS FPS Compound for operation with 100% hydrogen at the MOP of 40 barg.

The QRA considered the same potential threats to the integrity of the buried sections of the supply pipeline as to the Grangemouth to Granton pipeline. For the above ground section of the supply pipeline, where it is routed alongside the River Avon bridge, the following additional threats have been considered:

- Aircraft crashes.
- Vandalism.

The frequencies for aircraft crashes, external interference and vandalism on the above-ground section of the supply pipeline have been calculated in accordance with HSE recommendations.

The results show that the maximum individual risk levels are below the 1.0×10^{-6} per year level that is considered to be 'broadly acceptable' at all occupied locations, for operation at 40 barg.

Societal risk was calculated and compared against the IGEM/TD/1 tolerability criteria [6]. The societal risk was within the broadly acceptable region.

As the societal risk for all cases was well within the IGEM/TD/1 tolerability criteria [6], no additional ALARP demonstration has been completed. However, SGN committed to twice-weekly surveillance along the route of the 3" supply pipeline due to a short section where the depth of cover was constrained by existing INEOS infrastructure.

3.5.3 Policies and Procedures

A review of existing policies and procedures was carried out against the planned operations for the live trial. This enabled identification of those which were suitable for the trial in their current form and could be adopted, those which could be modified for hydrogen service and where new procedures would be needed.

When reviewing procedures, those that were adopted offered high level guidance focused on processes that were directly applicable to our project. These included:

- **SGN/PM/SCO/2 [41]**
  Management Procedure for Safe Control of Operations – Permits to Work on the Gas Network.
- **SGN/PM/SCO/4 [42]**
  Management Procedure for Safe Control of Operations – Non-Routine Gas Supply Operations.
- **SGN/PM/SHE/34 [43]**
  Management Procedure for Managing Change Safely.
- **SGN/PM/PS/5 [13]**
  Management Procedure for Managing New Works, Modifications and Repairs.
- **SGN/PM/SHE/76 [44]**
  Management Procedure for the Management of Contractors.
- **SGN/WI/PLANT/1 [45]**
  Work Instruction for the Delivery of Plant Projects.
- **SGN/PM/QA/1 [46]**
  Management Procedure for Quality Assurance of Suppliers of Scotia Gas Networks.
- **SGN/PM/ECP/2 [15]**
  Management Procedure for Cathodic Protection of Buried Steel Systems.

3.5.3.1 LTS Futures-Specific SMF Documents

The procedures specifically developed for the trial included a combination of management procedures and WIs. Management procedures provided a specification outlining how tasks would be completed and the application of relevant guidance and standards. The following management procedures were developed:

- Operation and Maintenance of the LTS Futures Pipeline.
- Commissioning and Decommissioning the LTS Futures Live Trial Project.
- Hydrogen Flaring (and Venting).
- Reporting, Managing and Rectification of Faults on the LTS Futures Trial Pipeline, Assets and Equipment.
- Escalation of An Incident within the LTS Futures Trial and Trial Area.
- LTS Futures Specific Critical Incident.

WIs provided detailed step-by-step instructions to complete a task. The following tasks were identified from the planned live trial operations and maintenance as requiring WIs:

- Operation and Maintenance for each site.
- Hydrogen Gas Sampling System for Odorant Level Analysis.
- Responding to Alarms and Other Notifications while managing the LTS Futures trial pipeline.
- Identifying Hydrogen Gas Escapes in the LTS Futures trial in conjunction with existing natural gas escape processes.

3.5.3.2 LTS Futures-Specific NROs

NROs were developed for all live trial operations. Due to the bespoke nature of each of the trial operations, the NRO process under SGN/PM/SCO/4 [42] allowed for the development of a sequence of procedures that covered each of the task to be completed. These NROs were supplemented with the developed WI for tasks that were repeated during the trial, such as gas sampling. Each NRO was reviewed by a cross-discipline team, signed off by an AE and supervised on-site by a CP. Briefings were carried out for all personnel prior to the commencement of each NRO. This was essential to ensure personnel across all sites were clear on the operation being completed and the communication between sites.

Table 10: Non-routine operations (NROs).

NRO	Operations included
Purging of 3" hydrogen supply pipeline and entry unit commissioning.	Introduction of hydrogen into the 3" line from INEOS. Purging of the 3" line and entry unit from nitrogen to hydrogen. Commissioning of all entry unit equipment including: • Pressure control. • Flow control. • Safety device (slam shut). • Instrumentation including pressure, temperature and flow. • Odorisation checks.
Hydrogen purge of the Grangemouth to Granton 18" (450 mm) pipeline followed by pressurisation to 26 barg.	Purging of the 18" pipeline from nitrogen to hydrogen including the NBV bypass. This included commissioning of the flare and assist gas supply. Following completion of the purge, the pipeline was pressurised in a stepwise manner up to 26 barg.
Hydrogen flow trial for welding operation and pipeline re-pressurisation.	Trial of the flowing operations required for live welding to demonstrate that the flaring rate could be controlled as required and the modelling estimates for the time available to complete the operation were accurate. Following this, the pipeline was repressurised with hydrogen to 26 barg in preparation for the welding operation.
Live welding of an 18" OD (450 mm) split tee onto the Grangemouth to Granton 18" (450 mm) pipeline.	Fitting and welding of the split tee was completed over 4 days by TDW. 1. Tee fit-up. 2. Welding of longitudinal seams. 3. Welding of 1st circumferential weld and 1st thread-o-ring fitting. This operation was completed with flowing hydrogen in the pipeline. The gas velocity was controlled using the flare at approximately 1 m/s, and the operation was carried out between 16–10 barg. 4. Welding of the 2nd circumferential weld and the 2nd thread-o-ring fitting in flowing conditions as above. The welding operation was carried out over 2 days with a circumferential weld completed each day. The pipeline was re-pressurised overnight between the days of welding.
Pipeline re-pressurisation.	Following completion of the welding operation, the pipeline was re-pressurised in preparation for flow stopping.
Hot Tap and Stopple Train – using the welded tee – and deployment of completion plugs.	The following operations to be completed by TDW: • Hot tapping of the welded tee in live hydrogen conditions. • Deployment of the stopple train including test of sealing capability in hydrogen. • Pressure equalisation and removal of stopple train. • Installation of a Teeman's and Lock-O-Ring Plus completion plugs under live gas conditions. These will also demonstrate their sealing ability in a hydrogen environment.
Installation of Grouted Tee.	Live installation of an 18" OD (450 mm) Grouted Tee (by DNV) onto the Grangemouth to Granton 18" (450 mm) pipeline while the pipeline contains hydrogen at a static pressure of 20 barg.
Hot Tap and BISEP – using the Grouted Tee – and deployment of a completion plug.	The following operations to be completed by Stats: • Hot tapping of the grouted tee. • Flow stopping using the BISEP tool including a test of its sealing capability in hydrogen with the pipeline pressure at 20 barg. • A completion plug will be installed into the grouted tee branch flange under live conditions after the BISEP tool has been removed. This will demonstrate the completion plug sealing ability in a hydrogen environment.
Depressurisation of the pipeline system.	Depressurisation of the 18" Grangemouth to Granton pipeline to 0.5 barg through flaring the pipeline contents.
Nitrogen purge of the hydrogen supply pipeline, entry unit, 18" pipeline and bypass.	Purging of the pipeline system using nitrogen at 0.5 barg. The flare and assist gas supply were utilised to ensure all hydrogen was combusted.
Emergency Response – Emergency depressurisation of the 18" Grangemouth to Granton pipeline using the Granton Flare.	This NRO was prepared in advance in case emergency depressurisation of the pipeline was required.

Figure 17 – Training and competency pathway

3.5.4 Training, Competency and Resourcing

Training and competency were essential for both the safety of SGN personnel onsite during the trial operations, contractors taking part and the safety of the general public as we operated in the public domain. Operating in a safe manner also ensured the integrity of SGN assets.

As part of our commitment to operating a safe and effective project, all personnel (SGN staff and contractors) operationally involved in the delivery of the LTS Futures Live Trial were provided with sufficient training to carry out their role. The development of project-specific training recognised the unique nature of the project while acknowledging the existing competencies of the workforce in natural gas network operations.

Knowledge retention and competency to carry out practical tasks with a high level of accuracy and compliance to procedures was essential to the safe completion of the trial. Knowledge and skills were assessed as part of the training programme and followed up with refresher workshops and briefings prior to the live trial.

3.5.4.1 Training Content

Training material was developed, delivered and assessed, covering targeted topics to ensure personnel had the required knowledge and capability to safely deliver the trial. The subject areas below were delivered depending on the individual's role in the trial.

3.5.4.2 Project Introduction

All personnel involved in any aspect of the trial delivery had a project introduction briefing. This provided everyone involved with an overview of the project and enabled them to identify where and how their role integrates into the successful delivery of the project.

3.5.4.3 Hydrogen Awareness

This ensured that the differences between hydrogen and natural gas in terms of physical properties and the practical application of this knowledge were understood by all personnel.

3.5.4.4 Site Inductions

Site inductions were developed for each AGI along the pipeline route as required by the Construction Design and Management (CDM) regulations [47]. These included details of the onsite operations and safety precautions while onsite including required PPE and emergency actions. Inductions were developed for:

- Bo'ness Road.
- Grangemouth (INEOS FPS).
- LTS Futures compound at INEOS FPS.
- Newton BV.
- Granton.

3.5.4.5 Emergency Response

Emergency response training was delivered in the form of a briefing or a full training module depending on the role of the trainee.

Emergency response training covered each step in the emergency response process including:

- PRE reported to OCC.
- Notification to and dispatch of FCO and HPRT.
- Immediate onsite actions – safeguard life, property and the environment.
- Escalation in the event of hydrogen being detected.

The emergency response process was stress tested prior to the live trial.

3.5.4.6 Gas Detection

Gas detection training covered familiarisation and use of the GMI GS700H for detection of hydrogen and natural gas. The GS700H is capable of detecting natural gas or hydrogen at a full range of concentrations (ppm, %LEL and %vol). It can also interpret hydrogen/natural gas mixtures.

3.5.4.7 Live Trial Operations (entry unit)

Operations training for the live trial involved familiarisation with the entry unit equipment, its setup and operation. This included flowmeters, flow/pressure control valves, odorisation unit and filtration. Operational tasks included gas sampling for monitoring of odorant concentration and temporary vent stack use. Identical equipment was also used at Newton and Granton.

3.5.4.8 Live Trial Maintenance/Inspections

Maintenance and inspection tasks for the live trial included routine checks of odorisation systems and functional checking of instrumentation including a flow meter as well as flame and leak detection. For instrumentation that maintains a permanent logging capability, swapping of battery packs was required.

For pressure control equipment, this included functional checking of slam shuts, regulators, flow control valves and filters.

3.5.4.9 Flare Operation

This included routine operation of the flare for live trial operations, such as purging and flowing operations required for live welding a split tee. Training also included emergency operations for flaring the inventory in the event of a confirmed hydrogen PRE.

3.5.4.10 Non-Routine Operation (NRO) Briefings

All live gas operations included in the live trial operated as an NRO. See Section 3.5.3.2.

Briefings were carried out for each NRO on the day prior to the operation and in preparation for specific tasks such as welding, hot tapping and flow stopping. Personnel involved in the trial attended factory acceptance tests (FATs) beforehand where the procedure was completed and verified.

3.5.4.11 Trial Personnel

SGN operational personnel were selected for the trial based on geographical location and operational capability. Existing personnel training records were reviewed to ensure all training was up to date and these personnel were then upskilled to complete the task of the live trial. Consistency was maintained across the development and delivery of revised procedures by ensuring personnel who attended factory acceptance testing performed the same role in the live trial operation.

Contractors for the trial operations were required to meet the same training standard. This included project and hydrogen awareness for all personnel. As with SGN personnel, there was consistency in operational staff involved in the development and factory acceptance testing of the trial procedures through to the completion of the live trial.

3.5.4.12 Training Records

On successful completion of knowledge assessment or practical assessment, an individual's training record was updated on the SGN Learning Management System (LMS) to reflect completion of the training and to maintain accurate records. Due to the short duration of the trial, there was no refresher training or repeat competency assessments required during the project.

3.5.4.13 Skills Assurance

Training assessments are required to ensure there is sufficient knowledge retention of the training material delivered and the practical skills required to carry out a task safely. This is particularly important in hydrogen operations where there are differences in how the task would be carried out in natural gas or where a new operation is required such as flaring.

The requirement for practical assessment depended on the nature of training completed and the criticality of the task. Some training modules only required a knowledge assessment, such as hydrogen awareness, whereas others required an additional practical assessment, such as hydrogen gas detection or entry unit operation. Individuals were required to pass both the knowledge and practical assessments for their required job role. Assessments were carried out on an individual basis against pre-set criteria.

3.5.4.14 Resourcing

A resourcing plan was developed for the trial based on the operations to be carried out and the skill set required to complete each task (E&I, pressure control, project team, pipeline maintenance). This plan provided assurance that sufficient personnel were trained and competent to complete each NRO and allowed scheduling for individuals to ensure operational personnel did not become fatigued and potentially make errors during critical trial operations.

3.6 Live Trial Operations

3.6.1 Pre-commissioning

Pre-commissioning works for the trial included a review of the interim integrity management plan actions, see Section 3.1.2.4, ensuring all activities had been completed.

Helium leak tracing was carried out on the hydrogen supply pipeline from the connection at Bo'ness Road to the entry unit 18" flange outlet. Helium was used as an inert proxy for hydrogen with the 3" pipeline and entry unit being pressurised in 5 barg increments up to 40 barg (MOP). At each pressure step, every flanged joint and equipment item was checked for leakage using a handheld mass spectrometer. Following completion of the leak check, the final connection was made to the Grangemouth to Granton pipeline. A sentry gasket was utilised at this flanged connection to allow the integrity of the seal to be proved. The gasket seal was tested with hydraulic oil to a pressure of 60 barg.

Oxygen-free checks were carried out at all gas sampling points across the pipeline route. These included sampling from the entry unit, Newton bypass, and the Granton flare site. Purging certificates were produced, and these were shared with INEOS to confirm that both pipeline sections were purged and ready for hydrogen to be introduced.

The final step completed before the introduction of hydrogen was the removal of spades in the INEOS pipework, which were put in place following the construction of the pipework on the O&P site. These were removed on 30th June 2025 immediately prior to purging.

3.6.2 Commissioning, Purging and Pressurisation

In preparation for the trial, an operational philosophy for all flowing gas activities was developed. This included modelling of flowing gas operations to inform and develop the live trial NROs. Purge modelling for the 3" and 18" pipelines was completed as well as flowing operations required for hot works. This modelling enabled the optimal pressures and flow rates to successfully complete the purge to be specified and the operation to be optimised in terms of hydrogen usage and the time to complete. For hot works, the modelling demonstrated that there would be adequate capacity in the system to maintain flow for the required durations.

3.6.2.1 Purging of Bo'ness Road compound, 3" hydrogen supply pipeline and entry unit

Purging of the hydrogen supply pipeline, including the Bo'ness Road compound and entry unit, was completed on 30th June 2025. Spades were removed from the INEOS connection point introducing hydrogen into the 3" line. The displaced nitrogen was 'vented' into the 18" pipeline, as only minimal venting to atmosphere for the purposes of gas sampling was permitted onsite. Modelling carried out in advance gave an approximate purge duration of 30 minutes. The flow into the system was controlled within INEOS O&P using a manual globe valve, and therefore control of the flow to a setpoint was not possible.

The actual duration of the purge was 46 minutes. This was longer than the time predicted, and this is likely to be due to there being a larger volume of nitrogen to be displaced prior to hydrogen entering the modelled volume. Hydrogen gas surveyors (GS700H) were used to confirm the purge at both the Bo'ness Road compound and entry unit.

Table 11: Modelling details for purging of the 3" hydrogen supply pipeline

Mass flow (kg/hr)	5
Pipe bore (mm)	80
Pipe length (m)	1,280
Upstream pressure (barg)	2.0
Pressure loss from pipe (mbar)	0.51
Purge velocity (m/s)	1.09
Transit time (hh:mm:ss)	00:29:23

3.6.2.2 Entry Unit Commissioning

Commissioning of the entry unit was completed on 1st July 2025. The NRO for this operation worked systematically through each equipment item to ensure it was functionally tested and operating as expected. This process also allowed for checks of all instrumentation, monitoring, and data capture systems.

A range of tests were completed using the flow control valve, demonstrating that flow rates up to 250 kg/hr could be readily controlled and stabilised. The pressure control valve was confirmed to be responding to set points using a downstream globe valve to create back pressure. Testing of safety devices was completed, including the safety shut-off valve and let-by checks on isolation valves. The safety shut-off valve demonstrated good repeatability across all tests and was within tolerance of the set point. Similarly, no let-by checks demonstrated any leakage past isolation valves. Flowing operations also allow for confirmation operation of the odorisation system unit.

Confirmation of the complete functional testing of the entry unit equipment allowed the project to progress to purging of the 30 km Grangemouth to Granton pipeline.

3.6.2.3 Purging of the 18" Grangemouth to Granton pipeline including Newton bypass and Granton flare commissioning

Purging of the 18" Grangemouth to Granton pipeline and commissioning of the Granton Flare was completed on 3rd July 2025. Hydrogen flowed into the 18" pipeline through the entry unit, which controlled the pressure and flow rate. At Newton, the gas flowed through the block valve bypass and inline instrumentation monitored the transition from nitrogen to hydrogen. Once the purge front had been confirmed at Newton, the assist gas supply to the flare was turned on to start combustion at the flare tip in preparation for the arrival of hydrogen at Granton. This ensured that there was a stable and sufficient flow of flammable gas to the flare and maintained complete combustion as the hydrogen front arrived.

Modelling of the purge was carried out as part of the preparation process, and this informed the operational philosophy. To purge the pipeline efficiently in terms of gas usage and time, the pressure in the pipeline needed to be kept low at approximately 0.5 barg. Due to the different densities of nitrogen and hydrogen, a substantially higher mass flow rate of nitrogen was vented at the Granton flare site. This was controlled to ensure that the inlet mass flow rate of hydrogen would not result in an outlet mass flow rate of nitrogen that exceeded design parameters. The flow rate to the flare was controlled using mass flow meters and manual valves at Granton.

Table 12: Modelling details for purging the 18" Grangemouth to Granton pipeline.

	Grangemouth to Newton	Newton to Granton
Mass flow hydrogen (kg/hr)	250	250
Pipe bore (mm)	445	445
Pipe length (m)	15100	15300
Upstream pressure (barg)	0.6	0.6
Pressure loss from pipe (mbar)	30.73	31.55
Purge velocity (m/s)	2.56	2.57
Transit time (hh:mm:ss)	02:27:43	02:28:42

The purge was carried out with an initial hydrogen flow rate of 125 kg/hr, and the pipeline pressure was to be maintained at 0.5 barg. Due to the elevation profile of the pipeline (NBV being the high point), there was a pressure increase in the section from Grangemouth to Newton as the hydrogen was compressed behind the denser nitrogen. This was monitored as the purge progressed, and the inlet flow rate was kept to 125 kg/hr. The arrival of the purge front was monitored at Newton and Granton using inline hydrogen sensors and confirmed using a GS700 (hydrogen gas surveyor).

Hydrogen was first detected at Newton after 1 hour and 38 minutes with the purge to Newton complete 23 minutes later. See Figure 18. This was faster than the modelling had predicted, and this is potentially due to hydrogen from the purge of the 3" line and entry unit commissioning being displaced into the 18" pipeline. Modelling also conservatively assumed a purge ratio of 1.5, and the actual operation may have been more efficient than expected.

The purge continued to Granton and was completed at 16:30, therefore it took 2 hours and 10 minutes to complete the purge from Newton to Granton. This was again shorter than the modelled duration, which is potentially due to efficiency. It should also be noted that modelling was completed based on 100% hydrogen gas composition while the trial specification was >96%. The purge transition at Newton and Granton was comparable, with the time for transition from 40 % vol hydrogen to purge complete being 14 minutes and 16 minutes, respectively.

Following confirmation of the purge, the assist gas supply was isolated. The flare was now commissioned and operating on hydrogen. Gas samples were taken at Newton and Kinneil for odorant analysis. Samples from both locations indicated low odorant levels. This led to a review of the sampling procedure. To ensure the sample taken was representative of the pipeline contents, the venting time before taking a sample was increased.

Figure 18: Transition of purge front at Newton site.
NB. A Linear trendline has been added to demonstrate the relations across the whole purge.

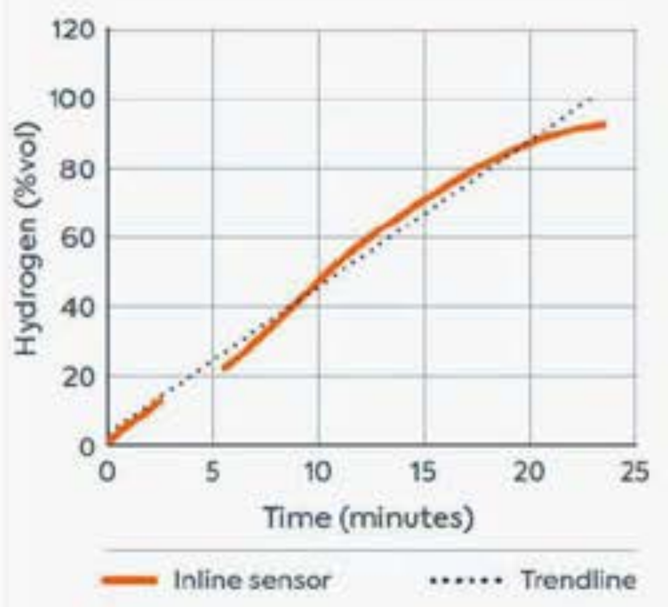
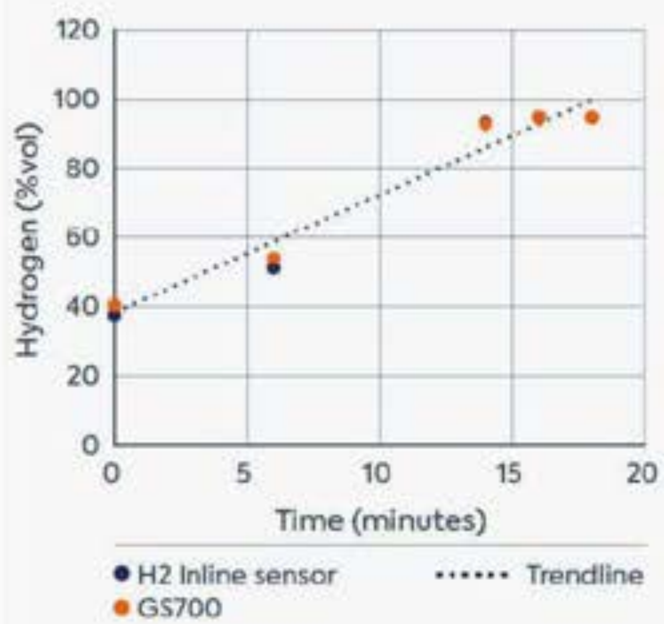


Figure 19: Purge front arrival at Granton.



3.6.2.4 Pipeline Pressurisation and Conditioning

Table 13: Live trial.

Date	Start pressure (barg)	End pressure (barg)	Noted events
04/07/25	1.0	3.1	Flare testing complete with a flow rate of 1074 kg/hr (pressure decreased from 3.6 to 3.1 barg).
05/07/25	3.1	8.3	
06/07/25	8.3	12.0	
07-10/07/26	12.0	9.0-10.0 (approx.)	Pressure in line reduced until the flare and then maintained with balance flow in and out of the pipeline for odorant conditioning.
11/07/25	9.4	16.0	Pipeline pressurisation.
14/07/25	16.0	26.0 (Grangemouth to Newton) 17.0 (Newton to Granton)	Pipeline pressurisation required for the flow trial was achieved.

Pressurisation and conditioning of the pipeline started on 4th July 2025 with the initial plan being to perform a stepwise pressurisation of the pipeline up to 26 barg (MOP) with leak checking to be completed at a max of 5 barg increments. During this process, the operation of the flare would also be tested to demonstrate its operability at a range of pressures.

During the first 3 days of pressurisation, gas samples were taken from each of the sites and transported to Granton for onsite analysis. While odorant levels did start to rise, they remained significantly below the level that would be recognised as odorised gas within the standard. This persistent low level of odorant in the gas was due to conditioning of the pipeline and adsorption of the odorant components onto the pipe wall.

Odorant New Blend (NB) was specified for the trial. This is the same odorant that is used for natural gas and had been determined by a previous project to be suitable for odorising hydrogen. The HSE have also suggested that for ease of identification by the general public, hydrogen should utilise the same odorant [48].

Odorant NB is made of up 2 components, Tetra Butyl Mercaptane (TBM) and Dimethyl Sulpide (DMS), and is dosed into the gas stream depending on the flow with the intent of achieving an odour intensity level of 2.0. Prior to the trial, analysis was carried out to determine the required dosing rate for the trial hydrogen composition. This was 7.3 mg/Sm³. There was potential for the gas composition to vary during the trial; however, these expected variations did not make an appreciable difference to the amount of odorant to be dosed.

The TBM component of the odorant can selectively adsorb to pipe walls and react with corrosion products inside a pipeline. Prior to the preparation for the trial, the Grangemouth to Granton pipeline had been out of service for 39 years but had been maintained with nitrogen preservation during this time. Cleaning pig runs and camera surveys had shown the pipeline to be in good condition, but corrosion products were present. This resulted in the TBM portion of the odorant being adsorbed onto the pipe wall and reacting with corrosion products in the pipeline and therefore not remaining in the gas stream creating the required odour.

On 7th July 2026, the pressure in the pipeline was decreased to approximately 10 barg and then maintained at this level by balancing flows in and out of the pipeline. The odorant dosing rate was also increased to compensate for the odorant being lost to adsorption and reaction. This continued until 10th July 2026 when required odorant levels were achieved at Granton. Following this, odorisation rates were reduced to approximately double the calculated rate, 15 mg/Sm³, to compensate for any further adsorption or reaction, as this increase level would have minimal impact on the odour intensity. The pipeline was pressurised to 26 barg in the section from Grangemouth to Newton and 17 barg in the section from Newton to Granton to conduct the flow trial prior to the welding operation. Samples continued to be taken for odorant analysis during this period, and the odorant levels did decrease as the gas in the system was not flowing.

Following discussion with internal and external Subject matter experts (SMEs), this was accepted by the project and discussed with the HSE. Pressure and leak detection systems on the pipeline did not give any indication of leakage and building line surveys, and additional vantage point surveys were initiated during this period as a precaution. It should be noted that the operation of the trial is not representative of gas network operation in terms of flow conditions. Odorant fade can occur with natural gas or hydrogen; however, it is not generally an issue in a live gas network that has been conditioned at commissioning and operated continuously.

Within the UK, odorisation is only legally required for the below 7 barg network [28]. The LTS is currently odorised as dosing at National Transmission System (NTS) offtakes required a much lower number of injection points on the network. The project followed this existing approach.

3.6.2.5 Flow trial

A flow trial was completed on 15th July 2025. This allowed modelling completed prior to the trial to be verified, ensuring that there was sufficient capacity in the system to maintain flow for the duration of the welding operation. This also allowed an additional check to be made on the operation of the pressure regulator at Newton, which would maintain the pressure in the downstream section at 16 barg until the pressure in the whole pipeline began to decay.

Flow modelling prior to the trial predicted a time window of 425 minutes for completion of the planned welding.

Figure 20: Flow modelling completed prior to the trial.

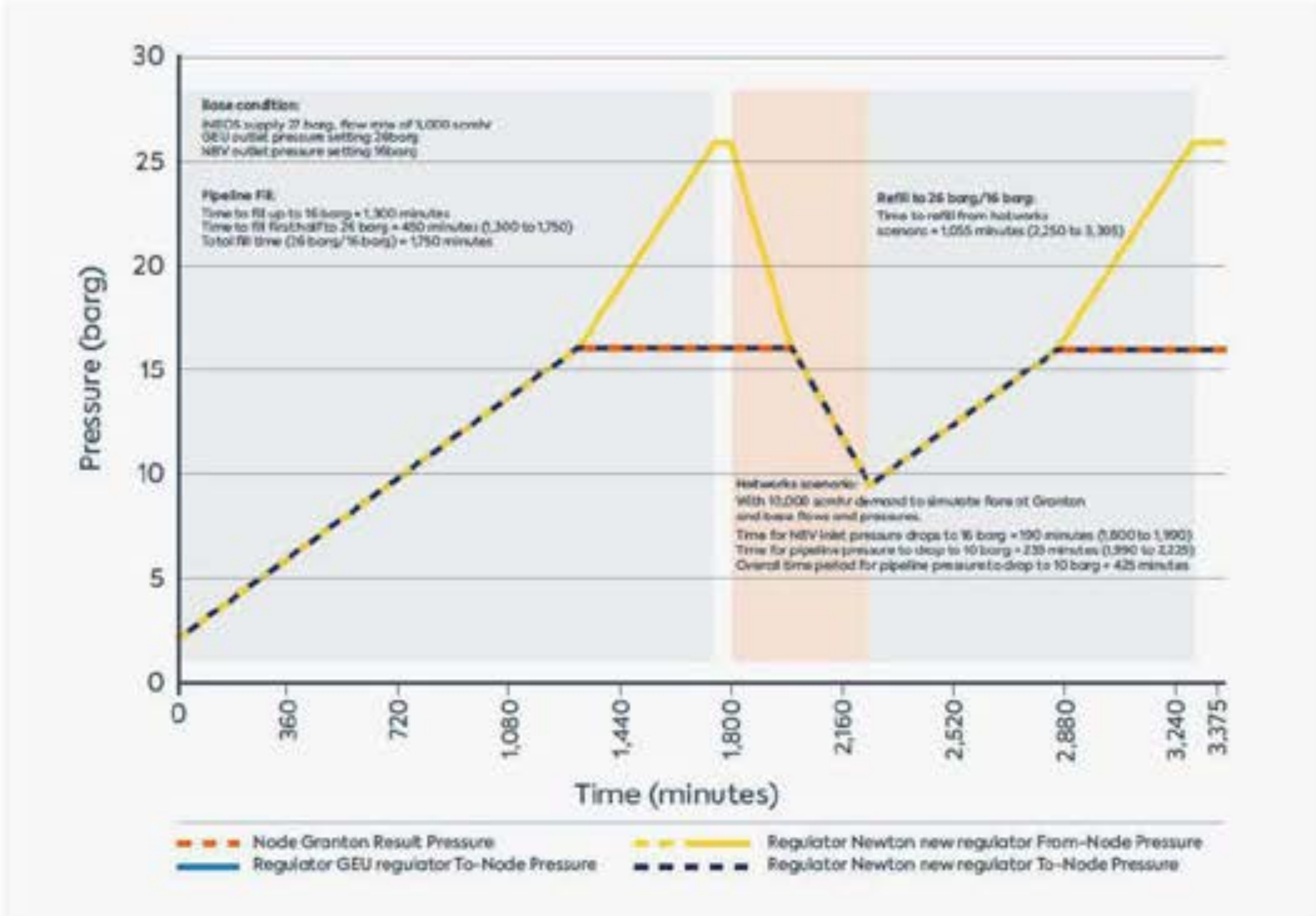
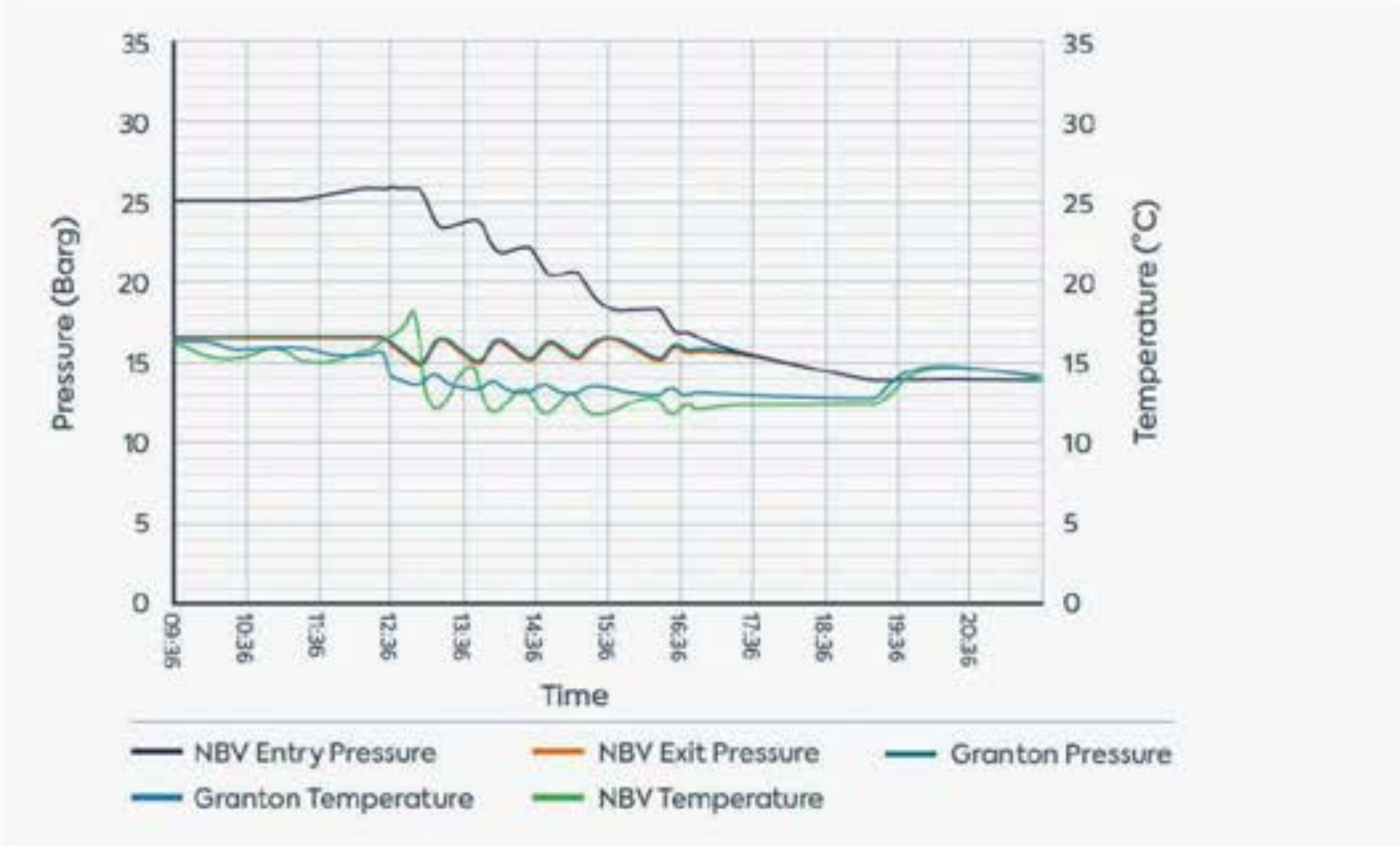


Figure 21: Data from flow trial.



During preparation for the trial, some further optimisation was possible with a slight increase in flow available from INEOS, and the adjustment of flow to the flare meant the velocity in the pipeline could be maintained as the pressure decreased. This increased the duration to 545 minutes during the flow trial. This was sufficient to carry out the welding operation with contingency.

Following the flow trial, the pipeline was re-pressurised to 26 barg in the section from Grangemouth to Newton and 18 barg in the section from Newton to Granton in preparation for the welding demonstration.

3.6.3 Making New Connections (Welded and Grouted Tees, Hot Tapping and Flow Stopping)

GDNs are required to make planned and emergency interventions to maintain assets while continuing supply to customers. To add new connections or complete maintenance, live welding, under-pressure drilling and flow stopping are essential operations.

Live welding on SGN's LTS pipelines is conducted in accordance with the procedural document IDN/SP/P/9 [49], a supplement to BS 6990 [50]. There is no recognised industry standard or procedure for live welding on hydrogen pipelines. Guidance in Table B Summary of Isolation Techniques of HSG 253 states that hot tapping and stoppling are not appropriate for systems containing hydrogen [51]. Alternative repair and connection attachment methods that do not require welding are also used on the network, e.g. the 'grouted' tee. Grouted tees are applied by specialist contractors in accordance with SGN/WI/P/19 [52]. Anecdotally, there is an equal distribution of welded and grouted tees on the SGN LTS with the preferred method dependent upon pipe WT, pipeline operating parameters and practical considerations. Under-pressure drilling and flow stopping on the LTS is performed by specialist contractors with procedures defined in RAMS and the management procedure T/PM/P/24 [53]. Currently, there is no recognised industry standard or procedure for under-pressure drilling or flow stopping on hydrogen pipelines.

Figure 22: Live welding.

Compared to conventional welding, specific hazards associated with live pipeline welding include 'burn-through' and elevated risk of 'hydrogen cracking' (cold cracking). Burn-through (blow-out) can occur if there is excessive heat input/weld penetration and the resulting hoop stress in the pipeline exceeds the strength of the remaining pipeline thickness beneath the molten weld pool. See Figure 23. Hydrogen cracking occurs when hydrogen is present within a susceptible microstructure and a stress system is present. See Figure 24. The sources of hydrogen may be the welding consumables, the presence of contaminants on the pipe surface or moisture. The microstructure of a carbon steel is a product of its chemical composition and thermal history from component manufacture, or other operations, such as welding and heat treatment. Stresses may be residual stresses from welding and other stresses from service or loading. Such hazards are understood and controlled appropriately for live welding on natural gas pipelines, e.g. the use of low-hydrogen consumables, limiting material harden ability and using elevated minimum preheat compared to conventional pipeline construction welding. Transitioning to live welding on pipelines containing a gas with different properties requires these hazards to be investigated and controls/procedures modified appropriately.

Figure 23: Live welding process showing weld pool and associated depth of penetration into parent material.

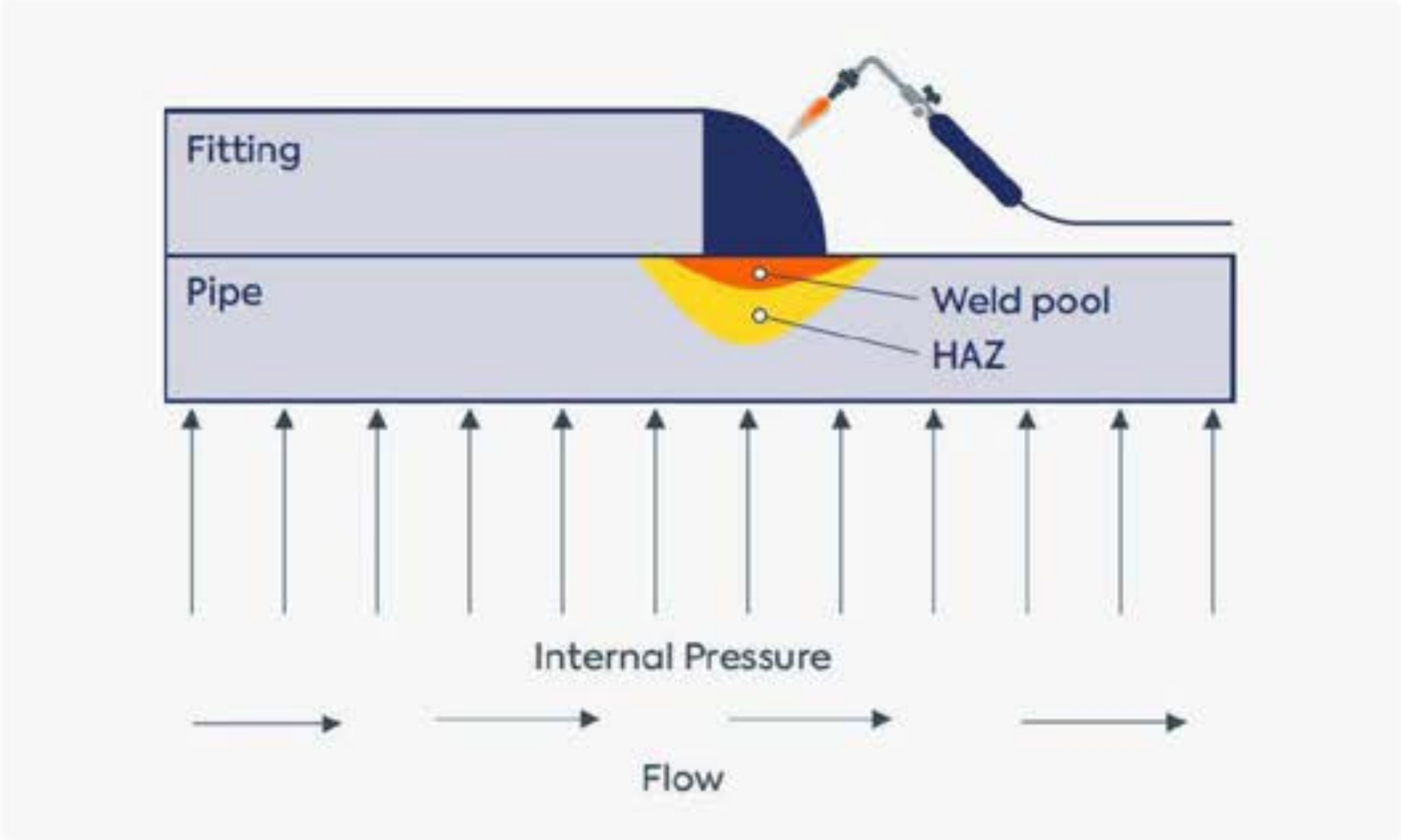
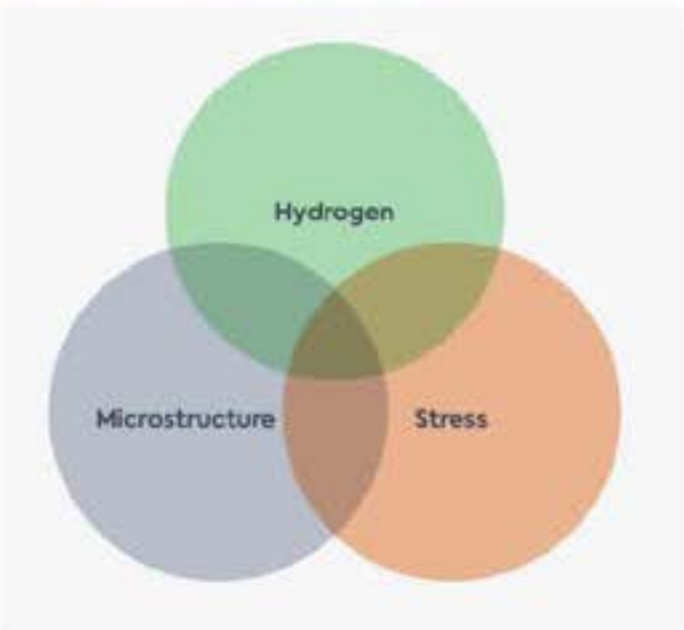


Figure 24: Hydrogen cracking requirements.



Hazards in under-pressure drilling include the potential presence of flammable gas, air and an ignition source (e.g. a hot spot during drilling) within the tapping body and venting (or flaring) of high-pressure flammable gas. The process is completed on pipelines across the world with many different fluids. The wider flammability range and lower ignition energy of hydrogen means that under-pressure drilling on hydrogen pipelines has additional threats that require adaptation of procedures to proportionately manage the risks.

To demonstrate that such activities can be completed safely on LTS assets repurposed to hydrogen, a full procedural qualification programme was completed in a test site environment. A hydrogen flow loop was fabricated using a section of material cut out from the Grangemouth to Granton pipeline. See Figure 25. Pressure and velocity in the flow loop could be controlled within the parameters specified for the LTS Futures live trial providing a representative qualification environment. Upon completion of the procedural qualification, a full-scale fatigue test was completed to evaluate the integrity of the new connections and demonstrate

Figure 25: LTS Futures hydrogen flow loop.

suitability for hydrogen. Welders and hot tap technicians from a hot tap service provider were then qualified to SGN's procedures through a full-scale FAT. Following this, the live trial was completed successfully whereby a split tee, and two set-on fittings, were welded and hot tapped under live hydrogen conditions to the pipeline. Full details on the welding procedure development have been published in Koronka et al [54].

3.6.3.1 Live Welding Procedural Qualification

Using a separate section of pipe, trials were completed to establish the inner wall temperatures and depth of penetration when welding using typical P/9 and modified approaches. Welding on an offline section of pipe was conservative regarding heat loss. The Pipeline Research Council International (PRCI) Thermal Analysis Model for Hot Tap Welding, developed by the Edison Welding Institute, defines the critical inner wall temperature for burn-through during welding as 982 °C [55]. An inner wall temperature limit of 723 °C could be used for pipelines containing hydrogen, as this is the critical temperature for phase transformation of ferrite to austenite (a microstructure with higher solid solubility of hydrogen than ferrite [56]). Predictions made using the PRCI model indicated that current P/9 welding procedures could result in inner wall temperatures close to or above these limits. Given that P/9 has been used for decades without incident, it was credible that the software predictions were conservative for the cases looked at. All tests recorded peak inner wall temperature values below 982 °C and a limited depth of weld penetration in relation to the WT that showed acceptable security for burn-through. Only one case (highest heat input and highest pre-heat level) exceeded the 723 °C phase transformation temperature. Given the trials were conducted in a conservative manner (e.g. no thermal decay from flowing gas), this provided confidence that the temperature limits would not be reached in-service when using similar combinations of welding variables. These tests allowed welding parameters to be defined for thermal decay and weld cooling trials.

Figure 26: Inner wall temperature trials.

Figure 27: Pre-heat application for split tee welding.

P/9 [49] requires that all welding be conducted on a pipe with surface preheat temperature greater than 150 °C. However, as the flowing gas in the pipe dissipates the heat at a significantly higher rate than conventional welding, the preheat applied in advance of welding is more than this, typically at 250 °C. The time it takes to cool between these two temperatures provides the practical window within which welding can be progressed. This is referred to as the temperature or thermal decay time, and it is measured both before and during P/9 welding operations. To achieve such surface temperatures, live pipelines are typically pre-heated using oxygen-propane torch, see Figure 27, or electrical resistance heating methods. Temperature indicating crayons or thermometers are then used to monitor the temperature during welding.

The minimum decay time that P/9 permits welding to take place is 40 s; any time recorded below this would mean welding would not be started or would be halted if already commenced. An additional important consideration, though more difficult to measure using basic equipment in the field, is the weld cooling time from 800 down to 500 °C ($T_{8/5}$). This time affects the microstructure of the weld and heat affected zone (HAZ). If the period is short, certain metallurgical phases may form that negatively impact the mechanical properties of the weld and HAZ, typically related to hardness. Due to the different properties of hydrogen, the heat dissipation during welding could be different, reducing the allowable time for welding and/or adversely affecting the mechanical properties of the weld by increasing hardness.

Figure 28: Preheat decay tests.

Figure 29: Weld cooling decay tests.

To evaluate the impact of hydrogen flow conditions on both the thermal decay and $T_{8/5}$ times, trials were performed using the bespoke flow loop and different pressure (7.1-18.7 barg) and velocity (0-5.6 m/s) combinations. For pre-heat thermal decay tests, an oxygen-propane torch was used to pre-heat a section of the pipe while hydrogen was flowing at the specified velocity and pressure. The pipe surface was pre-heated above 250 °C and a time recording started when the surface reached 250 °C (measured using a temperature indicating crayon). Type-K thermocouples mounted on a wooden frame were pressed against the pipe wall at the same location for each test combination. The time for the pipe surface to drop to 150 °C was recorded both manually and using the thermocouple datalogging equipment. In selected cases where a thermal decay test was carried out, a weld pad was deposited simulating a buttering layer, and a Type-J thermocouple was inserted into the weld pool using the harpoon method to measure and record the $T_{8/5}$ weld cooling time.

The tests demonstrated that the pre-heat thermal 250-150 °C decay time did not drop below 40 s for any of the pressure and flow combinations tested. The weld cooling trials demonstrated that the $T_{8/5}$ weld cooling time was generally independent of the pressure and flow rate combinations, with the expected trends related to heat input more prominent (i.e. low heat input producing a shorter weld cooling time and vice versa). These observations and recorded data allowed suitable welding parameters and variables to be proposed for the full-scale welding of a split sleeve and split tees on the flow loop.

Figure 30: Split tee qualification welding.

Figure 31: Grouted tee collar.

Figure 32: Injection of grout into vertical tee.

Figure 33: Pressure testing of horizontal tee.

A welded 'tee' connection requires two longitudinal and two circumferential welds. The longitudinal welds join the two half shells of the split tee together. Welded simultaneously, these incorporate a backing bar, meaning no direct contact with the pipeline occurs during welding. The circumferential (fillet) welds are applied consecutively and each in two stages. The first buttering layer provides controlled deposition of a weld pad of an appropriate width directly onto the pipe surface. The purpose of the buttering layer is to reinforce the pipe wall, to minimise bead penetration and reduce the risk of underbead cracking, as it is this first layer that poses the most risk. The fillet weld is then used to attach the tee to the pipeline on the buttering weld passes. The temperature trials work provided sufficient evidence that the current P/9 weld procedures could be used, with a minor modification of the buttering pass parameters, for welding on the hydrogen flow loop.

Procedures were applied and two split tees were welded in the horizontal position under flowing hydrogen at 13 barg successfully. See Figure 30.

3.6.3.2 Grouted Tee Procedural Development

Grouted tee installation parameters were largely unchanged from those currently on the LTS. The key activities during the qualification programme were to ensure the grouted tee collar, see Figure 31, and final cured grout provided adequate sealing with hydrogen during the installation process.

Two grouted tees were installed onto the loop under live, static hydrogen at 13 barg. One tee was installed vertically and the other horizontally. The shells were lifted into position, bolted up and fitted with a test blind flange. The seal on the grouted tee collar was checked by injecting hydrogen to a nominal pressure of 6.5 barg into the tee branch space and ensuring no pressure drop over a 30-minute period. End seals were then applied and grout injected into the space between the end seals and tee collar. See Figure 32.

The grout was allowed sufficient time to cure prior to completing a pressure test at 13 barg with hydrogen for a minimum time of one hour (excluding the time for stabilisation of the seal). Tests on both tees were successful in demonstrating the sealing capability of grouted tees with hydrogen.

Figure 34: Tapping machine, sandwich valve and cutter head.

3.6.3.3 Hot Tapping Procedural Development

All four tee connections (two welded and two grouted) that were applied to the flow loop were subsequently drilled under pressure. All under-pressure drilling was conducted using existing, standard natural gas equipment – a tapping machine and a gate (sandwich) valve. See Figure 34 The tapping machine consisted of a drill body with threaded ports for purging, venting, and pressure equalisation purposes, and a drilling mechanism encompassing pilot and annular cutter-style tools. Three tees were drilled in the horizontal position and one tee in the vertical position. Horizontal drilling is considered more challenging due to the increased possibility of cutting debris being dragged onto the tee's sealing collars when retracting the drill back into the drill body, and increased movement of the pilot drill and cutter.

A summary of the procedure for the under-pressure drilling is given below. The procedural changes to the under-pressure drilling included an additional hydrogen purge of the drill body after nitrogen purge and longer hold periods to monitor for leakage.

- Check equipment functionality and cutter depth.
- Attach the gate valve and drill to the tee.
- Purge the assembly with nitrogen, pressurise, hold, and confirm assembly is leak-free at line pressure.
- Purge the assembly with hydrogen, pressurise, hold, and confirm the assembly is leak-free at line pressure.
- Close the sandwich valve and depressurise the drilling assembly to half-line pressure by venting hydrogen. Confirm that the sandwich valve is holding pressure.
- Equalise the pressure across the sandwich valve and open.
- Begin the cutting operation and allow the pressure in the drill body to equalise as the pilot drill penetrates the pipe.
- Retract the drill fully once cut is complete and isolate.
- Vent the drill assembly and monitor for leaks.

The main hazard with under-pressure drilling is the potential for a flammable gas-air mix. While the presence of flammable gas and an ignition source (hot spots from drilling into pipe) are inherent to the process, the presence of air can be eliminated through appropriate purging and leakage checks. Purging the apparatus to nitrogen ensured no presence of oxygen, and holding at pressure for longer provides confidence in leak tightness. Purging to hydrogen and holding at pressure provides further confidence that all equipment is functional and will not leak hydrogen when the pipeline is 'tapped'. A suitable medium that provided both inert purging and leak tracing capability was noted as a replacement for nitrogen purging then hydrogen leak tracing. A helium-nitrogen tracer gas was noted to provide this option.

3.6.3.4 Completion Plug Procedural Development

The installation of a standard completion plug was attempted on one of the horizontal welded split tees. See Figure 35. The plug installation attempts utilised the same tapping machine as the under-pressure drilling. The same nitrogen/hydrogen purge and pressure hold/leakage check process was used pre-plug deployment. The plug was moved into position and secured by winding the holding segments into place via the external threads. Upstream of the plug was depressurised rapidly to the local vent stack. The plug did not manage to seal in hydrogen, with significant leakage occurring immediately after plug setting. The severity of the leakage suggested that the issue was not solely related to hydrogen. The trials were halted and the process and plug design put under review in NIA2_SGN0036 and the FAT Qualification. See Section 3.6.3.6.

Once decommissioned, significant levels of 'swarf' (metallic shavings and ribbons) were noted within the tee. See Figure 36. Although not confirmed, this likely affected sealing performance of the plug.

3.6.3.5 Full-Scale Tee Fatigue Test

A full-scale fatigue test was completed on a welded and grouted tee from the procedural development stage to demonstrate integrity of the new connections under hydrogen. The testing has been fully detailed in Cosham et al [57]. See Section 3.9.2.

Figure 35: Completion plug.

Figure 36: Swarf accumulation in split tee.

Figure 37: Hot tapping qualification.

Figure 38: FAT vessel.

3.6.3.6 Factory Acceptance Test (FAT) Qualification

To ensure readiness for the live trial, a FAT with TDW was completed. The aim of the FAT was to qualify all personnel to SGN procedures and evaluate the flow-stop and completion plug technologies for the live trial.

To undertake the FAT, a test vessel incorporating Grangemouth to Granton pipeline material was fabricated, see Figure 38, and a new split tee and set-on fittings were provided by SGN. The welding rods and split tee were as per the grade, size and manufacturer used in the live trial. The vessel was standalone and filled with a helium-nitrogen blend to 16 barg for the duration of the FAT. The tee was to be welded to the vessel in the horizontal position and set-on fittings in the vertical position. The helium-nitrogen blend provided an opportunity to evaluate the sealing performance of the flow-stop and plug technologies in a medium with a similar leakage propensity as hydrogen. Local pressure gauges and an internal camera were installed on the vessel for measuring leakage and monitoring the activities.

Welders were successfully qualified to SGN's procedures through offline plate and pipe butt welds, as per P/9 [49] and P/2 [58]. The split tee and set-on fittings were subsequently welded to the vessel using LTS Futures welding procedures with no remediation work required. See Figures 39 and 40. Four welders were qualified and completed the FAT to provide suitable personnel cover for the live trial. Two inspectors and the independent welding engineer witnessed all activities and reviewed the welders' qualifications.

Figure 39: FAT welding.

Figure 40: FAT vessel upon completion of welding.

Following the welding, a hot-tapping operation was completed. The exact same equipment to be used within the live trial was utilised, and a helium-nitrogen mix was used in place of the individual nitrogen and hydrogen purges and pressure holds. A flanged adaptor spool was bolted to the split tee, incorporating a machined groove required for deployment of an alternative plug technology. A hydraulic sandwich valve was then bolted to the adaptor spool. Measurements for the cutting process were taken to calculate key distances for the operation, e.g. contact point with pipe, plug set position etc. The tapping machine was then lifted into position and bolted to the sandwich valve. Purging and pressure-holds were then completed on the full assembly and sandwich valve as per the SGN procedure. The hot tap technicians then drilled the tee successfully under pressure. See Figure 41. A smaller, manual tapping machine was used for the set-on fittings with the same purging and pressure-hold procedures for the assembly and associated valve. Both fittings were successfully tapped under-pressure.

A Stopple-Train flow stopping tool was then set up for deployment. The Stopple-Train has two sealing heads providing a 'primary' and 'secondary' sealing element and was the flow-stopping tool recommended for hydrogen by TDW. The set-on fittings welded and tapped in the previous stage of the operation are used for venting the Stopple-Train annulus and re-pressurisation operations. The Stopple-Train is a separate tool from the tapping machines used for hot-tapping and completion plug setting. 'Swarf' from the hot-tap operation is known to interfere with sealing elements, particularly in low-flow pipelines and on horizontal tappings. The Stopple-Train 'swarf' management technique is 'sweeping' whereby the stopple heads are moved back and forth in the pipe once deployed to move swarf out of the area. Oversized seals are used to ensure sufficient contact with the inner pipe wall and move as much debris as possible. The tool is then removed, damaged sealing elements changed for new ones and the tool is re-deployed. The FAT vessel incorporated an in-line camera, which showed significant levels of swarf had been generated during the hot-tapping process (as would be expected).

Figure 41: FAT preparation of hot tap machine.

Figure 42: FAT stopple train.

Figure 43: Standard plug (without sealing element).

Figure 44: Lock-O-Ring Plus (without sealing element).

The Stopple-Train was prepared, lifted into position and bolted to the sandwich valve. The same purging and pressure hold procedures as per the hot-tapping process were completed. The tool was then deployed and sealing heads advanced into the vessel. The 'sweeping' action was completed several times and was successful in removing all the swarf shaving material. The tool was then removed from the vessel, damaged sealing elements changed for new and re-deployed. 'Setting' the tool was then attempted by depressurising (using external valves) the annuli downstream of the secondary and primary stopple heads to different levels to create a differential pressure across the sealing elements. Leakage was then monitored via pressure build-up in each annulus. In all tests, the annuli re-pressurised with little difference in re-pressurisation times between different differential pressures.

Flow stopping was noted to be an area of further investigation, and several trials were completed on a different flow-stopping tool under NIA2_SGN0036 and NIA2_SGN0052. Deployment of the Stopple-Train in the live trial was permitted to proceed to generate further data on its potential use in the future.

Two different types of plugging technologies were evaluated during the FAT, a standard plug, see Figure 43, and a Lock-O-Ring Plus plug. See Figure 44. The standard plug had been unsuccessfully trialled previously under hydrogen conditions, as noted within Section 3.6.3.4. The Lock-O-Ring Plus plug is a different design to the standard plug. The Lock-O-Ring Plus plug's locking segments are incorporated into the plug itself, whereas for the standard plug, locking segments are located inside the neck of the tee. The Lock-O-Ring Plus plug requires a tee with a specific machined groove, and therefore an adapter spool containing this groove was provided for use with SGN's standard tee. Both plugs were deployed using the same tapping machine and purge/pressure hold procedure as used for the hot tapping.

The standard plug was not deployed successfully during the FAT. A screw in the tee used to move one of the locking segments into position became stuck due to debris lodged within the neck of the tee from the hot tap and Stopple Train deployments (this was confirmed upon checks post-FAT). The Lock-O-Ring Plus plug was deployed successfully. No leakage was measured upstream of the plug over a 30-minute period, demonstrating 100% isolation.

All personnel and equipment used as part of hot tapping, flow stopping and plugging trials were utilised for the live trial to ensure familiarity with the process.

3.6.3.7 Live Trial Hot Works

The LTS Futures live trial hot works were completed successfully in July and August 2025. Two phases were undertaken – application of welded fittings and subsequent hot tap, flow-stopping and plugging operations and application of a grouted fitting and subsequent hot tap, flow-stopping and plugging operations.

3.6.3.7.1 Phase 1 – Welded Fittings

The live trial hot works site had a requirement to be as close to the Granton flare site as possible to minimise the volume of hydrogen flaring required for the stopple train deployment and evaluation. A site on Dalmeny Estate was as close to the pipeline termination point as possible without encompassing challenging gradients and pipe material that had not been used for welding qualification[1].

The site underwent initial checks and surveys including:

- Q/10 [59] sampling and testing to confirm suitable pipe chemistry for welding. See Figure 45.
- 10-metre slit trench along pipeline length to check for GWs.
- Environmental surveys (including archaeological watching brief during excavation).
- Survey, mapping and depth of cover checks on other high-pressure pipelines in the vicinity.
- Survey for suitable site access points, potential contraflow routes, overhead barriers/cables. See Figure 46.
- Calculations to determine suitable pipeline crossing types for HGVs and cranage on-site.
- Landowner engagement to notify of proposed works and consider access requirements for livestock.

Following these initial surveys, a full site design process was completed. The site design was typical of a temporary works site and included:

- Site welfare.
- Trackway matting to reduce site impact and provide safe pipeline crossing points.
- Excavation with suitable access, egress, drainage, base material and pipe supports.
- Hazardous area assessment for excavation post-hot tap and specified venting area.
- Flame and leak detection instrumentation (hydrogen-specific requirement).
- Security measures (Heras fencing and CCTV).
- Designated lifting area.

[1] The Grangemouth to Granton pipeline consisted of two distinct X52, 18" pipe materials – Pipe A (9.52 mm WT, SMLS) and Pipe B (6.35 mm WT, HSAW). Pipe A extended for several km from the Granton end of the pipeline. All welding, grouting, hot tapping, flow stopping and plugging qualifications were completed on Pipe B.

Figure 45: Q/10 Survey.

Figure 46: Access survey.

Figure 47: Excavation works.

Figure 48: Excavation after completion of NDT.

An excavation was opened to accommodate the works to be completed. This considered the requirements of P/9 [49] clearance, the need for multiple fittings (a split tee and two set-on fittings are required for stopple train deployment) and the horizontal orientation of the tapping. This led to a larger excavation being required, approximately 5 m by 12 m.

Along the length of the exposed pipeline, the coating was removed, and the surface was shotblasted. Before arrival of the TDW, NDT, magnetic particle inspection (MPI) and ultrasonic testing (UT) was completed to ensure the area of the pipe designated for works was suitable. The desired position of the fittings was mapped to ensure subsequent NDT was completed on the areas (and additional tolerances) where welding would take place. No indications were reported in the parent material or seam weld. As the pipe material was Helical Submerged Arc Welded (HSAW), interaction of the split tee with the seam weld was unavoidable. One of the set-on fittings was offset slightly from top dead centre, as allowed within the qualified welding procedure, to ensure that the welding was at least 100 mm away from the spiral seam weld. Visual and dimensional inspection was completed around the entire circumference of the pipe. See Figure 48.

Upon arrival at site, the TDW examined the pipe and completed repeat UT and MPI in accordance with their procedures. See Figure 49. No indications were noted. The seam weld areas that interacted with the fitting and subsequent fitting girth weld were dressed, and NDT was repeated to ensure no indications had been introduced. The tee was lifted into position and adjustments were made to ensure an appropriate, consistent tee stand-off distance from the pipe.

Figure 49: MPI on fitting area.

Figure 50: Longitudinal seam welding.

Figure 51: Circumferential welding.

Figure 52: Set-on fitting welding.

The live welding operations were then completed over the course of four days. See Figures 50-52. The flow conditions within the trial provided some limitations which were planned for in advance. Only welds that were to be deposited directly onto the pipe (the circumferential welds and set-on fitting welds) were to be completed under flowing conditions. The longitudinal seam welds which were deposited onto backing bars were completed under static conditions. The flow in the pipeline was controlled to meet a constant velocity of 1.1 m/s, which aligned within the qualified velocity range. As the supply flow rate into the pipeline could not match the demand flow rate required for this velocity, welding took place over a pipeline pressure range of 16 to 10 barg while maintaining a constant velocity within the pipeline. The split tee, two set-on fittings and a retention coupon were successfully welded onto the pipeline under live hydrogen conditions. See Figure 53. NDT was completed upon cooling of the welds with no indications reported.

Figure 53: Split tee and set-on fittings successfully welded onto a live hydrogen pipeline.

Hot tapping was completed of all fittings under static conditions at a line pressure of 20 barg. A common vent stack was used for all venting operations. The hose and vent stack were purged with nitrogen before and after any venting of hydrogen to prevent the formation of a flammable mixture in the vent stack or connecting hose.

To facilitate the use of the Lock-O-Ring Plus, the same adaptor spool as used during the FAT was bolted to the welded tee. The hydraulic sandwich valve was then bolted to the adaptor spool. Measurements for the hot tap, stopple-train and plugging process were taken, and when positioned, a dry run check was carried out to ensure the machine travelled without issues and measurements were accurate. See Figure 55.

Figure 54: SGN, TDW, PIE and ROSEN welding team.

Figure 55: Fitting the tapping machine to the sandwich valve.

Figure 56: Hot tapping of the split tee.

Figure 57: Hot tapping of set-on-fittings.

The assembly was then purged with nitrogen and pressurised with a helium-nitrogen blend to 24 barg. A 15-minute stabilisation period was completed, followed by a 30-minute leak test. Leakage was monitored using pressure gauges on the assembly with zero permissible pressure drop. Once completed, the sandwich valve was closed and the upstream spool assembly vented to 1 barg. The test was repeated to demonstrate no leakage from the sandwich valve.

Upon a successful completion of the leak checks, the hot-tapping process proceeded with technicians monitoring vibration and adjusting cutting speed when appropriate. See Figures 56 and 57. Once complete, the cutting head was retracted and sandwich valve closed. The tapping machine was then vented to a lower pressure and sandwich valve monitored for leakage. Once the test was complete, the assembly was vented and purged with nitrogen prior to being removed.

The set-on fittings were hot-tapped through a similar procedure successfully. However, overnight leakage through one of the sandwich valves was noted after tapping (the valve was plugged, so leakage was into a purged cavity). The valve was regreased and further leak checks were completed to demonstrate it could seal. The second sandwich valve was regreased prior to use and did not have any let-by.

Figure 58: Stopple train deployment attempt.

An attempt to deploy the Stopple-Train was then undertaken. The stopple train was fitted to the sandwich valve, see Figure 58, purged with nitrogen and then pressurised with a helium-nitrogen mixture to complete a leakage check. The stopple head was activated but could not be moved fully into the pipeline. Repeated attempts were made by technicians, but the deployment was ultimately abandoned. Upon leakage check, purge and removal of the tool, it was noted that a holding pin for a guide wheel on the Stopple-Train head was bent. In-field, it was noted that this may have been due to the wheel catching on the spiral seam weld of the pipeline as the tool was deployed; however, pre-works NDT confirmed that there was no excessive internal seam weld cap.

The final operational stage was plugging the two set-on fittings and split tee. The standard and Lock-o-Ring Plus plugs were planned for the split tee and associated adapter spool. The plugging operations were completed under static gas conditions. The standard plug on the split tee was deployed first. The tapping machine was bolted to the spool assembly, purged to nitrogen, pressurised with a helium-nitrogen mix and a leakage check performed. Upon a successful leakage check, the plug was positioned and set by activating the segments externally on the tee. The tapping machine was then depressurised through a 2" handwheel valve piped to the vent stack. The plug did not seal and setting could not be re-attempted as a segment jammed and could not be deactivated (likely due to swarf in the tee).

Figure 59: Split tee final blank.

The sandwich valve was closed and purging/leakage checks completed before removal of the tapping machine. The Lock-o-Ring Plus plug was attached to the tapping machine and the tool redeployed. Following purging and leakage checks, the plug was advanced and set in position. The tapping machine was then depressurised through a 2" handwheel valve piped to the vent stack. A 30-minute leakage test was then completed with no pressure increase upstream of the Lock-o-Ring Plus plug demonstrating 100% isolation. A blank flange was fitted to the adaptor spool, marking the end of the split tee operations. See Figure 59.

The set-on fittings were subsequently plugged successfully using the same purge and leakage procedure and standard (threaded) plugs. Blank flanges were bolted to the fittings marking the end of Phase 1 of the operations. See Figure 60.

3.6.3.7.2 Phase 2 – Grouted Fitting

Following completion of the welded tee works, the excavation was extended to facilitate the installation of a horizontal grouted tee and complete another hot-tapping, flow-stopping (using the BISEP tool) and plugging operation. Significant testing and a full FAT were undertaken by STATS and are detailed within NIA2_SGN00036.

Figure 60: Set-on fitting final blank.

Figure 61: Grouted tee install.

Figure 62: Hot tapping of grouted tee.

After the excavation extension was completed, the coating was removed and surface shot-blasted to SA 2.5. Visual and dimensional inspection was completed around the entire circumference of the pipe. MPI and UT were completed over the entire pipe surface where the grouted tee would be located. No indications were reported in the parent material or seam weld, demonstrating the area of pipe was suitable for the subsequent operation.

The grouted tee was installed by DNV in accordance with the SGN procedure developed in 3.6.3.2 (noting that this procedure is almost identical to the current grouted tee installation procedure). A helium-nitrogen blend was used as a leak check medium for the collar and the grout once cured.

A sandwich valve (termed branch isolation valve) was then bolted to the horizontal split tee. This sandwich valve included a 'swarf trap' (a machined recess), which would capture swarf in the lower area of the valve where material has the potential to interfere with sealing capability. Measurements for the hot tap, BISEP and plugging process were taken. The tapping machine was bolted to the valve assembly, purged to nitrogen, pressurised with a helium-nitrogen mix and a leakage check performed. After a successful leakage check, the sandwich valve was opened and the cutter advanced. The hot tapping was successful, with no excess vibration noted by technicians throughout the process.

The tapping machine was removed from the tee following venting, purging and sandwich valve leakage checks. A separate tool termed the 'Swarf Management Tool' (SMT) was then prepared for deployment. The SMT consisted of a collection of small-diameter stainless steel nozzles, which could connect to an external nitrogen source and be used to 'blow' the swarf away from the planned BISEP deployment location. The nozzles were contained within a tool similar to a tapping machine. The nozzles could be moved horizontally within the pipeline.

Measurements for the SMT were taken and it was connected to a nitrogen bottle pack. The tool was lifted into position, and purging and leakage checks were completed pre-deployment. The tool was advanced and the nozzle system successfully deployed into the pipe. A series of movements of the SMT within the pipe while blowing nitrogen was completed. The head was retracted and the tool removed from the pipeline following purging and leakage checks.

Figure 63: Swarf management tool head.

Figure 64: Swarf management tool.

Figure 65: BISEP flow stopping tool.

The BISEP flow stop tool was then prepared for deployment. The BISEP is a single head that includes two sealing elements, which are hydraulically actuated to provide a mechanical seal. The annulus between the two seals can be vented through the tool itself, and no external set-on fittings are required. The BISEP was positioned on the grouted tee and leak checks completed. The sandwich valve was opened and the tool was deployed successfully into the pipe. The sealing elements were energised to create the seal, and the annulus between these was vented. The void space was monitored for pressure rise for 15 minutes. No increase in pressure was recorded, and the hold time was extended to a further 15 minutes. The BISEP achieved a 100% seal in hydrogen, demonstrating that flow stopping can be carried out in hydrogen.

The BISEP seals were released and the head retracted. The final step was the installation of the completion plug. This was the standard plug procured for the tee. Purging and leak checking of the assembly were completed and the plug was successfully deployed. The branch isolation valve was then removed, and a blind flange was installed to complete the operation.

3.7 Materials

The LTS Futures project has completed a significant volume of testing to generate baseline knowledge for the development of ongoing industry standards including IGEM/TD/1 Edition 6 Supplement 2 [10] and IGEM/TD/13 Edition 3 Supplement 1 [18]. The material properties, such as strength, ductility, and toughness, of pipeline steel are key characteristics that affect how a pipeline responds to applied loads and its tolerance to defects. The LTS Futures project has completed small and full-scale tests on vintage LTS material in inert, non-aggressive environments (such as air or water) and in hydrogen gas, to provide comparative data and to quantify the effect of hydrogen.

3.7.1 Project Material

Three pipes designated Pipe A, B and C from the UK LTS have been tested. See Table 14. Pipes A and B were taken from the Grangemouth to Granton pipeline used during the live trial. Pipe C was redundant material resulting from a diversion of the Newton Longville to Crockmore (P069) pipeline.

From each pipe, the mechanical properties and microstructure of the Parent Material (PM), Girth Weld (GW) and Seam Weld (SW) were characterised in air. Characterisation testing included:

- **Optical emission spectroscopy** to determine the chemical composition of the parent and weld material. This allowed comparison to contemporaneous API 5L standards [60][61][62], to IGEM/TD/1 Edition 6 Supplement 2 Carbon Equivalent (CE) limits [10], and identification of any constituents above specification.
- **Vickers hardness surveys** on cross-sections of material containing PM/SW and PM/GW. This provided a measure of hardness in the through-thickness direction (i.e. from root to cap in the weld) and the axial/circumferential direction, including the HAZ of the parent material. The results provided a range of hardness values for the material, which could be used to correlate with material mechanical properties in hydrogen.
- **Charpy V-notch impact testing** to provide an indication of toughness in air and to determine the ductile-to-brittle transition temperature.
- **Transverse strip tensile testing** on PM and weld metal (WM) from each pipe to determine the tensile strength, yield strength, and percentage elongation. The average results were compared with contemporaneous API 5L standards [60][61][62].
- **High-power light microscopy** to identify different microstructures, inclusions, and other features within the material. The results can be used to support any findings regarding the effect of hydrogen on mechanical properties.

The characterisation testing provided a fingerprint for each material. It confirmed that the materials were as expected for their vintage. The testing also provided information for calculating full-scale test predicted failure values and correlations with material properties in hydrogen.

3.7.2 Strength and Ductility

High-pressure, gaseous hydrogen is known to marginally reduce the yield and tensile strength of pipeline steel and significantly reduce its ductility. The yield strength and tensile strength of pipeline material are required for several design calculations including defining a pipeline's MOP, and for pipeline defect assessments. The ductility of pipeline material is required for inputs into external loading resistance calculations and for certain pipeline defect assessments. The effect of hydrogen on these properties needs to be quantified.

Strength and ductility can be measured through small-scale tensile testing. The effect hydrogen has on these properties can be quantified through comparative testing with specimens in an environment representative of natural gas, such as air. Material strength is calculated directly from test data. Ductility can be described using the elongation of material directly measured during or after the test, or measurement of the Reduction in Area (RA) of the specimen cross-section after completion of the test. The loading rate during a tensile test will affect the result and is therefore controlled at a standardized, pre-determined rate. It has been proposed that, when testing gaseous hydrogen, a slower loading rate is required to ensure that there is sufficient time in the test for hydrogen to have an effect on the results. LTS Futures has therefore completed tensile tests at standard and slower rates of testing to demonstrate such effects. Slower rate tests are typically called Slow Strain Rate Tensile (SSRT) tests.

Table 14: Pipeline material details.

Pipe	Diameter (mm)	Wall Thickness (mm)	Grade	Type of Pipe	Commissioning Date
A	457.2	9.52	X52	Seamless	1977
B	457.2	6.35	X52	Helical Spiral Welded	1977
C	609.6	11.91	X52	Seam Welded	1969

When pipeline material is exposed to a load above its elastic limit, strain-hardening occurs. This results in a stronger but less ductile material. If a pipeline is subject to damage in service (e.g. external interference), a localized strain-hardened region may be present. This reduction in ductility, coupled with that from exposure to high-pressure gaseous hydrogen, might result in a greater effect on the material properties, compared to material that has not been pre-strained. LTS Futures has completed additional SSRT tests on pre-strained material to assess this.

Round-bar tensile tests (at standard rates of testing), SSRT and pre-strained SSRT tests were completed in air and in hydrogen on specimens taken from the PM of Pipe A, and the PM, SW, and GW of Pipes B and C. See Figure 66. The nominal strain rate was 0.00025 s^{-1} in the tensile tests, and 0.00001 s^{-1} in the slow strain rate tests (i.e. approximately 25 times slower). Testing in air was completed in accordance with BS EN ISO 6892-1 [63], and testing in hydrogen was completed following the principles of test preparation of ASTM G142-98 [64] but using guidance from BS EN ISO 6892-1 [63] for standard rate tests. Pre-straining was completed on material in air to a nominal 6 % before testing. Hydrogen tests were completed in high-purity gaseous hydrogen (99.99996%) at pressures equal to 94.2, 64.6, and 96.0 barg for Pipe A, B, and C respectively. Test pressures were equal to the design pressure for a design factor equal to 0.72, as defined in IGEM/TD/1 Edition 6 [6] for each pipe.

Figure 66: Setup of round bar tensile test in hydrogen.

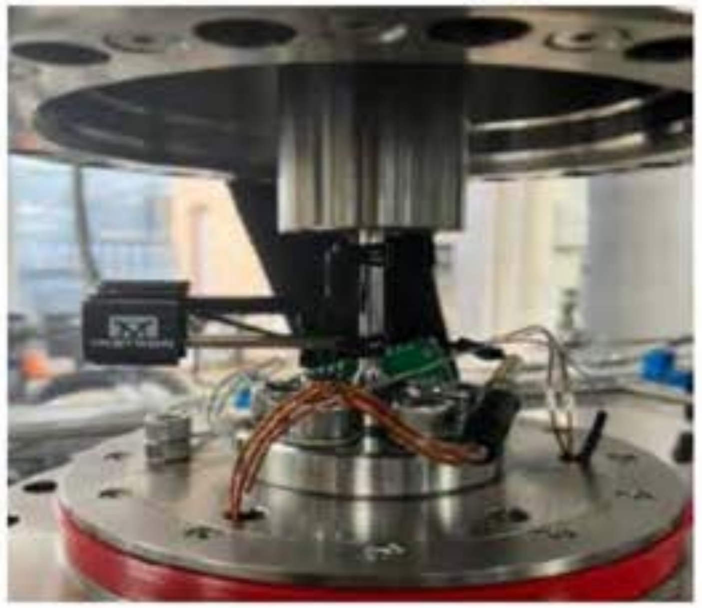


Figure 67: Round bar tensile test and SSRT test tensile strength results.

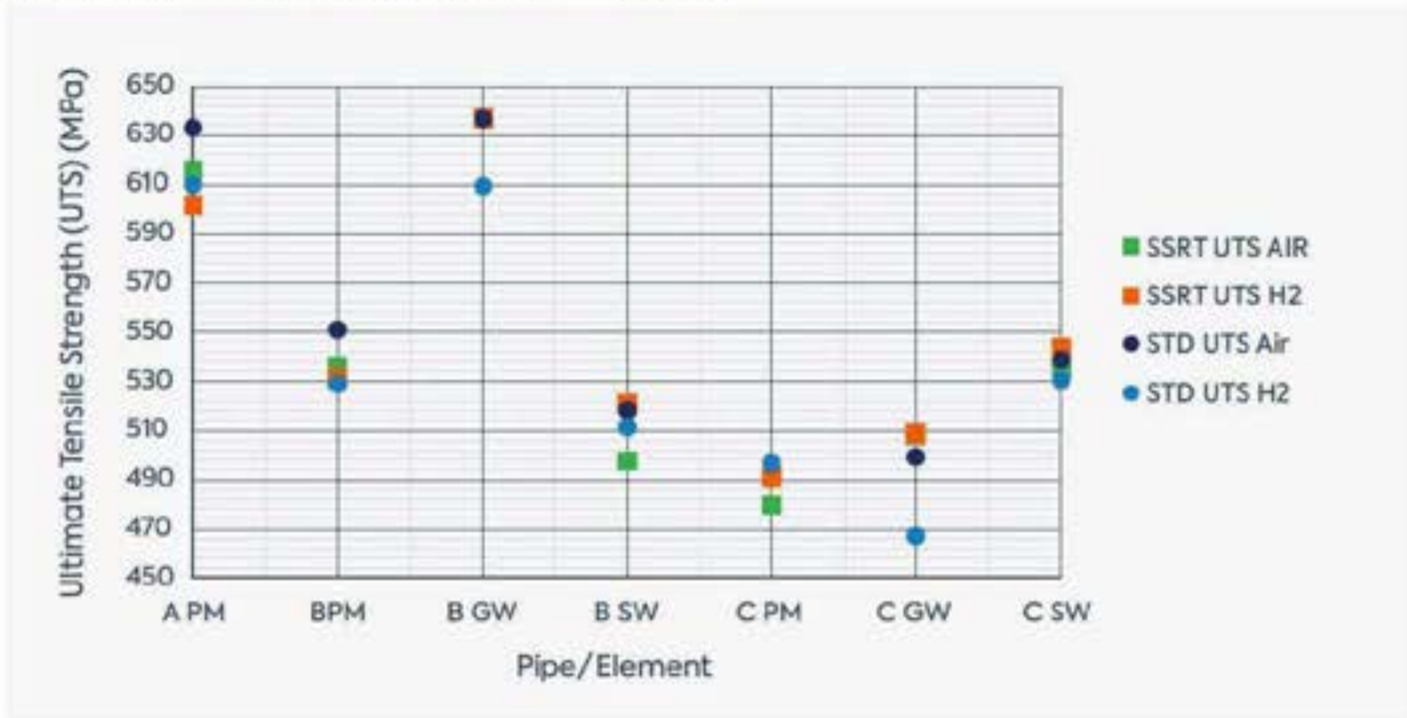


Figure 68: Round bar tensile test and SSRT test yield strength results.

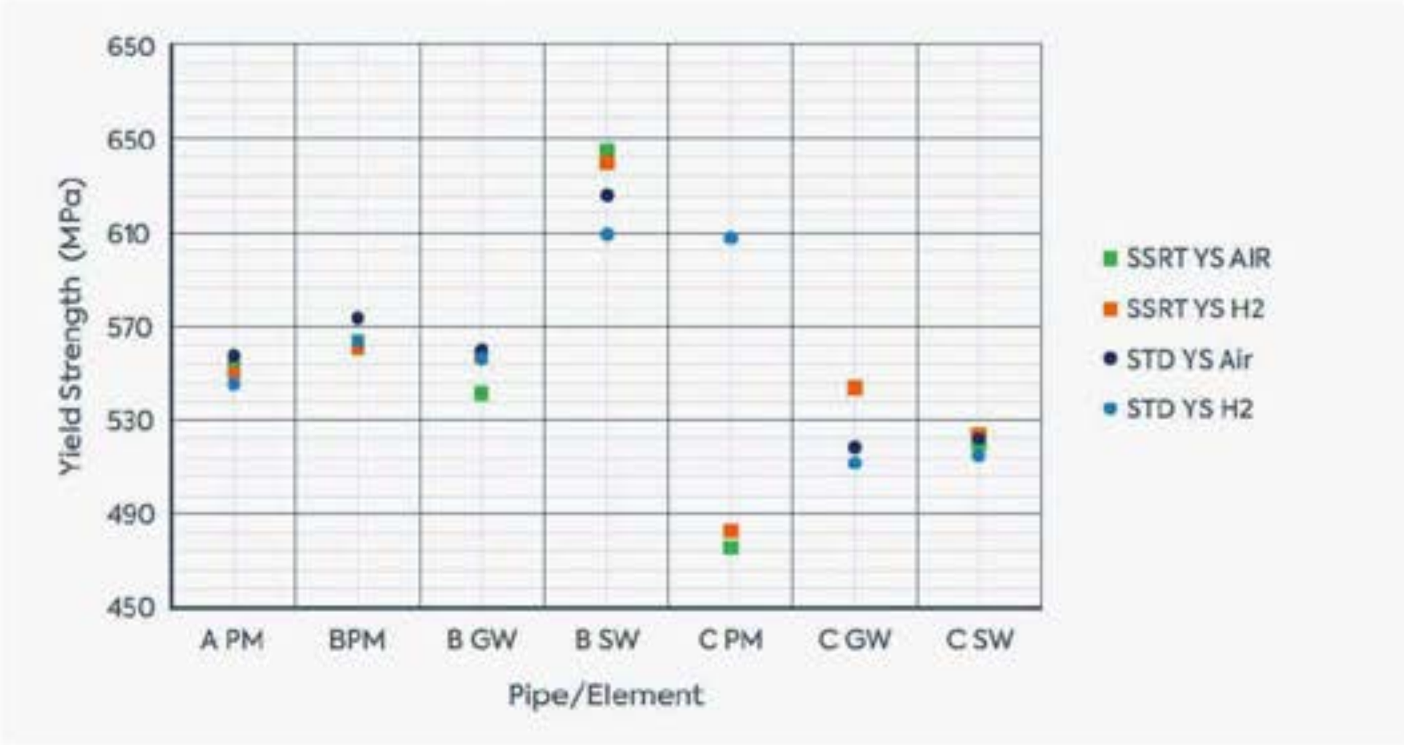
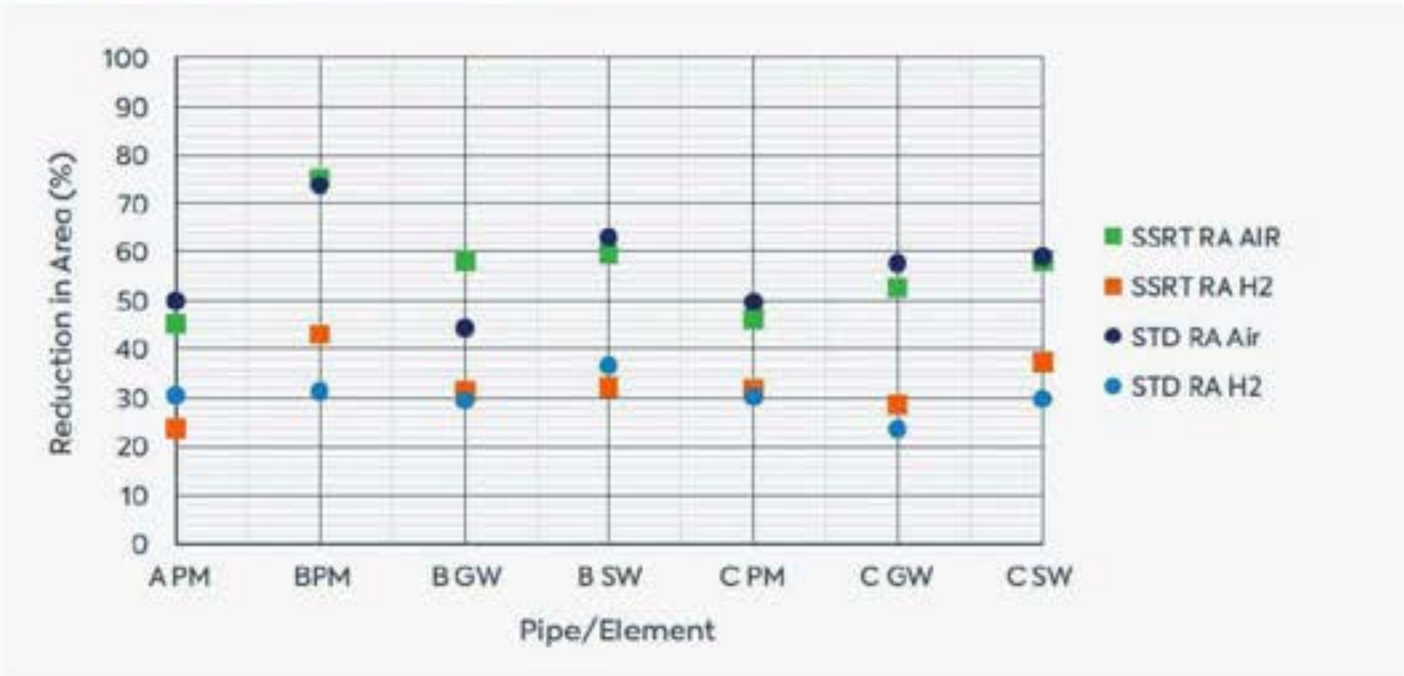


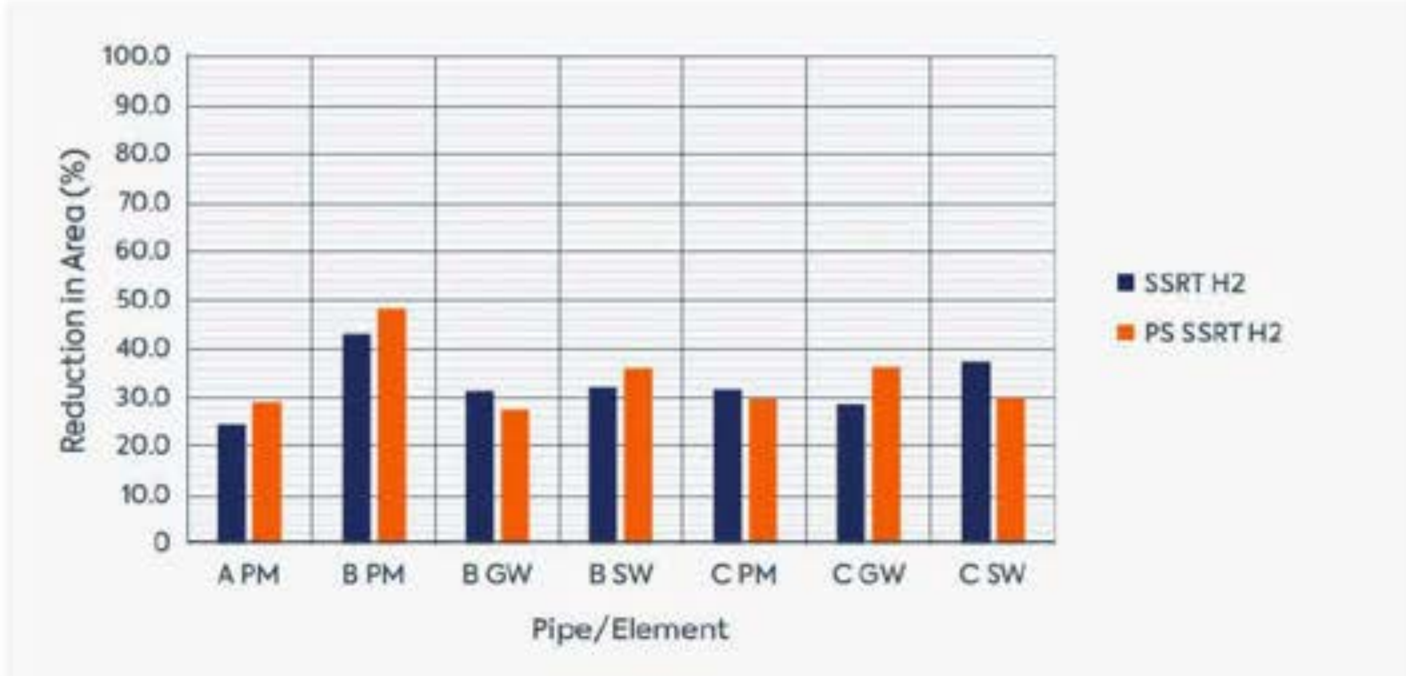
Figure 69: Round bar tensile test and SSRT test RA results.



The tensile and SSRT tests on Pipes A, B, and C in air and in hydrogen demonstrated that exposure to hydrogen resulted in a small (or no) decrease in the yield and tensile strength, and a large reduction in the ductility. See Figure 67 to Figure 69. The results of the tensile and SSRT tests are similar, indicating that a tensile test, conducted at conventional strain rates, is sufficient to illustrate the effects of hydrogen on the tensile properties.

SSRT tests on pre-strained material did not show any increased reduction in ductility compared to SSRT tests on material that had not been pre-strained.

Figure 70: SSRT Results (pre-strained vs no pre-strain).



The small reduction in yield and tensile strength will have little effect on any design calculations. The effect of exposure to gaseous hydrogen on the ductility will need to be considered for assessment of certain defects. The data generated within the LTS Futures project is considered to be representative of pipelines of similar vintage and grade. See Figure 70.

3.7.3 Fracture

The fracture toughness of a material quantifies its resistance to crack propagation. High-pressure gaseous hydrogen is known to reduce the fracture toughness of pipeline steels. To qualify a pipeline steel for hydrogen in a laboratory, IGEM/TD/1 Edition 6 Supplement 2 [10] requires fracture toughness testing in high-pressure gaseous hydrogen. A fracture toughness value is also required for QRAs and fracture mechanics assessments.

Different types of fracture toughness tests can be undertaken depending on the required outputs. IGEM/TD/1 Edition 6 Supplement 2 [10] references constant load/displacement or rising load/displacement tests. These tests can be used to define the threshold stress intensity factor for hydrogen-assisted cracking (K_{IH}), crack initiation toughness (J or K_J) or tearing resistance, depending on the specific details of the test. The LTS Futures project has looked to quantify the effect of hydrogen on fracture toughness for LTS pipeline material and welds through constant load K_{IH} and rising displacement J-R curve tests.

3.7.3.1 K_{IH} Tests

Constant load K_{IH} tests were conducted in hydrogen on compact tension specimens taken from the PM and GW of Pipe A, and the PM, GW and SW of Pipes B and C. See Figure 71. Specimens were notched in the through-thickness direction and fatigue pre-cracked to the required starting crack length in air. The test holds a specimen at a constant load for 1,000 hours in hydrogen. A target constant load corresponding to an applied K of 55 MPa.m$^{-0.5}$ was used for the hold period. This target value was chosen to align with minimum qualification criteria set by ASME B31.12 Option B [8]. Tests were completed in high-purity gaseous hydrogen (99.9999 %) at pressures equal to 94.2, 64.6, and 96.0 barg for Pipe A, B, and C respectively. Test pressures were equal to the design pressure for a design factor equal to 0.72, as defined in IGEM/TD/1 Edition 6 [6] for each pipe. Post-test, Scanning Electron Microscopy (SEM) of the fracture face was conducted to visually determine whether crack extension occurred during the test in hydrogen.

The results of the tests on Pipes A, B, and C are summarised below. The nature of the test is that the result is a 'pass' or 'fail', so it is only possible to define a range of values. It should be noted that specimens were too small (because of the thickness of the pipe) to meet the code requirements for small-scale yielding. The applied value of the K will have been greater than the calculated value, given below, because the calculation assumes small-scale yielding. The calculated value is the elastic component. It does not include the plastic component.

Pipe A

K_{IH} is greater than or equal to 55.5 $MPa.m^{-0.5}$.
[The minimum valid value was recorded in a test on the girth weld.]

Pipe B

K_{IH} is greater than or equal to 48.0 $MPa.m^{-0.5}$, and less than 56.0 $MPa.m^{-0.5}$. [The minimum valid value was recorded in a test on the girth weld. A test on a girth weld failed during loading, at the higher value. Evidence of hydrogen-assisted cracking was identified.]

Pipe C

K_{IH} is greater than or equal to 45.7 $MPa.m^{-0.5}$ (or, possibly, 53.0 $MPa.m^{-0.5}$). [The minimum valid value was recorded in a test on the girth weld. All three tests on the pipe body failed at a lower value during loading. No evidence of hydrogen-assisted cracking was identified in the tests on the pipe body, so it is plausible that the failures were simply due to overloading the specimens and were not significantly affected by hydrogen.]

Figure 71: K_{IH} test setup.

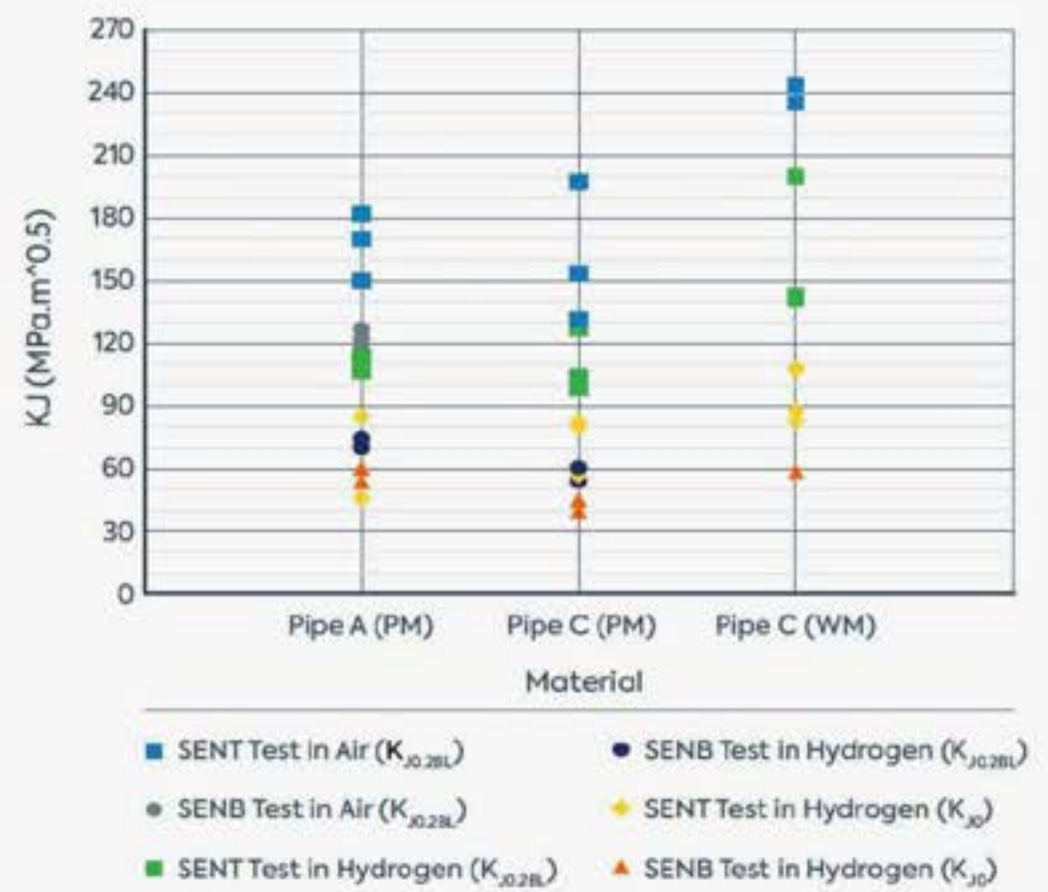
3.7.3.2 Rising Displacement J-R Curve Tests

Rising displacement J-R curve tests have been completed in air and hydrogen on Single Edge Notched Tension (SENT) and Single Edge Notched Bend (SENB) specimens taken from the PM and GW of Pipe A, and the PM, GW, and SW of Pipe C. SENB specimens are a high-constraint specimen that would be expected to produce a more conservative (lower) fracture toughness value in air relative to the low-constraint SENT specimens. The project aimed to investigate whether this effect was apparent in hydrogen and to evaluate which specimen type produced fracture toughness values similar to that calculated from the full-scale tests.

Tests in air were completed in accordance with BS EN ISO 12135 [65] for PM and BS EN ISO 15653 [66] for WM. Tests in hydrogen followed guidance provided in ANSI/CSA CHMC 1 and by EPRG (in lieu of an official test standard) [67] [68] (European Pipeline Research Group, 2024) and were completed in high-purity gaseous hydrogen (99.99996%) at pressures equal to 94.2 and 96.0 barg for Pipes A and C. Test pressures were equal to the design pressure for a design factor equal to 0.72, as defined in IGEM/TD/1 Edition 6 [6] for each pipe. Specimens were notched in the through-thickness direction and fatigue pre-cracked in air to the target starting crack length (approximately $a_0/W=0.5$). Testing in air was completed using both the unloading compliance method, whereby the sample Crack Mouth Opening Displacement (CMOD) is measured using clip gauges and the crack growth is measured indirectly through the change in sample stiffness, and the Direct Current Potential Drop (DCPD) method, whereby DCPD is used to directly measure crack growth. Testing in hydrogen utilised only the DCPD method. Tests in hydrogen were completed at a nominally slow initial K-rate of 0.005 $N/mm^{3/2}/s$ to ensure saturation of the crack-tip fracture-process zone with atomic hydrogen.

Following test completion, specimens were moved to liquid nitrogen, fractured and examined under microscope. Fracture faces were evaluated and crack lengths measured to determine if DCPD predictions were correct. The DCPD data was adjusted if predictions did not match the final measured crack length. Data from the tests was post-processed and tearing resistance curves produced to determine the initiation toughness values of $J_{0.2BL}$ and J_0 (the values of the J-integral at 0.2 and 0 mm of crack growth, adjusted for blunting, respectively), and the tearing resistance. The equivalent fracture toughness values expressed in terms of the stress intensity factor, $K_{J0.2BL}$ and K_{J0}, were subsequently determined. The measured $K_{J0.2BL}$ and K_{J0} in hydrogen and $K_{J0.2BL}$ in air for each material are shown in Figure 72. Only results for $K_{J0.2BL}$ in air are shown. K_{J0} would not be a valid measurement of fracture toughness in air, because crack-tip blunting and other non-crack-growth-related mechanical effects occur within this region of the test.

Figure 72: SENB and SENT test results in hydrogen.



The results demonstrate a significantly lower $K_{J0.2BL}$ in hydrogen compared to that in air for both specimen types and different materials tested. The values of K_{J0} are all, by definition, lower than those of $K_{J0.2BL}$.

The data continues to be generated within this programme and can be used to inform future updates to IGEM/TD/1 Edition 6 Supplement 2 [10] and fracture mechanics assessments for repurposing pipelines to hydrogen.

3.7.4 Fatigue

High-pressure gaseous hydrogen is known to affect the fatigue properties of pipeline steels. This includes an increase in the Fatigue Crack Growth Rate (FCGR) and reduction in the fatigue life. The LTS Futures project has looked to quantify this reduction for LTS pipeline material and welds through small- and full-scale tests. Small-scale fatigue tests include FCGR and fatigue endurance tests in air and in hydrogen. The fatigue life of defects, new connections, and set-on fittings in hydrogen has also been investigated through full-scale tests.

A simplified method (non-fracture mechanics approach) to calculate the fatigue life of a pipeline is provided in IGEM/TD/1 Edition 6 [6]. This approach may be used if a pipeline has been hydrostatically tested to a suitable pressure, constructed using suitably qualified materials, and will not experience pressure cycling above a minimum stress range. Cycles below a threshold stress range do not require inclusion in the calculation.

IGEM/TD/1 Edition 6 Supplement 2 [10] permits the same approach to be used; however, it has a factor-of-ten reduction on fatigue life compared to that in IGEM/TD/1 Edition 6 [6], as shown in Figure 73 on the following page. It also requires inclusion of all fatigue cycles in hydrogen no matter the stress range.

IGEM/TD/1/Edition 6 [6] requires a detailed fracture mechanics calculation to determine the fatigue life where the simplified method is not appropriate (e.g., for a pipeline that has had a lower pressure hydrotest) or where it is required to assess the fatigue life of defects detected in service. BS 7910 [69] provides recommended methods for the calculation. IGEM/TD/1 Edition 6 Supplement 2 [10] provides a recommended FCGR law for pipeline steel in hydrogen for use in the calculation.

The simplified and detailed approaches in Supplement 2 have not been derived based on LTS or NTS material testing in hydrogen. To provide input for future updates to IGEM/TD/1 Supplement 2 [10], the LTS Futures project carried out fatigue endurance and crack growth rate tests in hydrogen and air to provide empirical data.

3.7.4.1 Endurance Tests

Figure 73: IGEM TD/1 SN curves.

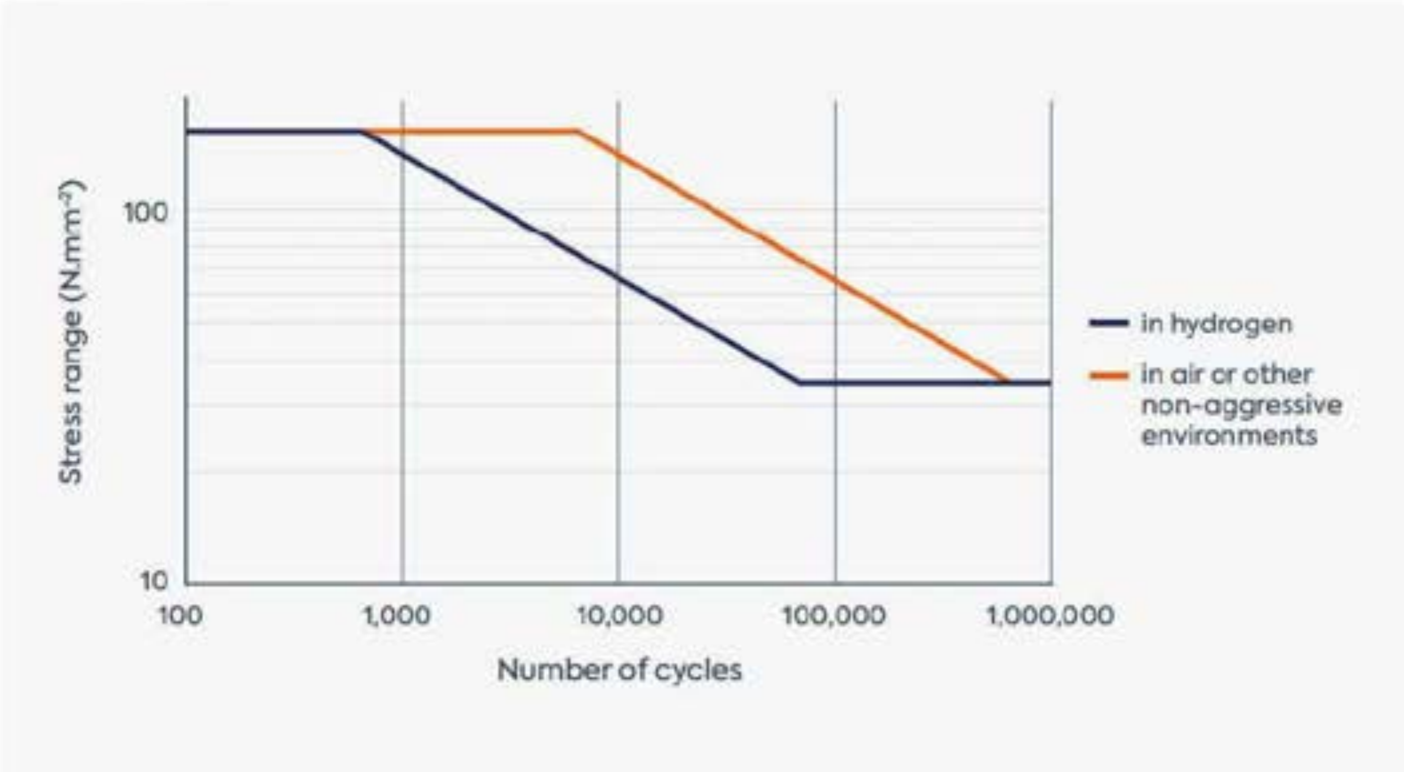
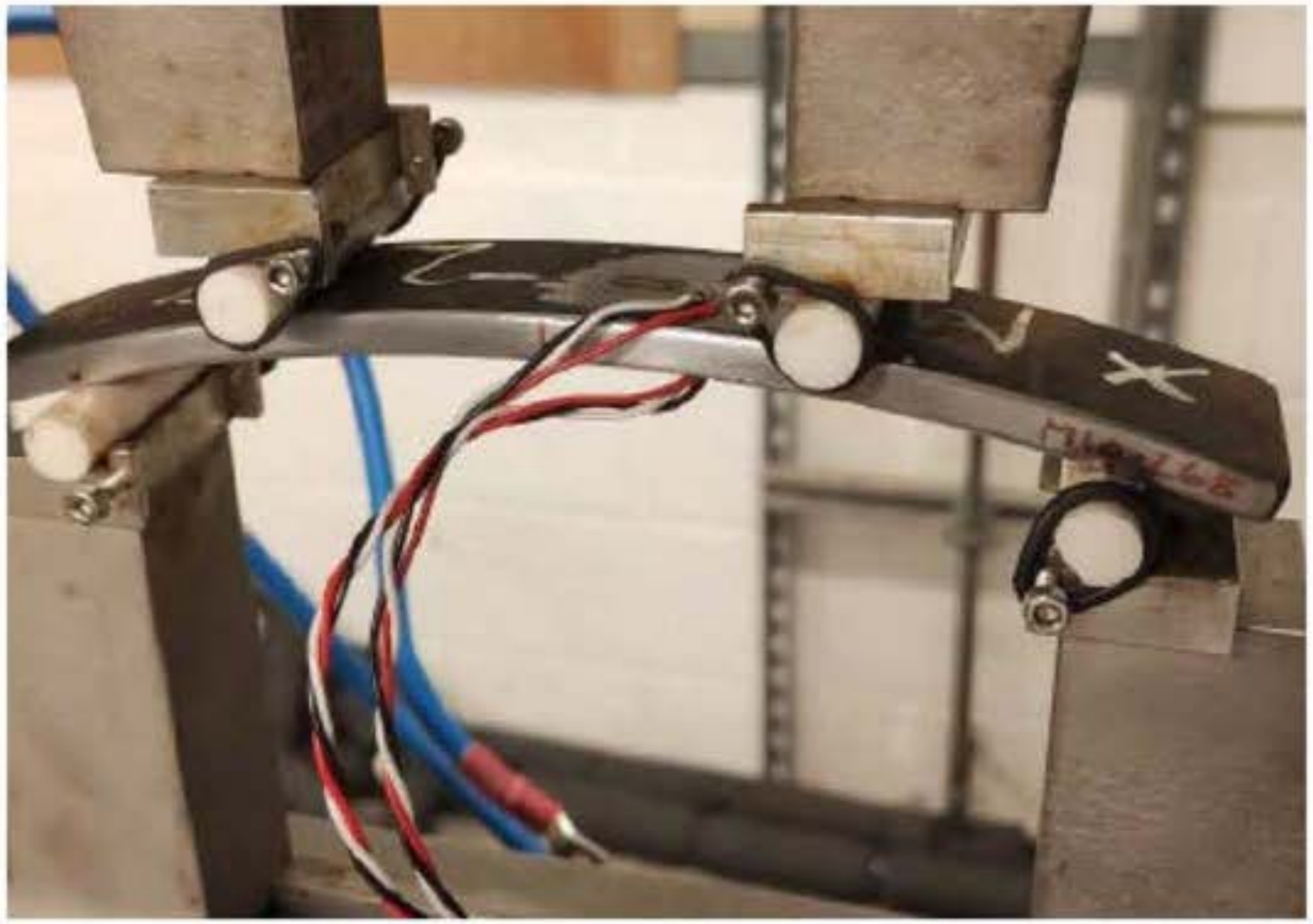


Figure 74: Fatigue endurance test in air.

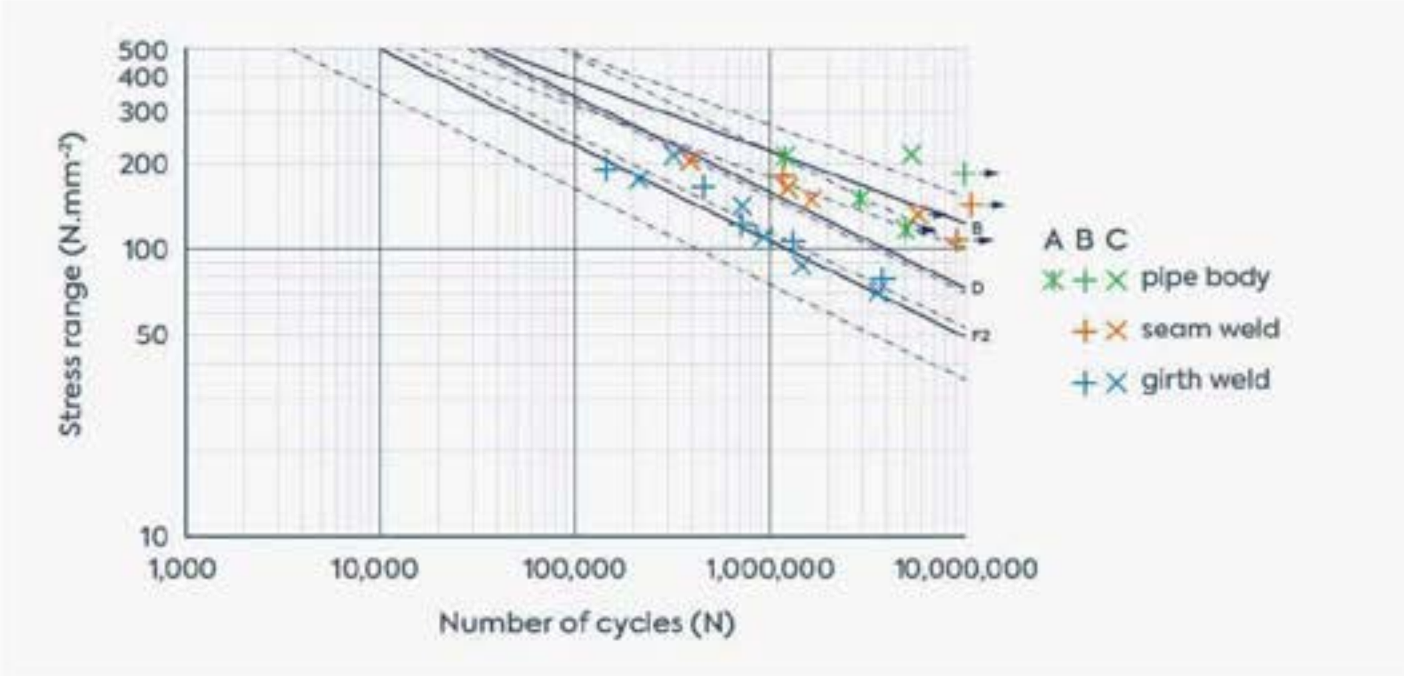


Fatigue tests were carried out using four-point bend specimens as shown in Figure 74. Tests were completed on PM of Pipe A and the PM, SW, and GW of Pipes B and C. Transverse specimens were taken from the pipe body and the seam weld (so, the spiral weld was at an angle). Longitudinal specimens were taken from the girth weld. The weld cap in the specimens taken from the seam weld and girth weld was ground smooth. Hydrogen tests were completed in high-purity gaseous hydrogen (99.9999%) at pressures equal to 94.2, 64.6, and 96.0 barg for Pipes A, B, and C respectively. Test pressures were equal to the design pressure for a design factor equal to 0.72, as defined in IGEM/TD/1 Edition 6 [6]for each pipe. Air tests were completed at a loading frequency of 2 – 6 Hz and all hydrogen tests completed at 1 Hz. Stress ranges were chosen to give three or four sets of data for each material and depending on test results and run-outs.

The endurance test results would be expected to be consistent with S-N curves in Table 18 of BS 7608 [70]. Different S-N curves within BS 7608 exist for different structural classifications. For example, PM can be nominally class B, SW material nominally class D, and GW material nominally class E, F, or F2.

Twenty-three endurance tests across all three pipes were completed in air with results shown in Figure 75. The results were compared with the basic (mean) and standard design (mean minus two standard deviation) S-N curves from BS 7608 [70]. PM tests were (qualitatively) consistent with Class B, SW tests were (qualitatively) consistent with Class D, and GW tests were (qualitatively) consistent with Class E, F, or F2.

Figure 75: Fatigue endurance test results in air.



Fifty-five endurance tests across all three pipes were completed in gaseous hydrogen with results shown in Figure 76. The results have been compared with the basic (mean) and standard design (mean minus two standard deviation) S-N curves from BS 7608 [70].

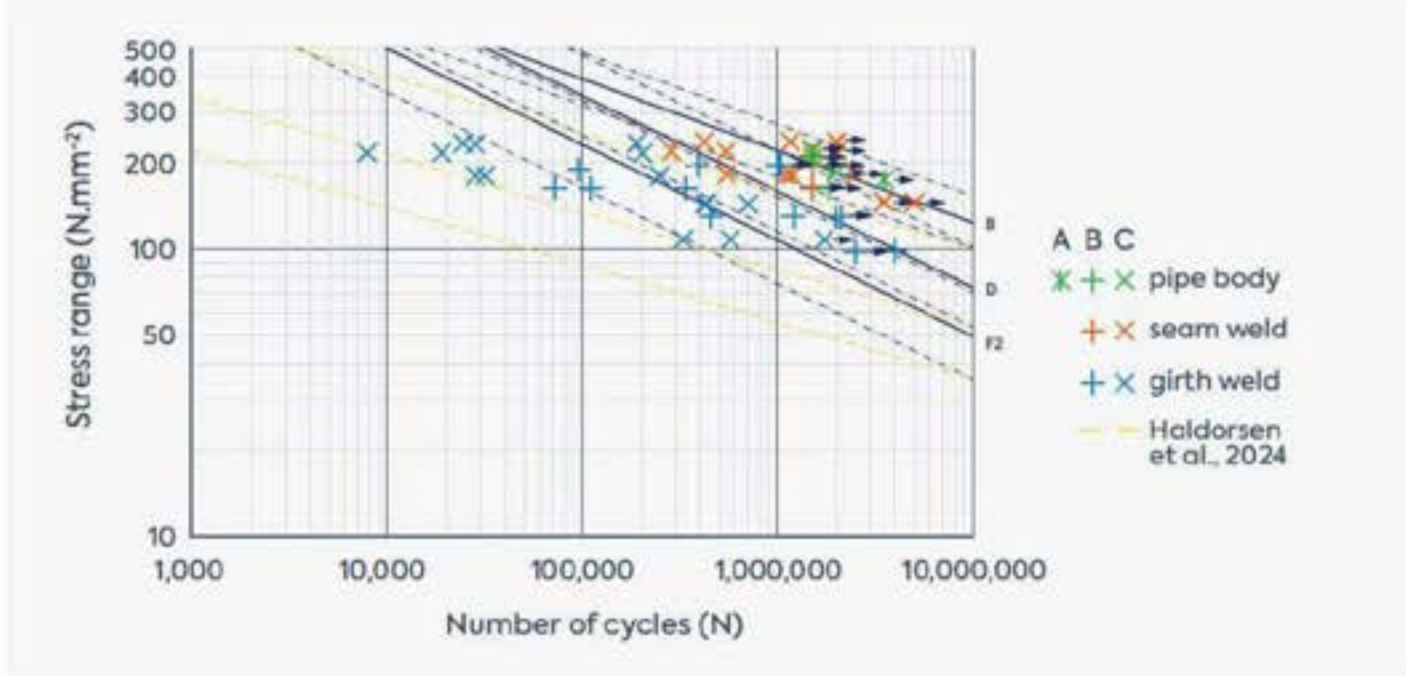
The results of the endurance tests in hydrogen on the girth welds of Pipes B and C show a significant reduction in the fatigue strength. The reduction increases as the stress range increases. The results also show (very) significant scatter (greater than an order of magnitude). The behaviour of the girth welds in Pipes B and C is similar. The results of the tests on the seam weld show a small reduction, albeit the scatter is (again) significant. The results of the tests on the pipe body of Pipes A, B, and C are inconclusive because all of the (limited number of) tests were run-outs. The results imply that the fatigue strength in hydrogen is very dependent on when (if) a fatigue crack initiates.

Haldorsen et al. (2024) [71] propose a modification to the design Sr-N curves to account for the effect of a hydrogen environment. The design Sr-N curves for steels in hydrogen are based on the curves for steels in sea water with CP. The curves in hydrogen are an extrapolation of the transition in the curves for steels in sea water with CP between 106 and 107 cycles. The curves intersect with the in-air curves at 10^7 cycles. The inverse slope of the log Sr-log N curves is equal to 5.0. The penalty on the fatigue life in air increases as the stress range increases.

Clause S7.11.2 in IGEM/TD/13 Edition 2 Supplement 1 [9] applies a penalty (a factor) on the fatigue life equal to fifty (50) to the S-N curves given in IGEM/TD/12 Edition 3 [72].

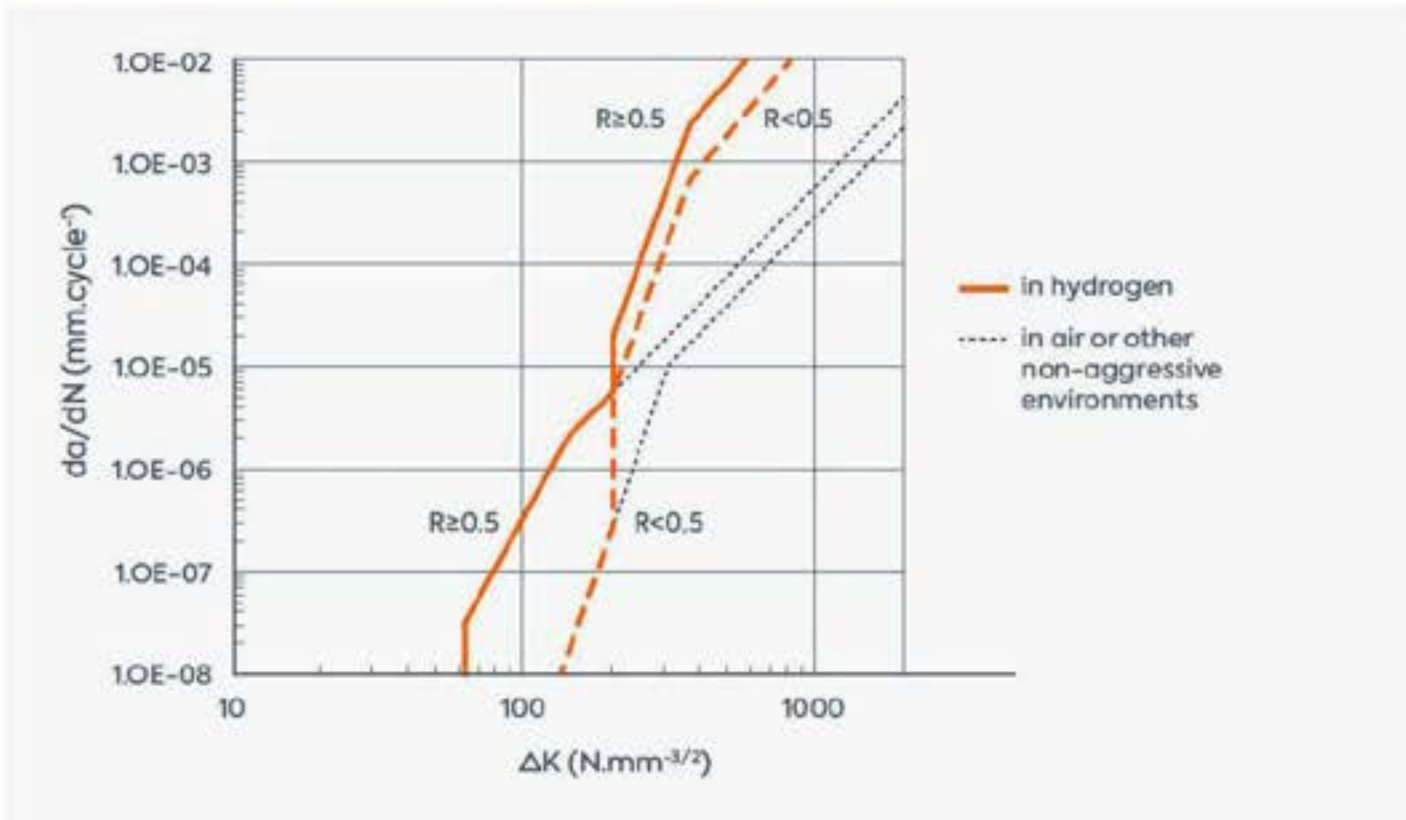
The results of the endurance tests in hydrogen on the pipe body, and the seam and girth welds of Pipes A, B, and C, see Figure 76, are (qualitatively) consistent with, or at least conservatively described by, the modified classes B, D, and F2, respectively. A penalty of fifty (50) is also conservative.

Figure 76: Fatigue Endurance Test Results in Hydrogen compared with Haldorsen et al. 2024



3.7.4.2 FCGR Tests

Figure 77: TD/1 Edition 6 supplement 2 FCGR law in hydrogen and BS7910 FCGR law.



FCGR tests were completed using three-point bend apparatus in air and in hydrogen on the PM of Pipe A and the PM, WM, and HAZ of the SW and GW of Pipes B and C, as shown in Figure 77. Specimens were notched in the through-thickness direction and pre-cracked in air. Hydrogen tests were completed in high-purity gaseous hydrogen (99.9999 %) at pressures equal to 94.2, 64.6, and 96.0 barg for Pipes A, B, and C respectively. Test pressures were equal to the design pressure for a design factor equal to 0.72, as defined in IGEM/TD/1 Edition 6 [6] for each pipe. Air FCGR tests were completed at a loading frequency of 1 Hz and increasing ΔK. Hydrogen FCGR tests were completed at a loading frequency of 0.1 – 1 Hz and increasing or decreasing ΔK. Frequency scanning tests in hydrogen were also completed where ΔK was fixed and the frequency decreased from 1 Hz to 0.001 or 0.0001 Hz.

Air test results were compared to the mean and mean plus two standard deviations fatigue crack growth laws for steels for R < 0.5 and R ≥ 0.5 given in Table 8.3 of BS 7910 as shown in Figure 79. The results on Pipes A, B, and C were consistent with the fatigue crack growth law for R ≥ 0.5.

Figure 78: FCGR Test in Air

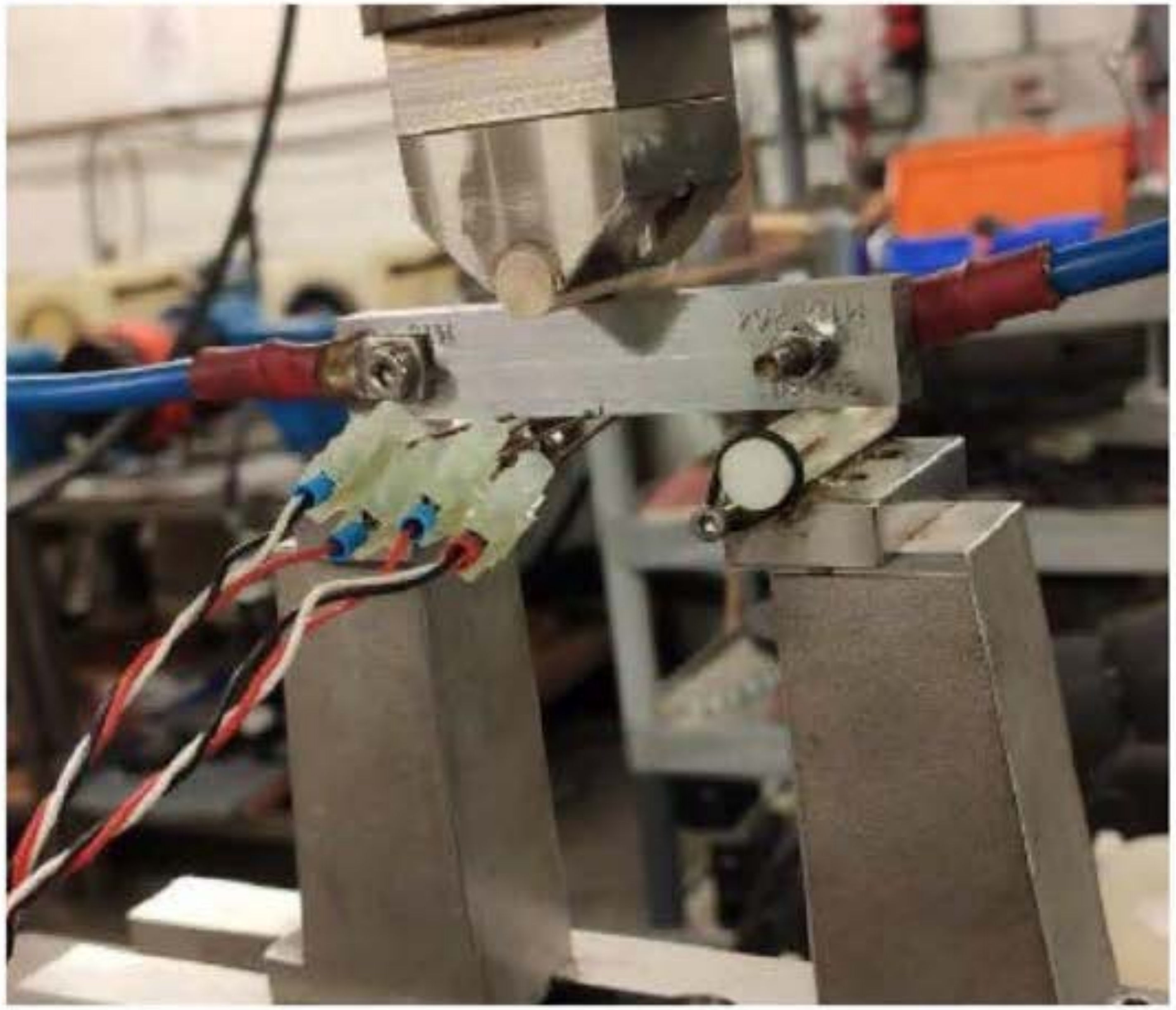
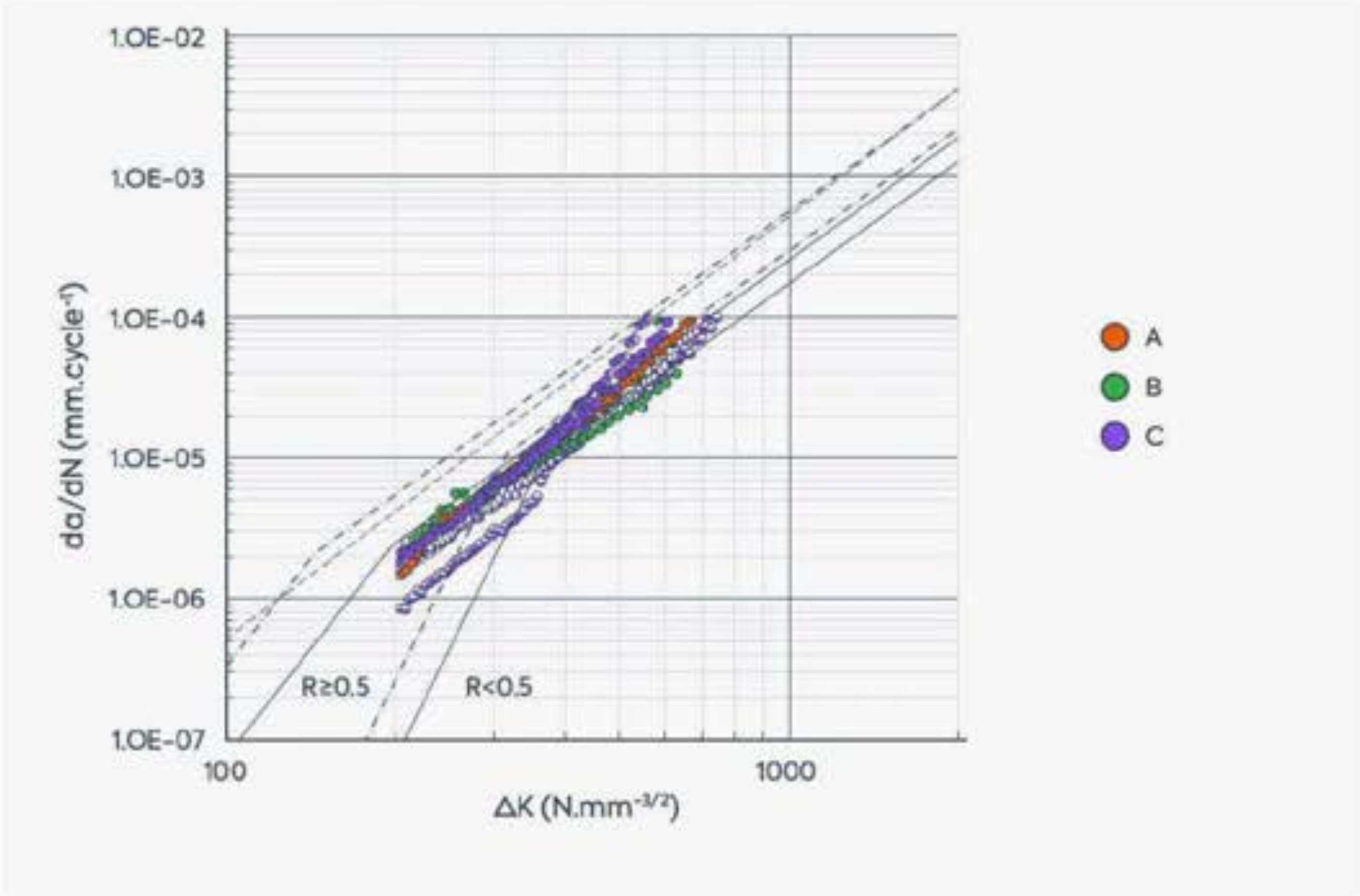


Figure 79: FCGR test results in air.



Hydrogen test results were compared with the recommended fatigue crack growth laws for steels in hydrogen service as shown in Figure 80. The fatigue crack growth law in IGEM/TD/1 Edition 6 Supplement 2 [10] is conservative with respect to the results of the FCGR tests in hydrogen.

The results of the FCGR tests in hydrogen on Pipes A, B, and C show a significant increase in the rate of fatigue crack growth. The growth rate is similar to that in air at lower ΔK, but then the rate and the difference increase at higher ΔK. See Figure 80. There is no significant difference between the rates observed in the pipe body and/or the seam weld and girth weld of Pipes A, B, and C (albeit the scatter in hydrogen is higher than that in air).

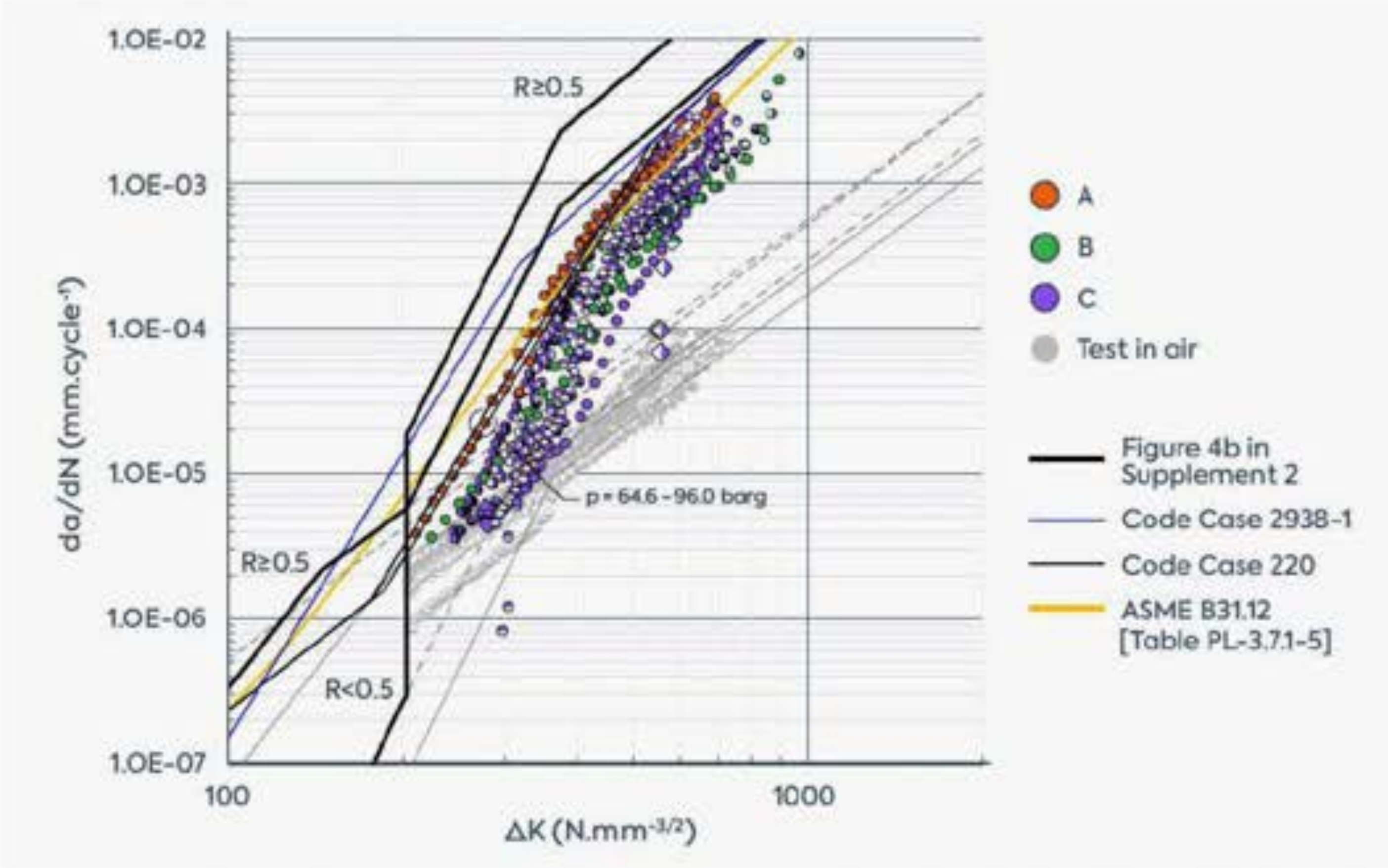
Table PL 3.7.1-5 in PL-3.7.1(b)(2)(-a)(-4) of ASME B31.12 [8] defines a fatigue crack growth law for steels in hydrogen service. It is only applicable for R < 0.5.

The code case for ASME BPVC.CC.BPV-2023, Code Case 2938-1 [73], and the similar code case for ASME B31.12-2023, Code Case 220 [8], also define fatigue crack growth laws for steels in hydrogen service. The effect of R is included in the growth laws. Code Case 2938-1 is bi-linear. Code Case 220 is tri-linear. It also includes the effect of the pressure of the hydrogen. The growth laws are identical at high ΔK.

Table S2 and Figure S4b in Clause S6.6.2.3 of IGEM/TD/1 Edition 6 Supplement 2 [10] define recommended fatigue crack growth laws for steels in hydrogen service for R < 0.5 and R ≥ 0.5.

The results of the fatigue crack growth tests in hydrogen on the pipe body, and the seam and girth welds of Pipes A, B, and C, see Figure 80, are (qualitatively) consistent with the fatigue crack growth laws given in ASME B31.12 and in Code Case 220 [8]. However, the observed rate is, in some cases, slightly higher than the predicted rate. The FCGR results generated within LTS Futures will be provided and incorporated into future updates to IGEM/TD/1 Edition 6 Supplement 2 [10].

Figure 80: FCGR test results in hydrogen.



3.8 Defects

Pipeline defects on the LTS are assessed in accordance with GN/PM/P/11 [74]. The assessment criteria in GN/PM/P/11 provides a classification for defects that has been calculated using various empirical or semi-empirical criteria e.g., the corrosion and gouges are assessed using the semi-empirical NG-18 equations [75]. The NG-18 equations were developed using fracture mechanics theory and full-scale experiments. The limits for plain dents and for dents and gouge were similarly developed using full-scale experiments. These experimental programmes provided an understanding of real-world material and mechanical effects which were not captured by the theoretical approaches.

Simplified assessment methods for defects on hydrogen pipelines have not yet been developed. IGEM/TD/1 Edition 6 Supplement 2 [10] requires all existing pipeline defects to be confirmed to be acceptable for hydrogen service through detailed technical assessments.

Small-scale tests in hydrogen demonstrate an effect on the material properties of line pipe steels. The technical assessments need to address these effects using empirical, semi-empirical, or theoretical criteria. Similarly to the development of the NG-18 equations, full-scale tests are required to ensure any assessments consider real-world material and mechanical effects. To support the development of future hydrogen pipeline defect assessment methodologies and detailed technical assessments, the LTS Futures project has completed initial full-scale burst and fatigue tests on pipeline defects in water and in hydrogen. Burst tests provided a failure pressure for defects in hydrogen and fatigue tests an indicative fatigue life for defects in hydrogen. The burst and fatigue tests were completed using Pipe C, providing material continuity throughout the testing programme. Pipe C is Grade X52. It was a nominal diameter of 609.6 mm (24 in.) and a nominal WT of 11.91 mm. It was taken from an LTS pipeline that had been commissioned in 1969.

External corrosion and mechanical damage are the two main causes of faults in the United Kingdom Onshore Pipeline Operators' Association (UKOPA) Pipeline Fault Database [76], and two of the three main causes of product loss incidents (the other being girth weld defects). Therefore, the defects tested in the burst and fatigue tests were: external, blunt, part-though-wall defects, representing external corrosion; external, sharp, part-though-wall defects, plain dents, and dents containing a sharp, part-though-wall defect, representing mechanical damage; and lengths of pipe containing the original girth and seam welds, with and without dents, reflective of typical features.

3.8.1 Burst Tests on Pipeline Defects

Initially within the LTS Futures Project scope, five full-scale burst tests in hydrogen and four in water were completed. Following these initial tests, an additional three full-scale tests in hydrogen and two in water were completed within NIA2_SGN070: Burst testing of internal sharp defect in hydrogen – conditioning investigation. Tests were conducted on nominally identical pairs of vessels containing nominally identical defects in hydrogen and water to investigate the effect of hydrogen on the burst strength of pipeline defects. See Figure 81. Reference tests in water provided a representative control for natural gas without the additional hazards of flammable gas and significant stored energy.

Five different types of defects were tested in the initial LTS Futures Project, with the subsequent NIA2_SGN070 project focusing on internal sharp defects, with two different depths, and vessel conditioning. Table 15 and Table 16, on the following page, display the defect type and dimensions across the two projects.

The sharp and blunt defects were orientated longitudinally. Defects in the original project were sized based on previous natural gas burst test programmes.

Figure 81: Burst test vessel pre-test.

Table 15: LTS Futures project defect dimensions.

Defect	Depth (mm)	Length (mm)	Width (mm)
Plain Dent	61	n/a	n/a
External Blunt	7.5	132	34.9
External Sharp	7.5	132	0.15
External Dent and Gouge	3.8 (Gouge) 15.0 (Depth)	132	0.15
Internal Sharp	7.5	132	0.15

Table 16: NIA2_SGN070 defect dimensions.

Defect	Depth (mm)	Length (mm)	Width (mm)
Internal Sharp – 1	7.5	132	0.15
Internal Sharp – 2	7.5	132	0.15
Internal Sharp – 3	3.8	132	0.15

Prior to testing, all hydrogen vessels were purged to and subsequently conditioned with hydrogen. Full conditioning regimes for the tests are displayed in Table 17 and Table 18. At the start of the conditioning period for hydrogen vessels, defects were heated to accelerate hydrogen permeation into the pipeline steel and/or break down any passivation layer (caused by prior exposure to oxygen in the atmosphere). The oxide/passivation layer has been noted as a potential inhibitor to hydrogen permeation and resultant degradation of material properties. The inhibition effect is likely (although not fully proven) to be time dependent and eventually hydrogen will permeate into the ferritic microstructure. Understanding the effect of hydrogen on the steel material without such a barrier is therefore critical to long-term integrity management.

Table 17: LTS Futures project burst test conditioning.

Defect	Conditioning
Plain Dent	Nominal 20 barg/120 °C for 5 days Nominal 20 barg/ambient temperature for 98 days Nominal 0.5 barg/ambient temperature for 6 days
External Blunt	Nominal 20 barg/120 °C for 5 days Nominal 20 barg/ambient temperature for 98 days Nominal 0.5 barg/ambient temperature for 12 days
External Sharp	Nominal 20 barg/120 °C for 5 days Nominal 20 barg/ambient temperature for 98 days Nominal 0.5 barg/ambient temperature for 8 days
External Dent and Gouge	Nominal 20 barg/120 °C for 5 days Nominal 20 barg/ambient temperature for 98 days Nominal 0.5 barg/ambient temperature for 7 days
Internal Sharp	Nominal 20 barg/120 °C for 5 days Nominal 20 barg/ambient temperature for 98 days Nominal 0.5 barg/ambient temperature for 9 days

Table 18: NIA2_SGN070 burst test conditioning.

Defect	Conditioning
Internal Sharp – 1	No conditioning
Internal Sharp – 2	Nominal 20 barg/150 °C for 4 days Nominal 20 barg/ambient temperature for 89 days Nominal 0.5 barg/ambient temperature for 126 days
Internal Sharp – 3	Nominal 20 barg/150 °C for 4 days Nominal 20 barg/ambient temperature for 89 days Nominal 0.5 barg/ambient temperature for 128 days

Following conditioning, tests for both water and hydrogen vessels were completed at a pressurisation rate of 0.5 – 1.0 bar per minute until failure. The results are summarised in Table 19 and Table 20.

The failure pressures of the external blunt and sharp part-through-wall defects, plain dents and smooth dents, and gouges (notches) in hydrogen and in water were similar.

The failure pressure of the internal sharp part-through-wall defect in hydrogen within the LTS Futures Project was significantly lower than that of the external sharp part-through-wall defect in hydrogen and in water. It was approximately 40.1% of that of the external defect in hydrogen and 41.9% of that of the external defect in water. The failure pressures of the internal, sharp, part-through-wall defects in hydrogen and in water were similar within NIA2_SGN070.

Table 19: LTS Futures burst test results.

Defect	Hydrostatic test result	Hydrogen test result
Plain Dent	166 barg (118% SMYS)	166 barg (118% SMYS)
External Blunt	142 barg (101% SMYS)	149 barg (106% SMYS)
External Sharp	112 barg (80% SMYS)	118 barg (84% SMYS)
External Dent and Gouge	108 barg (77% SMYS)	111 barg (79% SMYS)
Internal Sharp	No test carried out	47 barg (33% SMYS)

% SMYS calculated using nominal WT (11.91 mm) and OD (609.6 mm).

Table 20: NIA2_SGN070 burst test results.

Defect	Hydrostatic test result	Hydrogen test result
Internal Sharp – 1	121 barg (85% SMYS)	120 barg (85% SMYS)
Internal Sharp – 2		122 barg (86% SMYS)
Internal Sharp – 3	155 barg (110% SMYS)	160 barg (114% SMYS)

% SMYS calculated using nominal WT (11.91 mm) and OD (609.6 mm).

The external defect results do not align with the reduction in fracture toughness of Pipe C PM observed during small-scale tests. No significant effect of hydrogen on the burst pressure of these defects was observed. The effect of hydrogen on the burst pressure of external pipeline defects might not be significant, because the defect is not directly exposed to the hydrogen; however, further testing would be required to confirm this initial set of results. PRCI project JEFI-04-08 [77] is also undertaking burst tests on external defects in hydrogen, which should provide further useful data.

The initial internal sharp defect result aligns with the reduction in fracture toughness of Pipe C PM observed during small-scale tests in hydrogen. The subsequent internal sharp defect test results do not align with the initial sharp defect test result or the observed reduction in fracture toughness of Pipe C PM. The disparity between results in the initial and subsequent tests is potentially a result of conditioning regime differences. Further tests have been scheduled under NIA2_SGN0111 to investigate this.

3.8.2 Fatigue Tests on Pipeline Defects

Full-scale fatigue tests were conducted on a nominally identical pair of vessels containing nominally identical defects in hydrogen and water to investigate the effect of hydrogen on the fatigue life of pipeline defects.

As with the burst tests, a reference test in water provided representative control results for natural gas without the additional hazards of flammable gas and significant stored energy. Multiple defects were introduced on one vessel for each test medium, as the tests take significantly longer to complete compared to burst tests.

Five different types of defects were tested in hydrogen and four in water. A vintage girth and seam weld were also tested. Table 21 displays the defect type and dimensions across the two projects. Defects were located in the pipe parent metal (PM), seam weld (SW), and girth weld (GW).

Figure 82: Fatigue test vessel pre-test.

Table 21: LTS Futures project defect dimensions.

Defect	Nominal defect size
Plain Dent	Depth at zero pressure = 30 mm
Dents on Girth and Seam Weld	Depth at zero pressure = 15 mm
External Sharp	Depth = 3.8 mm, length = 66 mm, width = 0.15 mm
Internal Sharp	Depth = 3.8 mm, length = 66 mm, width = 0.15 mm

Sharp defects were orientated longitudinally. Defects were sized based on previous natural gas fatigue test programmes.

Prior to testing, the hydrogen vessel was purged to and subsequently conditioned with hydrogen. This consisted of a nominal 20 barg/120 °C for 5 days and nominal 20 barg/ambient temperature for 98 days. At the start of the conditioning period for hydrogen vessels, defects were heated to accelerate hydrogen permeation into the pipeline steel and/or break down any passivation layer.

For both vessels, a water/monoethylene glycol (MEG) mixture was pumped in and out of the vessel to create a pressure cycle. The hydrogen vessel contained an inner vessel with slots at the top and an outer annulus of hydrogen in contact with the inner surface of the pipe wall. This allowed a water/MEG mixture to be pumped in and out of the inner vessel, pressurising the annulus of hydrogen. This approach was taken to limit the hydrogen inventory in the rig and accelerate the cycle time over a purely pneumatic vessel. A layer of oil was added to the water in the inner vessel, to reduce the diffusion of hydrogen into the water and water into the hydrogen.

Both vessels were instrumented with strain gauges at key locations and a clip gauge on the external sharp defect to measure any crack growth over time. The hydrogen vessel was also instrumented with a Time of Flight (ToF) sensor to measure any crack growth from the internal sharp defect as part of NIA2_SGN0065.

Periodic stoppages occurred with the vessels due to test-site restrictions and significant maintenance requirements.

The hydrostatic vessel has been cycled between a nominal 50.5 and 101 barg (36 % and 72 % SMYS) for 113,200 cycles. Three failures in the vessel occurred at:

- 101,858 cycles – seam weld (the failure was potentially related to contact with support resulting in a local stress concentration).
- 111,500 cycles – seam weld dent.
- 113,200 cycles – girth weld dent.

3.9 Fittings

3.9.1 Set-on Fittings

Set-on fittings are small-bore, welded connections to pipelines and installations to connect instrumentation, sampling, and commissioning pipework. Vibration of the connections can be caused by flow of gas within the pipe, creating a mechanical fatigue loading on the connection. High-pressure gaseous hydrogen is known to affect the fatigue properties of pipeline material and welds. The LTS Futures project looked to complete a series of vibration tests on a selection of set-on fittings to understand the effect of hydrogen on the fatigue life of the connections.

Eleven set-on fittings ranging from one- to two-inch nominal bore were welded to a vessel fabricated using Pipe C PM. See Figure 83. Fitting types included sockolets, weldolets, threadolets, and weldoflanges, all installed in a vertical orientation. The BS 7608 [70] design class and constant amplitude fatigue limit is provided in Table 22. Each connection was fitted with a short section of pipework and terminated with a blind flange. A vibration motor was mounted on the end of each connection. Strain gauges were installed around each weld location to monitor strain response.

The vessel was partially filled with deoxygenated (less than 0.1 % mol) water to minimise hydrogen volume during the test. The vessel was purged and conditioned with hydrogen and heat for approximately three months at a pressure of 20 barg.

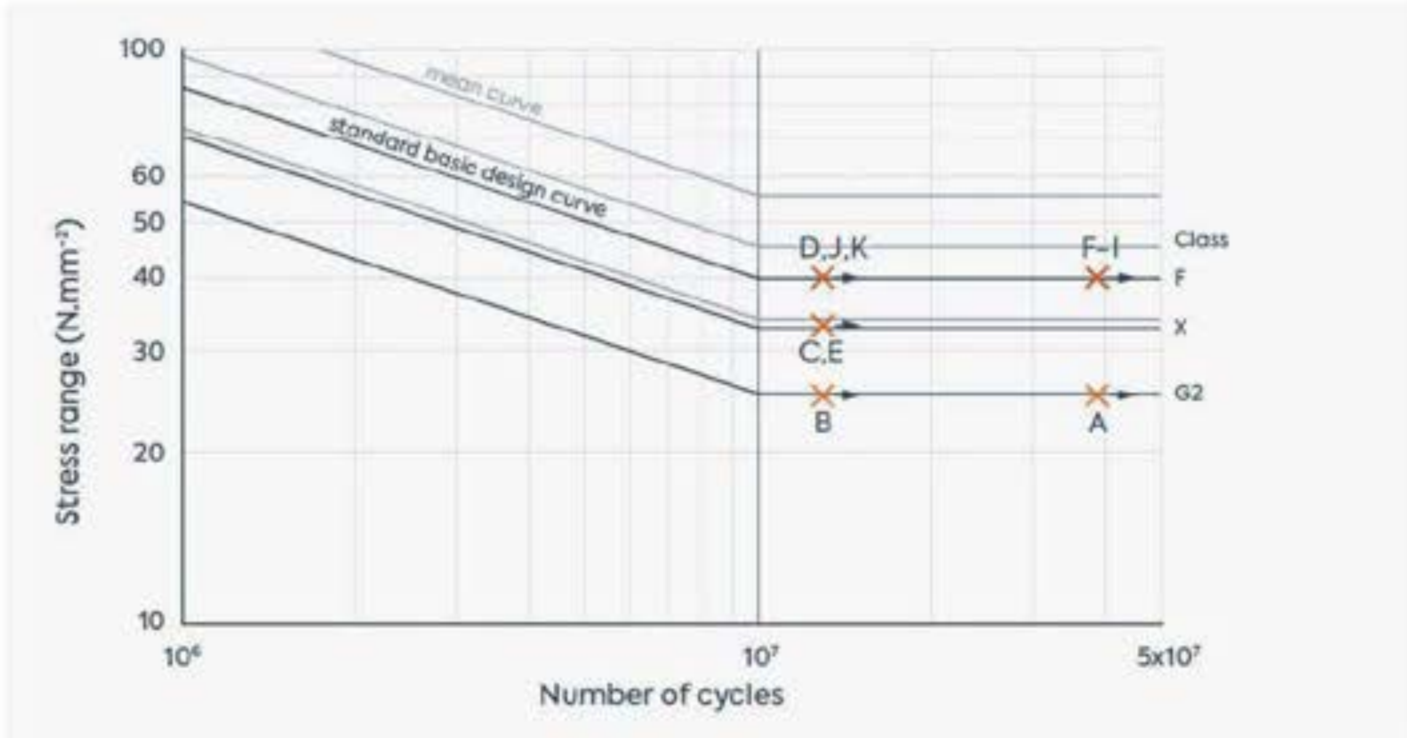
Figure 83: Set-on fitting fatigue vessel.

Table 22: Set-on fittings.

Identification	Fitting	Length of pipework (m)	Attachment to pipework	Class	S_{oc}, N.mm^{-2}
A	1" Sockolet	0.4	Raised face weld neck flange and blind flange.	G2	25
B	2" Sockolet	0.4		G2	25
C	1" Threadolet	0.4		X	33
D	1" Weldolet	0.05		F	40
E	2" Threadolet	0.4		X	33
F	1" Weldolet	0.4		F	40
G	1.5" Weldolet	0.4		F	40
H	1" Weldolet	0.4		F	40
I	1" Weldolet	0.4		F	40
J	2" Weldoflange	-	Blind flange.	F	40
K	2" Weldoflange	-	Integral flanged valve and impulse pipework.	F	40

Following conditioning, fatigue testing was completed at a stress range approximately equal to the constant amplitude fatigue limit of the connection. Connections were tested either individually or in grouped configurations to prevent any interaction effects. Each connection was subjected to a minimum of approximately 1×10^7 fatigue cycles with five connections achieving approximately 4×10^7 cycles.

Figure 84: Set-on fitting S-N curve.



Post-test visual and MPI was completed on the external surfaces of the connections. Sections containing the connections were then removed from the vessel to allow internal visual and MPI. No crack indications or defects were identified, with all tests classed as run-outs. There was no observed effect of hydrogen on the fatigue life of set-on fittings within this programme.

3.9.2 Live Connections and Repairs

Live application of fittings and repairs to the LTS is required for maintenance and new connections without interrupting customer supply. New connections and repairs consist of welded tees, grouted shells and tees, composite repair wraps, and compression fittings. The integrity of such connections under pressurised hydrogen requires evaluation. Following initial welding trials, see Section 3.6.3.7, a full-scale pneumatic hydrogen fatigue test on a welded split tee and an epoxy grouted tee that had been applied under live hydrogen conditions was completed.

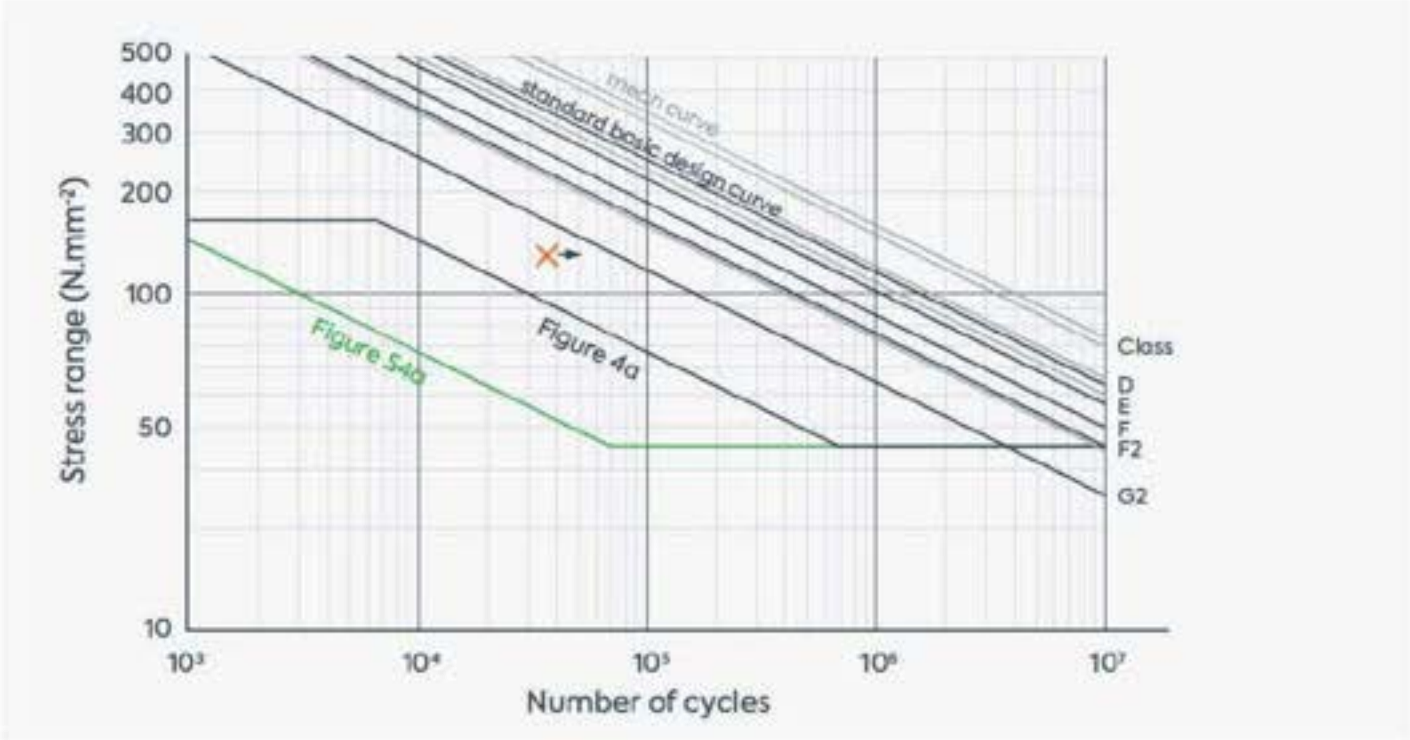
A section of material containing the two tees was used to fabricate a full-scale fatigue vessel. See Figure 85. During the test a water/MEG mixture was pumped in and out of the vessel to create a pressure cycle. The vessel contained an inner vessel with slots at the top and an outer annulus of hydrogen in contact with the inner surface of the pipe wall. This allowed a water/MEG mixture to be pumped in and out of the inner vessel, pressurising the annulus of hydrogen. This approach was taken to limit the hydrogen inventory in the rig and accelerate the cycle time over a purely pneumatic vessel. A layer of oil was added to the water in the inner vessel, to reduce the diffusion of hydrogen into the water and water into the hydrogen.

The vessel was instrumented with strain gauges at key locations, tracking the mechanical response of the pipeline material, welds, grout, and fittings to the pressure cycles. Periodic stoppages occurred during the test due to test-site restrictions and maintenance requirements. The vessel was cycled between a nominal 35.9 and 71.8 barg (36% and 72 % SMYS) for 36,287 cycles.

No failures occurred in the test vessel. MPI and manual UT were subsequently conducted on the welded tee. No indications were reported. Figure 86 plots a summary of the results of the test and the standard design S_r-N curves for classes D, E, F, F2, and G2 given in Table 22 of BS 7608 [70].

Figure 85: Fatigue vessel incorporating grouted and welded tee connections.

Figure 86: Full-scale fatigue test result.



As no failures in the vessel occurred, the result is considered a run-out. The IGEM/TD/1 Edition 6 [6] and IGEM/TD/1 Edition 6 Supplement 2 [10] Sr-N curves are conservative relative to the datapoint.

3.10 Vent and Flare Testing

Gas transmission networks require a safe means of pressure reduction and decommissioning to carry out maintenance on operational assets. AGIs contain several components that could require isolation and depressurisation to remove gas inventory during maintenance or replacement. Natural gas pipelines are directly purged between natural gas and air upon commissioning or decommissioning. These activities are normally carried out using portable vent stacks. Procedures define exclusion zones for these portable stacks based on line pressure and outlet diameter. Most of these operations are limited to small quantities irregularly released, but, on occasions, large-scale extended venting of natural gas is required.

All networks adhere to IGEM standards, IGE/SR/23 [78] Venting of Natural Gas, and IGEM/SR/25 [22] Hazardous Areas when undertaking venting operations. Flaring is not an operation typically undertaken on the LTS. No bespoke high-pressure hydrogen flaring standard exists, with the industry generally using API 521 [79] for the design of different liquid and gas flares. In the case of hydrogen, where significant overpressure could be generated during a delayed ignition event and there is a higher probability of ignition of vented gas, flaring could be a safer approach for large releases.

During venting and flaring operations of natural gas, exclusion zones based on noise and thermal radiation are required. The potential effect on these exclusion zones when transitioning to hydrogen requires evaluation. Additional exclusion zones could potentially be required for hydrogen due to the overpressure generated during a delayed ignition. The LTS Futures project completed a series of hydrogen vent and flare tests to gather data for feeding into QRAs and updated standards regarding noise, thermal radiation, and overpressure from delayed ignition of accumulated hydrogen.

A bespoke test rig was fabricated to generate and record noise, thermal radiation, and overpressure data during venting or flaring from a hydrogen reservoir at different mass flow rates. The rig consisted of a storage reservoir, flow control/measurement system, and adjustable outlet pipework (vent or flare tip) in the vertical direction at a nominal height of 4 m.

Figure 87: Test set-up (control valve, flow measurement, vent/flare stacks).

Prior to each release, the stack was purged with nitrogen to eliminate the potential for ignition of hydrogen when released. This indirect purging procedure was critical in ensuring no air was present in the stack prior to the introduction of hydrogen. In each test, hydrogen was vented until the flow rate stabilised. The release was then ignited pyrotechnically. Noise was recorded downwind at 30 and 100 m distances from the release location. Overpressure and thermal radiation were measured at locations noted in Figure 88. Each test was recorded using high-speed and thermal video. Environmental conditions before and during each test were monitored to assess their impact on the recorded data.

Five hydrogen vent and flare tests were conducted with different pressure and mass flow combinations. See Table 23. In all five tests, no immediate or unexpected ignition of hydrogen occurred. Appropriate purging procedures were implemented during the tests to reduce the probability of ignition and should be carried into any subsequent procedures for hydrogen venting or flaring.

Figure 88: Thermal radiation and overpressure measurement distances.

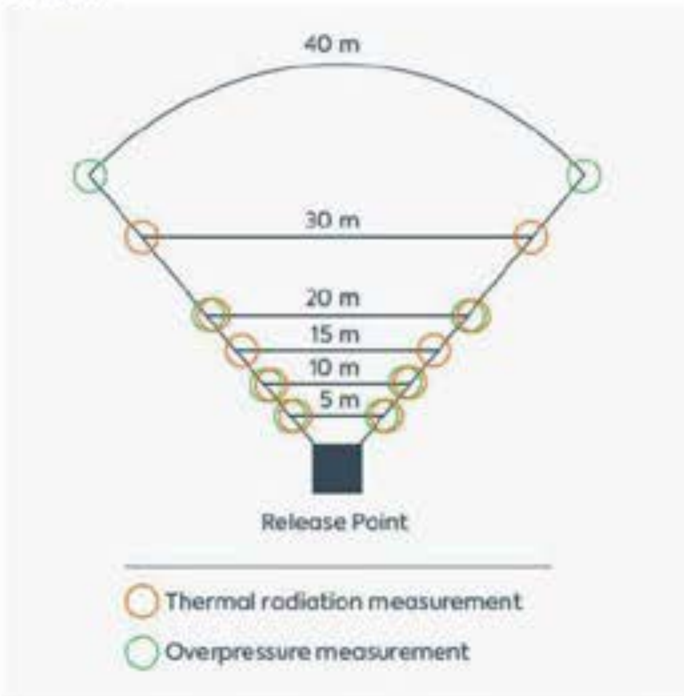


Table 23: Vent and flare tests.

Test ID	Release diameter (mm)	Release pressure (barg)	Mass flow (kg/s)	Exit velocity (m/s)
1	50	7	0.7	4,259
2	50	30	2.7	16,427
3	250*	30	2.7	657
4	250*	> 31	4.4	1,071
5	250*	7	0.8	199

*A 50 mm restrictor was used upstream of the release point.

Noise and thermal radiation values from the tests were compared to those calculated within SR/23 [78] for natural gas vents with the same release pressure and diameter. Measured overpressure values from the delayed tests were compared to consequence values within relevant guidance documents and standards [39].

Overpressures above the 70 mbar HSE LUPA [39] 1–5% fatality rate (for vulnerable indoor populations) were recorded in a delayed ignition scenario, but in all cases decayed below this value at 30 m. A delayed ignition during a release with a mass flow rate greater than 0.8 kg/s would have resulted in damage to buildings at 30 m according to CIA values [80]. Consideration of potential overpressure during delayed ignition should be taken when defining an exclusion zone for a hydrogen vent stack.

The noise generated during the venting tests would require suitable protective equipment in all cases. The measured flaring noise levels were not significantly higher than the venting noise levels.

IGEM/SR/23 [78] provides guidance on thermal radiation in the unlikely event of a natural gas ignition. It notes that an exclusion zone should be put in place if the predicted thermal radiation level exceeds 6.3 kW/m² at ground level. This corresponds to the level at which personnel would be expected to be able to escape in the event of an ignition (also noted in API 521) [79]. Flaring would require a more appropriate thermal radiation limit exposure because the thermal radiation is constantly present, and an 'escape' value should not be used. 1.58 kW/m² is noted within API 521 [79] as the exposure limit for personnel with appropriate heat-shielding PPE. The hydrogen flaring tests demonstrated that the thermal radiation was greater or close to the 1.58 kW/m² limit in API 521 [79] at 30 m for almost all tests. Mitigation measures such as thermal shields, flare enclosures, or higher stacks could be used to reduce this distance. The potential for a delayed ignition is reduced for flaring, and once flaring has started an overpressure exclusion zone would not be required. However, any equipment failure (e.g., pilot burners) could lead to a build-up of unignited gas and would require consideration when repurposing or, potentially, redesigning an AGI.

3.11 Pressure Reduction Installation Testing

IGEM/TD/13 Supplement 1 [18] details the design, operation, and modification of Pressure Reduction Installations (PRIs) when used with hydrogen or hydrogen/natural gas blends above 7 barg. PRIs are responsible for safely reducing gas pressure within the network; the supplement recognises that hydrogen introduces different challenges compared to natural gas.

PRI testing is being undertaken to confirm that an existing natural gas installation can safely and reliably operate with hydrogen. To meet the equivalent demand for natural gas, significantly higher volumetric flow rates of hydrogen would be required. This presents potential challenges regarding current pipework and component sizing, vibration, and noise.

To evaluate these challenges and confirm operability in hydrogen, a full-scale test rig is under construction at the DNV Spadeadam test site. An existing natural gas PRI skid and filter skid will be incorporated in the test rig for evaluation under flowing hydrogen conditions. Three regulator models will be tested as part of the programme at different flow rates to evaluate their ability to meet significantly higher demand. The models include:

- Fisher 310A regulator types 32A pilots.
- IGA Z138 axial flow regulators with ZSC 100 pilots.
- Mooney Flowgrid regulators with Mooney FloSeries 20 pilots.

Each regulator is to be tested within the PRI under flowing hydrogen conditions across nominal flow rates of approximately 10,000, 20,000, and 60,000 scm/h, corresponding to low, medium, and high-flow scenarios with inlet pressure up to 20 barg and regulator set points in the range of 7 barg. The lower flow conditions represent half and full natural gas demand respectively, while the highest flow condition represents the equivalent hydrogen volumetric flow required to deliver the same energy as natural gas.

The provided PRI and filter skids include filtration, isolation, pressure regulation, and safety devices and are typical makes/models of those found on the network. The skids will be tested as received, ensuring their condition is representative of those on the LTS.

Figure 89: SGN filter skid.

The filter skid, see Figure 89, is positioned upstream of the PRI skid, removing particulates and debris from the gas stream before they enter the PRI skid. Leakage checks, flow checks, isolation capability, and operational tasks will be completed on the skid with hydrogen during the test programme. The filter skid serves as protection for the PRI, as any blockage can influence pressure drop, regulator response, and overall system behaviour.

The PRI skid contains a range of key components. This includes:

- Active regulator: the primary control device that continuously reduces and maintains the downstream pressure at the required setpoint during normal operation.
- Monitor regulator: a standby regulator set slightly above the active regulator, which automatically takes over the pressure control if the active regulator fails or allows pressure to rise.
- Safety shut-off valve/overpressure protection: a quick-acting safety device that instantly shuts off gas flow if pressure exceeds predefined limits.
- Associated valves and skid pipework: the supporting isolation valves, pipework, fittings, and connections mounted on the PRI skid that enable safe routing, control, isolation, and maintenance of gas within the installation.

The results of the testing will be fed into an updated version of IGEM/TD/13 Edition 3 Supplement 1 [18] and the LTSF Blueprint.

Figure 90: SGN PRI skid.

3.12 Additional Studies

A number of supplementary studies were undertaken as part of the LTS Futures project to enrich the overall evidence base and maximise learning. Aligning with the project direction deliverables, these additional reports capture deeper insights and broaden the understanding gained during the programme. Outputs include a comparative assessment of linepack and the completion of a generic QRA. This section highlights the key findings and learning outcomes from these reports.

3.12.1 Linepack Comparative Assessment

Linepack is a critical element of the LTS system to provide reliable supply for diurnal demand. As part of the LTS Futures project, a comparative assessment was completed on two LTS network case studies to understand the impact on linepack from a transition of gas from natural gas to hydrogen.

Using modelling of the two representative UK LTS case studies (Southeast and Southwest), the assessment showed that hydrogen's lower calorific value means significantly higher gas volumes are required to meet the same energy demand. As a result, available linepack is reduced and flow velocities increase, leading to greater pressure swings and potential operational constraints. Overall, the modelling indicated that hydrogen systems would require more storage estimated at approximately 3.2 times that of natural gas to ensure equivalent performance.

The analysis completed also demonstrated that existing LTS networks, if directly converted, would not have sufficient linepack to meet demand without intervention. Several mitigation strategies were tested as part of the assessment, including reducing demand, increasing MOP, and enhancing supply flexibility or external storage. While demand reduction and higher pressures can assist, both would require significant changes to current operation of the LTS network. The most effective solution identified was the use of additional external storage (e.g. upstream linepack or dedicated storage facilities), which can compensate for reduced pipe storage and improve overall system resilience.

3.12.2 Generic QRA

A number of supplementary studies were undertaken as part of the LTS Futures project to enrich the overall evidence base and maximise learning. Aligning with the project direction deliverables, these additional reports capture deeper insights and broaden the understanding gained during the programme. Outputs include a comparative assessment of linepack and the completion of a generic QRA. This section highlights the key findings and learning outcomes from these reports.

From this assessment, it was determined that:

- For both hydrogen and natural gas operation, puncture failures are significantly more likely than rupture failures.
- The average individual risk across the LTS is predicted to be 50 times greater for hydrogen operation in comparison to natural gas.
- For natural gas, the average individual risk value sits well below the 1×10^{-6} 'broadly acceptable' level at 5.9×10^{-8}. For hydrogen operation, it was determined that approximately 60% of the LTS had an associated individual risk above the 'broadly acceptable' level but below the unacceptable level of 1×10^{-4}. The average result across the LTS was valued at 2.9×10^{-6}.
- Societal risk was determined to increase by an approximate 75 times for hydrogen, in which 75% of the total predicted risk for hydrogen operation is a result of overpressure risk. The consequences and risk of overpressure are not normally considered within a natural gas scenario, as the overpressures generated present a negligible hazard. This is not the case for hydrogen and has been conservatively accounted for within the assessment.

The generic QRA shows significant variation in risk across the LTS. For repurposing a pipeline, the Blueprint recommends, as a minimum, that a screening assessment should be performed and the highest population area assessed with the hydrogen QRA methodology as a proxy for the whole route.

3.13 Lessons Learnt

Lessons learnt reviews were carried out throughout the project to ensure that valuable experience, best practice and areas for improvement were captured at appropriate stages of delivery. A series of targeted sessions were undertaken with the relevant contractors and stakeholders when key activities or milestones arose, ensuring that learning was not lost. This approach enabled the attendees to identify successes, address issues and implement improvements in real time, helping to reduce the risk of repeating mistakes.

Learnings were collated from review groups that provided an open forum for discussion and feedback among the project team and contractors. Each session was structured to answer three questions:

- What had gone well?
- What had not gone well?
- How could we do things differently?

Identifying what went well enabled recognition of processes and established good practices that supported the delivery of the project. This helped create a positive environment and encouraged participants to be more open and forthcoming with their views and experiences.

Identifying what had not gone well allowed issues to be documented and enabled the identification of root causes and implementation of improvements, reducing the likelihood of similar issues occurring again. To ensure the discussions remained constructive and solution focused, any issues raised had to be accompanied by a recommendation or suggestion for what could be done differently in future. This approach promoted continuous improvement, collaboration and shared learning across all contributors.

The key outcomes below have been broken down into:

- Project-wide.
- Construction, design and live trial.
- Procedures and emergency response planning.
- Training.
- Research and development.

3.13.1 Project Wide

Key successes

Communication between all parties was conducted in an open, transparent, and professional manner, which fostered a strong team ethos, encouraged the sharing of knowledge and expertise, and enabled all stakeholders including regulators to work collaboratively towards achieving the project objectives.

Key personnel were identified early in the project and were involved throughout, allowing knowledge to be retained, strengthening working relationships and providing greater continuity in the delivery of works.

Key learnings

Due to the highly compressed project timelines, multiple workstreams were undertaken concurrently, which resulted in some work packages being developed less efficiently than would have been achievable under a more phased delivery programme.

Consistent and robust project governance with a clear route to approval and key responsible personnel was essential to the successful and safe delivery of the project. For LTS futures, this was achieved through a HGG which was established during the project.

3.13.2 Construction, Design and Live Trial

Key successes

Communication between all parties was conducted in an open, transparent, and professional manner, which fostered a strong team ethos, encouraged the sharing of knowledge and expertise, and enabled all stakeholders to work collaboratively towards achieving the project objectives.

Engagement with landowners for the live trial and public engagement for road works during construction was effective as this was identified as a potential major risk.

Key learnings

It was identified that detailed scopes of work are required to ensure that expectations between the project team and the contractors were clear and aligned. It was acknowledged that the LTS Futures project was a first of a kind with significant research being undertaken, and therefore some detail was not fully developed at the time of contracting.

For different workstreams, resourcing management for ancillary activities was not fully considered at the planning stages, which resulted in inefficiencies and avoidable downtime onsite and offsite.

Accurate inventory checks on delivery of equipment are essential to ensure all necessary items and spares are present, preventing any last-minute efforts to source replacement which ultimately caused downtime or delays.

Despite the existing natural gas framework for contractors and suppliers providing established procurement routes, it limits the potential options. Contractors and suppliers needed to be selected for appropriate experience, expertise and capability. There were also ongoing challenges associated with the import and export requirements for European and worldwide procurement activities, which created additional complexities in the ordering and delivery process. It was also noted that having a dedicated procurement specialist to help with these issues would have been beneficial.

Due to both INEOS sites being high-security and having top-tier COMAH classification, it was imperative that permits to work were issued and close engagement with INEOS asset control of work teams was carried out to discuss works inside the SGN compound within INEOS FPS. INEOS and SGN established a close relationship and supported each other's safety engineering due diligence through attendance of safety reviews. For project replication and interface with industrial hubs such as Grangemouth, it is imperative to understand established procedures onsite and combine with external contractors' own processes.

3.13.3 Procedures and Emergency Response Planning

Key successes

NROs were comprehensive and fit for purpose, having the essential detail which guided operational personnel through all the required steps.

Following significant work and collaboration, trial-specific procedures were developed and refined to ensure they were fit for purpose.

Operational personnel were included in the review groups, which enabled issues to be identified and addressed at an early stage. Their involvement also promoted collaboration across the wider team, improving buy-in and reducing challenges during later implementation stages.

In some instances, the equipment was set up offsite, which allowed operational personnel to gain practical experience in a controlled environment before the live trial. This provided an opportunity for real-time feedback on the procedures, enabling improvements and refinements to be made.

Early engagement was undertaken with East of Scotland Regional Resilience Partnership and LAs, ensuring there was a clear understanding of the timelines, requirements, and expectations associated with the desktop emergency response exercise. This collaborative approach enabled effective planning, alignment between all parties, and helped ensure the desktop exercise was productive and delivered in a structured and coordinated manner.

Completing testing activities, such as FAT and SAT, between procedure drafts allowed for learnings to be incorporated.

Key learnings

It is necessary to assess whether existing procedures are suitable for adaptation or used as a foundation to be built upon. This prevents significant time and energy being spent debating whether certain elements of a procedure being adapted is applicable.

When the NRO and procedure activities and methodologies are outside of the companies' usual practices, early and sustained internal stakeholder engagement is essential to support approvals. Providing clear guidance, building understanding and ensuring alignment throughout the process help to facilitate open communication and ultimately achieve timely sign-off.

Undertaking design and procurement, in parallel with procedure development, requires confirmation that maintenance and operating manuals are available. Without these, effective procedure development may be hindered and lead to inefficiencies or rework as information becomes available later in the process.

3.13.4 Training

Key successes

Assessors were involved in the final development phase, and the familiarisation training enabled any required updates or reassurances to be addressed prior to final delivery.

A training and competency plan was developed, considering the roles and responsibilities of all those involved in the project, which enabled a smoother and more efficient sign-off of the formal training as clear requirements had already been defined.

Bringing together multiple departments onsite for simultaneous training facilitated cross-departmental learning and knowledge sharing, ensuring a clear understanding of each other's roles and responsibilities.

The training programme incorporated sufficient time for operational personnel to gain hands-on experience with the equipment both before and after their assessments, deliberately allowing for further familiarisation and the development of confidence in its use prior to the live trial.

Training was delivered as close as practicable to the trial period to maximise knowledge retention and minimise the risk of errors during operations.

Key learnings

Where equipment testing activities, such as FAT and SAT, are not completed prior to the finalisation of training materials, there is an increased risk of requiring subsequent amendments. Aligning testing completion with training content development ensures accuracy, reduces the need for onsite changes, and supports a more efficient and consistent delivery of training.

It is important to ensure sufficient time after equipment set up to remediate snagging defects prior to training delivery. Adequate scheduling between these activities supports the remediation of minor defects in advance, improving readiness and reducing disruption during training delivery.

Projects involving specialised or unfamiliar equipment (e.g. hydrogen specific) require early and proactive engagement with suppliers to secure and integrate critical operational expertise. Insufficient time allocated for this engagement can limit the effectiveness of knowledge transfer and the incorporation of supplier guidance into project deliverables.

3.13.5 Research and Development

Key successes

Consistent personnel were maintained across testing activities to ensure continuity and retention of knowledge, enabling learning to be effectively carried forward between phases.

An agile team approach was maintained throughout, enabling opportunities to be effectively capitalised upon as they arose. Where challenges were encountered, proactive problem-solving ensured that solutions were identified and implemented successfully.

Well-defined scopes of work were developed and maintained throughout the project, providing clear definition of activities, responsibilities, and deliverables. This ensured alignment among stakeholders, reduced ambiguity, and supported efficient planning, execution, and control of project activities.

Key learnings

There is limited availability of laboratory facilities capable of conducting mechanical testing in hydrogen environments. With only a small number of laboratories offering this specialised capability, this constraint can impact testing timelines, accessibility, and overall project planning, highlighting the need for early engagement and careful coordination when such testing is required.

Laboratory testing standards for hydrogen environments remain at an early stage of development, with critical parameters such as loading rates, gas quality, and specimen size and type not yet consistently standardised across facilities. This lack of uniformity can lead to variability in results from different testing methods and underscores the importance of careful planning and alignment when specifying and interpreting test programmes.

Lead times for the build or replacement of hydrogen-rated equipment can be prolonged. This presents potential schedule constraints and reinforces the importance of early specification, procurement planning, and supplier engagement to mitigate delays and ensure timely project delivery.

Manual post-processing of data can introduce variability, as outcomes may be influenced by technician-specific interpretation. This highlights the importance of establishing clear methodologies, standardised procedures, and peer reviews to ensure consistency and reliability in data analysis.

Full-scale test setups require strict control of external variables to ensure that results are reflective of the test. This emphasises the need for robust experimental design and careful environmental control to maintain the accuracy and reliability of results.

3.14 Outcomes and Achievements Summary

The LTS Futures project has met and succeeded its planned outcomes. Table 24 details the outcomes defined in the project direction, and signposts the supporting evidence. Table 25 shows the additional outcomes which were achieved in the expansion of the project, adding to the overall value and learning.

Table 24: Planned outcome evidence.

Planned outcome		Was this achieved	Evidence
Provide evidence to determine the safety and suitability of LTS network assets for hydrogen culminating in a live trial to prove the practical and operational aspects.	Develop a methodology (Blueprint) for future repurposing and uprating projects.	YES	A Blueprint methodology has been developed and will be published in June 2026. See Section 7.1 for further information.
	Determine wayleave suitability, access, and landowner engagement requirements.	YES	A review of SGN wayleaves was conducted by Legal Land and determined to be suitable for conveying hydrogen.
	Determine the suitability of LTS materials for 100% hydrogen.	YES	This has been determined through full-scale and lab-scale testing programmes. Material testing information can be found in Section 3.7, 3.8 and 3.9.
	Validate the operational strategy for operating a hydrogen network.	YES	Planning and execution of the live trial provided critical learning and validated operational strategy. Further information regarding this can be found in Section 3.5 and 3.6.
	Develop the skills and competencies for managing, operating and maintaining assets in the hydrogen economy.	YES	The training and competency plan was developed for the live trial. This provided valuable insight into approaches for transitioning to a hydrogen economy, highlighting the importance of upskilling personnel to build upon their existing competencies. Further information can be found in Section 3.5.4.

Planned outcome		Was this achieved	Evidence
Provide the technical foundation and investor confidence to support delivery of industrial cluster decarbonisation.	Develop knowledge and acceptance of hydrogen within the public, industry, standards bodies and regulatory agencies.	YES	Section 6 details the engagement which has been undertaken with landowners, regulatory bodies and LAs. There is currently ongoing discussions with IGEM about how the Blueprint will provide insights for updates and creation of standards for hydrogen. Engagement with the public was in line with other high-pressure pipeline activities and reflective of the project having no end users.
	Optimise and validate the cost model for future repurposing projects.	YES	A cost model for repurposing pipelines has been developed as a part of the Blueprint. See Section 7.1.
	Provide visibility of the commercial and regulatory aspects for future operation of conversion hydrogen networks; this insight will support future regulatory models.	YES	The project addressed various regulatory and commercial requirements, including establishing clear contractual arrangements for hydrogen supply from an industrial cluster. An understanding of the legal and regulatory framework for the trial to go ahead while complying with SGN's legal obligations as a gas transporter can be found in Section 3.4.
	Understanding interface and commercial arrangements with hydrogen suppliers.	YES	Commercial contracts were set up with a hydrogen supplier and shipper for the trial. See Section 3.4.
Define the role of LTS in system transformation and facilitate industrial clusters.	Develop and test the regulatory (safety, commercial, and environmental) framework required for the GB Hydrogen network.	YES	Commercial contracts and the safety dossier were developed to ensure that the regulatory and commercial requirements for the live trial were met. Further information can be found in Section 3.4 and 3.5 respectively. Engagement was also carried out with regulatory bodies such as the ECU, LAs and the HSE. See Section 6 for further information). There were no objections from these agencies to the live trial, demonstrating that the current regulatory framework was suitable with minor modifications.
	Confirm a repurposed LTS will deliver the required operating pressures, flow rates and linepack to facilitate the green recovery.	Partial	Comparative scenarios were modelled for natural gas and hydrogen to review linepack and storage.. Further analysis was limited due to unknowns of future supply and demand and would be unlikely to produce meaningful results at this stage. In addition, PRI testing will provide information on the capability of existing infrastructure to meet potential increased demand. Further information can be found in Section 3.11.

Table 25: Additional outcome evidence.

Additional Outcomes from Project Expansion		Was this achieved	Evidence
Evidence that the network can effectively be operated in hydrogen service.	Ability to make new connections.	YES	During the live trial, welded and grouted tee connections were successfully made. Following this, these tees were hot tapped, demonstrating that new connections can be made. See Section 3.6.3.
	Ability to carry out flow-stopping operations .	YES	Following on from making new connections, flow-stopping operations were attempted. A 100% seal was achieved by the BISEP. A stopple train was attempted but not successfully deployed. See Section 3.6.3.7.
	Ability to fit and seal completion plugs.	YES	Standard and Lock-o-Ring Plus completion plugs were fitted during the trial. See Section 3.6.3.4 and Section 3.6.3.7.
	Ability to flare.	YES	A flare was commissioned and operated for the live trial to facilitate flow for purging and welding operations. Operational procedures and training were developed to facilitate this. See Sections 3.6, 3.5.3, and 3.5.4.
	Ability to purge full-scale pipelines successfully.	YES	For commissioning and decommissioning the pipeline and AGIs, indirect purging was completed. In-line sensors were used to collect data during these operations to expand the dataset for full scale pipeline purging. For further information regarding this, please see Section 3.6.2.
Informed future NIA project.	Provided guidance for development of projects to fill future gaps.	YES	Asset compatibility tool had previously been developed for below 7 barg; however, the LTS Futures project highlighted the need to expand this to cover the above 7 barg network.
Adapted and expanded test programme.	Expansion of burst test programme to consider internal oxide layers and vessel conditioning.	YES	The burst test plans adapted to take learnings from other test programmes, specifically around hydrogen permeation through oxide layers to expand the knowledge developed from the LTS Futures test programme. Further information can be found in Section 3.8.1 and Section 2.8.2.

4. Finance Performance

The LTS Futures project has been completed within the original funding allocation. Throughout delivery, a strong focus was maintained on value for money, applying robust procurement processes and identifying opportunities to control expenditure while delivering the required scope and maintaining quality. Risks and issues were proactively managed to ensure that additional expenditure was minimal and efficiencies were sought where possible. As a result, total project costs remained below the planned budget baseline.

The total approved funding for the LTS Futures project was £25.92 million in 2018/2019 prices, which consisted of:

£23.78 million
consumer funding via Ofgem.

£2.14 million
financial contribution from SGN and Cadent.

In nominal values, this was a total of **£31.06 million.** In addition, **BIK contributions were made by the GDNs of equipment and technical support to an estimated value of £850,000.**

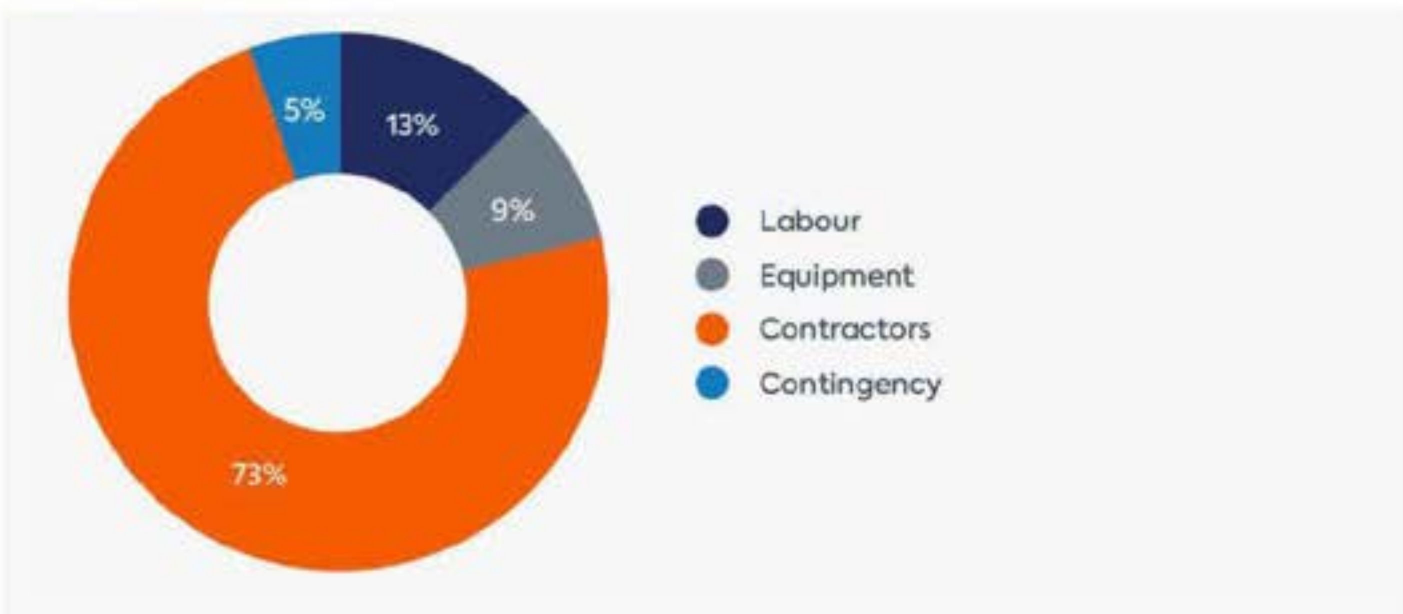
A detailed financial breakdown covering each element of the LTS Futures scope and the percentage variance between actual expenditure and budget is provided in Table 26.

Table 26: Project financial performance.

	Project element	Total spend including forecast for ring-fenced budget		Budget spend (in nominal values)	
		£k	%	£k	%
1	Enabling works and live trial design	5,829	19	8,664	28
2	Laboratory testing	3,114	10	3,248	10
3	Offsite testing	7,933	24	9,584	31
4	Construction and Live Trial	9,546	31	6,260	20
5	Documentation and preparation for live trial (emergency response, CfS, QRA etc)	1,630	5	1,055	3
6	Knowledge dissemination	1,331	6	7,66	3
7	Contingency	1,674	5	1,480	5
Project Total (nominal)		**31,057**	**100**	**31,057**	**100**

Figure 91: Project budget and spend comparison.

Figure 92: Project spend breakdown.



4.1 Financial Summary

Element 1
Enabling works and live trial design

The project experienced an underspend in element 1. Surveys completed on the pipeline as part of the enabling works showed the pipeline to be in good condition, meaning a reduction in the number of repairs required. A site-specific QRA indicated that risk levels were broadly acceptable or ALARP and, therefore, no diversions were required. Due to flow conditions in the pipeline, it was not possible to carry out an ILI, and the hydrotest results provided the integrity information needed.

Element 2
Laboratory testing

Completion of laboratory testing saw a small cost reduction in comparison to budget as a result of a refinement of the small-scale testing programme. Further small-scale testing and management of this past project completion date in June 26 will be managed through a ringfenced budget agreed with Ofgem.

Element 3
Full-scale testing

The contract for full-scale testing was one of the first set up for the project in 2022. As a fixed-price contract, this has not been affected by inflation in the same way as other project elements. Procurement of a compressor for testing was originally budgeted for within this element; however, the costs of this exceeded the budget, and the alternative approach for PRI testing is expected to have a slight cost saving.

LIVE

Element 4
Construction and live trial

Figure 91 shows an overspend for the live trial. This cost increase was due to market volatility experienced on construction and equipment procurement. Due to some works occurring within INEOS, this restricted the ability for competitive tender due to incumbent design and construction contractors. The construction of the 3" hydrogen supply pipeline also saw an increase in cost against budget due to the nature and location of the works in addition to increased material costs. Further construction at live trial sites (Grangemouth network entry facility, Newton pressure control facility and Granton flare facility) added to the costs within this element.

Element 5
QRA and Case for Safety

The project experienced a small increase in cost against budget within this element due to additional technical expert input being required for the Case for Safety. Further documentation submissions as part of the project safety dossier and engagement with the HSE also increased cost against budget.

Element 6
Knowledge dissemination

Knowledge dissemination is a cornerstone of the LTS Futures project, and learning has been maximised where possible. As a result, this element saw an increase in spend against budget due to attendance at conferences, launch events and extensive engagement with key stakeholders. Opportunities to expand knowledge sharing were taken, accounting for the increase in spend against budget.

The LTS Futures project has demonstrated strong financial discipline despite operating in a volatile market environment. While the funding received by Ofgem was later influenced by inflationary mechanisms to account for the final nominal funding value, the market pressures in construction and materials meant the project team had to maintain effective cost control throughout delivery.

Through robust planning, close commercial management, and proactive risk mitigation, the project minimised the impact of market fluctuations. Efficient procurement and supplier engagement ensured continued value for money, even as sector-wide costs increased.

As a result of this disciplined and efficient approach, the project has not only met its financial objectives but has also retained value. This highlights the effectiveness of the project governance and reinforces the project's strong performance in delivering savings while maintaining high delivery standards.

4.2 Retained Budget for Completion of Testing

The project has experienced a delay in some testing within Elements 2 and 3, which exceeded the agreed project completion date (30th June 2026). To mitigate the impact of these delays and ensure the completion of all research commitments, a ring fenced budget has been established. This funding covers the following costs for Element 2, fracture toughness testing, and Element 3, PRI testing:

- LTS Futures project team's labour for continued management of the work packages.
- Technical service provider support.
- Ongoing contract costs for the delivery of testing.
- Hydrogen supply for completion of the test programme (Element 3 only).

This ring fenced budget remains essential to ensure continuity of testing and delivery of outstanding technical evidence beyond the date of formal project close down.

The key financial risks associated with completing the outstanding research activities include:

- **Hydrogen pricing variability:** Costs of hydrogen for PRI testing remain subject to market fluctuations, which may increase the expenditure required to complete the testing programme.
- **Equipment repair and return delays:** Any delay in repairing failed PRI components and returning them to site may extend the testing period, resulting in potential increases in labour and technical service provider costs.

These risks continue to be managed actively to avoid any cost impact on the remaining budget provision.

At the time of publication, site deconstruction activities are ongoing and are scheduled for completion by the end of July 2026. Budget provision has been retained within the ring fenced amount to manage any residual risks associated with this work.

5. Material Change Information

The LTS Futures Project successfully completed all deliverables as detailed within Annex 2 of LTS Futures Project direction documentation. However, the project has experienced a delay in some testing within Elements 2 and 3, which exceed 1 year of the project completion date (30th June 2026), constituting a material change. Delayed testing elements include:

Element 2 – Fracture toughness

Construction, commissioning, and subsequent malfunction of test machines and associated equipment at TWI have incurred delays to the programme. The remaining testing has been streamlined where possible to ensure that only testing relevant to future repurposing is included. SGN continue to work on streamlining the programme as results become available.

Element 3 – PRI testing

Failure of a critical component within the DNV test rig equipment has incurred delays to the programme. The component and associated equipment have been sent back to the manufacturer for full investigation, re-manufacture, and testing prior to re-installation at DNV. A full SAT of the equipment is planned when it returns to DNV prior to LTS Futures beginning testing.

Ofgem have been notified of the material change. The delay has no impact on costs, which remain aligned with those in the original project direction. The budget for these tests has been securely ring-fenced. This closedown report will be updated with results when they become available. Discontinuing works at the completion date of 30th June, 2026, would constitute a missed opportunity to close out current industry gaps for revision of IGEM TD/1 Edition 6 Supplement 2 [10] and IGEM TD/13 Edition 3 Supplement 1 [18]. Ofgem approved the extension of the project to include the remaining testing on 13th May 2026.

6. Knowledge Dissemination

Knowledge dissemination was a core element of the LTS Futures Project. This section summarises the full programme of stakeholder engagement, communication activities, evidence sharing, and learning outputs delivered from 2022 to project closeout, and demonstrates fulfilment of the Knowledge Dissemination Plan submitted to Ofgem.

6.1 Knowledge Dissemination Approach

The project adopted a structured and iterative engagement strategy to ensure transparent, timely, and proportionate dissemination of project findings.

The approach was based on:

- Clear mapping of internal and external stakeholders.
- Defined engagement routes aligned to stakeholder roles and influence.
- Mechanisms targeted to minimise disruption, support regulatory assurance, and provide learning to industry.
- Alignment with project milestones, including Stage Gate One and Stage Gate Two regulatory submissions to Ofgem.

6.2 Stakeholder Engagement Overview

Stakeholder engagement spanned regulators, government, industry bodies, landowners, residents, academic institutions, emergency services, utility partners, local businesses, and community bodies. Engagement activity broadly fell into the following categories:

6.2.1 Regulatory and Policy Stakeholders

Over the course of the project, engagement was undertaken on a regular and proportionate basis, with frequency tailored to the requirements and expectations of each stakeholder group. This ensured that there was full transparency regarding the timing of deliverables and facilitated opportunities for stakeholder input and feedback where appropriate.

6.2.1.1 HSE

Throughout the project, there were regular six weekly meetings with the HSE, which provided updates to the project and the opportunity to discuss the different submissions requirements through the project, such as:

- PSR notifications (Gas Act, PSR 20, PSR 21, PSR 22).
- Research to Evidence Review Groups (ERGs) with critical documentation such as Case for Safety and Safety Dossier. For further information, please see Section 8.2.1.
- Attendance at a desktop emergency response workshop.
- Site visits.

6.2.1.2 Ofgem

Monthly meetings were held with Ofgem to report on project progress and obtain approval at stage gates. When significant developments occurred, such as the construction of the 3" line and the live trial operations, meetings were conducted onsite to enable direct engagement and observation.

6.2.1.3 DESNZ and Scottish Government

Engagement was centred on regular briefings, site visits, and structured updates aligned with the evolving hydrogen economy policy framework. This approach ensured continuous communication, provided opportunities and updates regarding project activities, and maintained alignment with relevant policy developments.

6.2.2 Local Authorities and Elected Representatives

Targeted engagement across Falkirk Council, West Lothian Council, City of Edinburgh Council and councillors ensured support for planning, environmental screening, access, and trial operations. All LAs participated in the emergency response workshop, see Sections 3.3.3 and 3.3.4, and consultation process.

6.2.3 Landowners and Businesses

Landowner engagement was essential to ensure efficient delivery of the LTS Futures Project. Engagement covered direct, bilateral engagement primarily focused on access and property-specific impacts.

- **Site-Specific Agreement:** Negotiated access agreements for land and conducting above-ground surveys.
- **Legal**: Managed detailed servitude discussions to ensure long-term land rights were clearly understood and documented.
- **Communication**: Prioritised in-person visits and direct phone calls to build trust and address any queries regarding land use.
- **Affected Landowners and Businesses Forums:** Hosted town hall meetings in 2023 and 2025 to present the LTS Futures roadmap and gather feedback.

The project implemented a thorough plan for landowner engagement to ensure they were well informed and classed as critical element of the project journey and success. The project experienced engagement well in excess of success criteria stipulated within the stakeholder and engagement plan with a 100% engagement rate through town hall attendance or direct one-to-one follow-up.

6.2.4 Community

Providing a broad, transparent communication aimed at public information and operational safety was of the highest priority for the project. Community engagement was focused on:

- **Operational Transparency:** Implemented local signage and public notifications to manage expectations during construction.
- **Education programme**: Delivery of the "Green Machine" STEM workshops to 420 pupils across 14 schools along the pipeline route.

6.2.5 INEOS

INEOS Group were a critical partner to the project supplying hydrogen from the INEOS O&P facility in addition to siting of our NEP on INEOS FPS land. Engagement was covered through monthly updates for the duration of the project with an increased frequency of meetings during critical construction and operational phases.

- **Technical assurance engagement:** The project completed a series of technical assurance assessments through a PSSR and a PHSER to ensure INEOS were provided with all information regarding the LTS Futures system. INEOS PHSER and PSSR taskforces reviewed and provided their approval for go live.
- **Site Visits:** SGN and INEOS conducted site visits during all stages of the project to discuss plans for construction and live trial operations to ensure efficient completion while not impeding on INEOS plant activities.
- **Hazard Identification (HAZID):** INEOS attended all project HAZID, HAZCON, and HAZOP studies providing support and input. Ineos also supported the review of key project NRO documentation and WIs pertinent to operations on the INEOS FPS site.
- **Communication:** During the live trial there was daily communication regarding hydrogen flows and scheduling of required volumes for the following operational day. During operations, there was continuous engagement with the INEOS SOL (shift optimisation lead) for routine operations. Wider INEOS land teams also consulted during works in proximity to INEOS assets.

6.2.6 Gas Distribution Network Operators (GDNs)

GDNs and National Gas Transmission (NGT) engaged through the GDN Steering Group, IGEM, Network Safety and Impacts Board (NSIB) direct briefings and were offered site visits during the trial. The engagement of GDNs and NGT has been key to shaping the overarching Blueprint and through provision of supporting case study information to test the methodology developed.

6.2.7 Emergency Services & Resilience Partners

A multi agency emergency response workshop in April 2025 achieved full representation across Police Scotland, Scottish Fire and Rescue Service, NHS, HSE, SEPA, and LAs. The planned full-scale exercise was revised to a desktop exercise due to it achieving the same intended outcomes and would likely gain higher attendance. See Section 3.3.4 for further information.

6.3 Engagement Delivery and Mechanisms

The project deployed a wide range of communication and engagement mechanisms, including:

- **Project-specific events:** Launch event, landower townhalls, resilience partners workshop and project briefings.
- **Press and media:** Local and national press releases at key milestones; positive coverage across outlets.
- **Digital channels:** LTS Futures website, local radio announcements (INRIX integration), social media, educational film content.
- **Direct communications:** Email updates, letters, planning consultations, engineering workshops, site access discussions.
- **Site visits:** For Ofgem, HSE, DESNZ, Scottish Government, IGEM, GDNs, MPs/MSPs, SGN internal teams and industry visitors at the Granton and Dalmeny live trial sites.

These mechanisms ensured broad accessibility of project information and provided tailored communication for stakeholders with differing levels of interest and impact.

6.4 Academic and Industry Dissemination

The project generated a significant academic and technical evidence base, including peer reviewed papers, conference presentations, and specialist publications. Key dissemination forums included:

Table 27:

Conference	Date	Location	Paper/presentation title
Hydrogen Industry Leaders (HIL) Enhancing the Hydrogen Economy 2023	Nov-23	Glasgow	LTS Futures.
Pipeline Pigging and Integrity Management (PPIM) 2024	Feb-24	Houston (USA)	The LTS Futures Project – a UK Operator's (SGN) experience of assessing the feasibility of repurposing their natural gas transmission system to transport hydrogen.
IGEM Young Persons Paper Competition 2024	Jul-24	Birmingham	LTS Futures: Hydrogen Transmission.
ASME International Pipeline Conference (IPC) 2024	Sep-24	Calgary (Canada)	• LTS Futures: Hydrogen Live Transmission. • Full-scale burst tests with hydrogen. • Defect Modelling.
IMechE International Conference on Pressure Vessel Technology (ICPVT) 2024	Sep-24	Glasgow	Full-scale fatigue tests on grouted and welded split tees, and small-bore connections, in hydrogen.
EPRG Energy Pipeline Innovation Conference (EPIC) 2025	Sep-25	Cambridge	LTS Futures: The Design of the Live Trial.
Hydrogen Industry Leaders Conference	Oct-25	Glasgow	LTS Futures: The Design of the Live Trial
Hazards35 (IChemE)	Nov-25	Birmingham	LTS Futures: Development of Safe Hydrogen Pipeline Operational Procedures - hot works and venting/flaring.
IGEM Annual Conference	Nov-25	Nottingham	LTS Futures project and live trial.
Bellingram annual conference	Nov-25	Crieff	Overall project overview.
Safe Net Zero 2025 HSE	Nov-25	Edinburgh	Safety aspects of Hydrogen in the LTS trial at Grangemouth.
EUA LTS futures update	Dec-25	Online	Whole project/live trial.
PPIM 2026	Feb-26	Houston	The LTS Futures Project – an update of a UK Operator's (SGN) experience of assessing the feasibility of repurposing their natural gas transmission system to transport hydrogen.
NECCUS Decarb Scotland 2026	Feb-26	Edinburgh	LTS Futures Overview.
IGEM Young Persons Paper Competition Scottish Heat 2026	Mar-26	Edinburgh	LTS Futures: Understanding Hydrogen Compatibility in Existing Gas Networks.
21st Pipeline Technology Conference (PTC) 2026	Apr-26	Berlin	LTS Futures: Live Welding on Hydrogen Pipelines.
AMPP The Corrosion & Protection Conference & Expo (2026)	Jun-26	Genoa	Characterisation of the effects of hydrogen on three line pipe steels in the LTS.
IPC 2026	Sep-26	Calgary	Full-Scale Burst Tests With Hydrogen on internal, sharp, part through wall defects.


6.4.1 Awards

LTS Futures submitted applications for project awards during the course of the programme after completion of the enabling works and post completion of the live trial. The LTS Futures Project was nominated for a number of awards over the duration of the programme and went on to win 2 awards in 2026 following the completion of the live trial. Details of these awards are listed below:

IGEM Gas Industry Awards 2024 –
Net Zero Innovation Award Shortlist

IGEM Gas Industry Awards 2026 –
Net Zero Innovation Award Shortlist

IGEM Gas Industry Awards 2026 –
Project Of the Year Winner.

Hydrogen UK Awards 2026 –
Infrastructure Project Winner.

6.5 Completion of Engagement Against Plan

Engagement activity was completed in line with all regulatory requirements and Ofgem direction obligations. Minor timing adjustments were made to accommodate:

- Revised planning and EIA screening schedules.
- Weather impacted landowner event attendance (alternative follow ups were completed).
- Changes to DESNZ personnel during the live trial.

Despite these timing shifts, all success criteria were met, with evidence provided through formal submissions, meeting minutes, attendance records, correspondence logs, and the detailed engagement table contained in the full report.

6.6 Outcomes, Learning and Legacy

Effective communication has been fundamental to the successful delivery of the LTS Futures project, enabling an unbroken chain of approvals with Ofgem and positive engagement with the HSE. This has included clear, consistent engagement and the timely provision of information to support decision-making processes where appropriate.

In parallel, strong and collaborative relationships have been established with LAs and emergency services, fostering a supportive environment that has enabled alignment, cooperation, and the smooth delivery of the emergency response desktop exercise and live trial.

Engagement with INEOS was critical to project delivery, as activities were undertaken within their operational sites, requiring full adherence to their control of work procedures. In addition, as the hydrogen supplier, their role was instrumental, making close coordination essential to ensure continuity and successful execution of the live trial.

Knowledge dissemination focused on sharing key lessons to inform future hydrogen trials, including construction sequencing, landowner engagement, and emergency planning. This was supported by a programme of academic publications, conference participation and further facilitating the transfer of knowledge.

The GDNs and NGT were identified as key stakeholders and have been actively engaged through regular quarterly meetings. In addition, further opportunities have been available for engagement and learnings from the outputs of LTS Futures, including site visits during the live trial and input into the development of the Blueprint.

All engagement methods applied within LTS Futures are fully transferable and can be replicated across similar projects. This repeatability enables other teams to realise comparable positive outcomes, supporting effective delivery through proven approaches to stakeholder engagement and collaboration.

7. Planned Implementation

The LTS Futures project set out to define the role of the LTS in a hydrogen system transformation, and the knowledge developed and learning achieved through the delivery of both the live trial and the research programme exceed this requirement. The Blueprint provides guidance for assessing any pipeline in the LTS and the outputs from the project are being used to inform and update hydrogen standards as well as making recommendations for new standards so that best practice can be used across the network for operations such as hot tapping and flow stopping.

7.1 Blueprint

The LTS Futures Blueprint [5] is a guidance document providing a methodology for repurposing existing LTS pipelines and installations for hydrogen service. It specifies a clear, repeatable and staged process for GDNs to follow and apply to their LTS assets. The Blueprint includes several sections depending on the type of asset to be repurposed:

Viability, capacity, commercial and cost benefit analysis

- Assess the feasibility of repurposing based on potential supply, demand, existing asset condition and any knowledge gaps. Consider the cost associated with repurposing for desired parameters.

Methodology for repurposing LTS pipeline.

- Demonstrate integrity under the proposed hydrogen service, confirm that the risks associated with hydrogen operation are ALARP and that conditions for repurposing are clearly defined.

Methodology for repurposing installations

- Assess design, condition and integrity status. Evaluate performance under hydrogen conditions and define required modifications. Confirm that the risks associated with hydrogen operation are ALARP. Demonstrate that the installation can be safely operated in hydrogen service and that all required modifications, mitigations, and assurance activities have been completed.

Implementation, assurance, and handover

- Complete Network Operation Reviews (NORs). Develop a stakeholder engagement plan for regulators, landowners/tenants, LAs, the resilience partnership, and internal departments. Review and update emergency planning and response procedures. Undertake a formal independent approval and appraisal process for repurposing activity. Complete a change of service process including handover and required documentation updates.

Operation and maintenance

- Review, adapt, and develop maintenance procedures, WIs, and risk assessments for repurposed pipelines and installations. Check and ensure tools, equipment, and PPE are suitable for hydrogen. Develop and implement a training and competency plan for all personnel involved in hydrogen operations.

Future considerations

As with other industry guidance documents, a regular review and update of the Blueprint should be completed. Other considerations for future work include:

- Engagement with the HSE to determine how HSG253 [51] can be updated to recognise that the hot tap and stoppling operations can be safely undertaken on hydrogen pipelines.
- Develop a standard for carrying out hot taps and stoppling on hydrogen pipelines and update */SP/P/9 for use on hydrogen pipelines.
- Agree criteria for girth welds of unknown quality for use in hydrogen service and develop a methodology for assessment.
- Develop a standard for venting and flaring hydrogen from transmission pipelines and installations.
- Develop a methodology and standard for assessing pipelines that may be affected by ISCC if a pipeline has transported manufactured gas.
- Adopt the Asset Compatibility Tool and ensure that it is periodically reviewed and updated to reflect current knowledge on material suitability for hydrogen service.
- Develop a standard for inspection, assessment and repair of damaged hydrogen pipelines operating at pressure great than 7 bar (i.e. a hydrogen version of GN/PM/P/11).
- Develop an approach for emergency planning hazard distances for hydrogen pipelines.
- Review and agree an approach for recording and retaining asset information in a structured manner.

The Blueprint was developed using learnings from the LTS Futures project and published standards. Several review stages were completed with involvement of multiple internal SGN departments and other GDNs. It is expected that the Blueprint will be used for subsequent LTS repurposing projects by SGN and other GDNs.

7.2 Case Studies

Case studies were carried out to ensure that the draft Blueprint methodology could be practically applied. These were carried out on LTS pipelines and installations nominated by GDNs and included five pipeline and five installation desktop repurposing studies. The pipelines and installations selected covered a range of construction periods and pipeline materials. The learning from these case studies was used to develop and refine the process within the Blueprint methodology.

The case studies were taken through a standards-led assessment using IGEM/TD/1 Supplement 2 [10] for pipeline studies and IGEM/TD/13 Supplement 1 [18] for PRI repurposing assessment. Pipelines and PRIs followed a Blueprint assessment through completion of:

Design and operability review

- Construction material, hydrotest and operating conditions.

Condition and integrity assessment

- Defects, corrosion, fatigue, pressure cycling, CP.

Functional system assessment

- Component level evaluation (valves, regulators, vents, E&I, filters).

Risk and compliance validation

- QRA and Hazardous area assessment.

Gap analysis

- Further testing, inspection or design update requirements.

Learning from the case studies has shown that hazardous zones for hydrogen can extend significantly further than existing natural gas zones and, in some cases, either extend beyond the site boundary or into unwanted areas, such as pathways or occupied buildings. Where this occurs, measures to reduce risk must be considered, including:

- Making the item suitable for hydrogen service e.g. through replacement.
- Changing the design type of equipment item to reduce the zone – e.g. replacing a non-ideal vent for an ideal vent may reduce the radius of the zone.
- Relocating the equipment item to say a freely vented area or away from a site boundary.
- Changing the design of the operation.
- Restricting flow rates and/or pressures.
- Reducing ignition source risks within areas adjacent to hazardous zones.
- The correct use of suitably zone-rated electrical equipment.

The completion of case studies, in addition to the completion of the live trial, allowed iterative development of the Blueprint methodology. The exercise also identified a significant reliance on complete historical records and component-level detail to provide an accurate assessment on repurposing. Case studies across all GDN operating areas allowed LTS Futures to test the Blueprint to improve the overall robustness of the methodology on completion of the project.

8. Project Performance

8.1 Project Direction

The LTS Futures Project was delivered in accordance with the requirements set out in Annex 2 of the Schedule 1 Direction to SGN (Ofgem, 2022), with all deliverables either completed or progressed in line with agreed governance and regulatory processes.

There are five deliverables provided in the direction including the two stage gates. Together, Stage Gate 1 and Stage Gate 2 provided structured, regulator led decision points that ensured the LTS Futures Project progressed only when proportionate, independently assured evidence was in place.

This staged approach formed a central pillar of the project's governance and underpinned regulator, safety authority, and stakeholder confidence in the first of a kind LTS Futures Live Trial.

SG1

Stage Gate 1 confirmed whether repurposing should proceed.

SG2

Stage Gate 2 confirmed whether hydrogen could be flowed safely.

8.1.1 Deliverable 1 – Stakeholder Engagement, Knowledge Dissemination, and Hydrogen Ownership

- Revised stakeholder engagement and knowledge dissemination plan.
- Hydrogen ownership proposal for Ofgem decision.

Delivery Summary:

SGN developed and submitted a comprehensive stakeholder engagement and communications plan covering pre trial, live trial and post trial activities. This plan set out structured engagement with Ofgem, HSE, DESNZ, LAs, landowners, emergency responders, industry partners and wider stakeholders.

A hydrogen ownership and contracting proposal was also developed, providing Ofgem with clarity on hydrogen title transfer, transportation arrangements and compliance with Gas Act requirements. This subsequently informed the commercial contracting arrangements implemented for the live trial detailed within Section 3.4 of the report. A commercial contracting environment closely replicating the existing established natural gas market arrangements was developed for completion of the works.

Outcome:

Deliverable met in full, with Ofgem oversight shaping subsequent engagement and contracting arrangements.

8.1.2 Deliverable 2 – Recommendation to Progress to Pipeline Modification and Construction (Stage Gate 1)

Stage Gate 1 was the first formal Ofgem decision point under the NZASP Direction [7]. Its purpose was to determine whether the evidence presented was sufficient to justify repurposing the Grangemouth to Granton pipeline and proceed with enabling works and construction of hydrogen supply infrastructure to support a future live hydrogen trial.

Delivery Summary:

The Stage Gate 1 submission in April 2023 provided a comprehensive integrity and safety assessment of the existing Grangemouth to Granton pipeline. SGN submitted a detailed Stage Gate 1 evidence pack, including:

- Pipeline integrity assessments and IGEM/TD/1 Edition 6 [6] compliance review.
- Pigging reports, hydrotest certificates,and condition surveys.
- A QRA for the pipeline route demonstrating risks to be broadly acceptable and ALARP.
- A defined set of mitigation actions to be addressed prior to hydrogen service.

Evidence was independently assured and reviewed through SGN's strategic governance prior to submission.

Outcome:

Stage Gate 1 confirmed the technical and safety viability of repurposing the pipeline for hydrogen service, subject to completion of defined actions and further assurance at Stage Gate 2. Ofgem approved progression through Stage Gate 1, enabling pipeline modifications, hydrogen supply infrastructure construction, and development of safety and operational evidence for the live trial.

8.1.3 Deliverable 3 – Recommendation to Progress to the Live Trial. (Stage Gate 2)

Stage Gate 2 was the second and final Ofgem decision point which was submitted in November 2024. Its purpose was to determine whether the project could safely and compliantly commission and operate the live hydrogen trial, based on fully developed safety, operational, regulatory and commercial evidence.

Delivery Summary:

SGN submitted a comprehensive Stage Gate 2 submission, bringing together:

- A CfS, aligned to the ENA Hydrogen Safety Case Framework (Energy Networks Association (ENA), 21/10/2022) [33].
- Independently appraised designs for all trial assets (pipeline, entry facilities, pressure control, and flare systems).
- Updated QRAs for the repurposed pipeline and new hydrogen supply pipeline.
- Regulatory notification logs, emergency response plans, training and competency arrangements.
- Completion of IVoR and operational readiness processes.

An IVoR was completed to provide independent review of all business requirements which are necessary for the safe operations of the trial, such as:

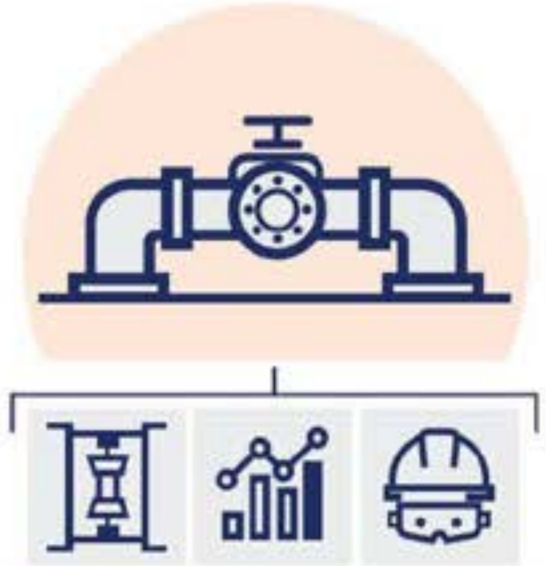
- Maintenance and inspection documentation.
- Health and safety documentation.
- Completions and commissioning.
- Operational documentation.
- Competency documentation.
- Commercial arrangements.
- Safety and compliance.

Independent reviewers were assigned to the appropriate action from each associated department, including Asset, Maintenance, Engineering Policy, Safety, Health, and Environment. The closure of IVoR actions was independently reviewed with supporting evidence submitted to validate and verify that it met the project and business needs.

Close engagement with the HSE occurred throughout evidence gathering and CfS development, with HSE confirming it had no objections to proceeding to live trial.

Outcome:

Ofgem confirmed progression through Stage Gate 2, permitting commissioning and live trial activities.



8.1.4 Deliverable 4 – Confirmation of Project Completion – June 2026

The LTS Futures live trial was successfully delivered in summer 2025, where live welding, hot-tapping and flow-stopping operations where completed. Small and large scale testing has demonstrated suitability of the LTS material for hydrogen. This work has been integrated into the development of the blueprint.

Delivery Summary:

The project has completed delivery of its core research, testing, demonstration, and evidence gathering scope, including construction, commissioning, live trial execution, and decommissioning activities as defined in the approved project plan.

Outcome:

Project completion confirmed in line with Ofgem Direction requirements.

As detailed in Section 4.2, there is ringfenced budget for full-scale fatigue testing, PRI testing and remaining fracture toughness testing. This has been approved by ofgem and is expected to be completed by end of 2026.

8.1.5 Deliverable 5 – Project Closedown Report

The closedown report must confirm:

- Delivery of a Blueprint [5] for future LTS uprating and repurposing projects.
- Completion of knowledge dissemination in line with the approved plan.
- Submission of all required information to the HSE addressing the evidence gaps identified in SGN's re-opener submission, with no objections raised.
- Compliance with any additional requirements set out in the Re-opener Governance Document (Ofgem, 2021) [81].

Delivery Summary:

This closedown report fulfils Deliverable 5 by:

- Confirming development of a nationally scalable Blueprint methodology for hydrogen repurposing of LTS pipelines and installations.
- Evidencing structured dissemination of learning across regulators, industry, and network operators.
- Confirming submission of evidence to the HSE through the Evidence Review Group process, supporting the closure or partial closure of identified evidence gaps. The remaining gaps within the published CFA assessment [82] carried out by the HSE are included within the report for completeness.
- Demonstrating compliance with NZASP governance, reporting and assurance expectations.

Outcome:

Deliverable met, completing SGN's obligations under Annex 2 of the Direction [7].

8.2 Technical Evidence Submissions to the HSE

LTS Futures has delivered a comprehensive and robust body of evidence for repurposing assets to hydrogen. The project began engagement with the HSE from its initiation in 2020. This included six weekly progress meetings and direct engagement through the development of the project Case for Safety.

In 2020, a series of evidence gaps were identified in the Department for Business, Energy & Industrial Strategy (BEIS) Hydrogen for Heat Programme that needed to be addressed ahead of any gas network hydrogen trials and before a wider policy decision could be taken on the use of hydrogen (HSE, 2020). LTS Futures completed a structured mapping exercise to overlay its programme outputs against the gaps identified by HSE, ensuring that the project's research and analysis was targeted towards closing these gaps.

LTS Futures developed an HSE Evidence Pathway document setting out when, how, and through which mechanisms evidence generated by the project would become available to the HSE over the course of project delivery. To support the UK Government's Net Zero targets, the HSE were asked by the DESNZ to assess evidence on the risks from storage, distribution, and use of 100% hydrogen for heating. The GDNs, NGT and DESNZ were responsible for the production and presentation of the evidence base to the HSE coordinated through the Network Safety and Impacts Board, Safety and Technical Board and the Project Management Board. All evidence submissions were required to be completed prior to 30th September 2024 to allow the HSE time for review. HSE provided an independent assessment of the evidence, releasing a final report termed the "Comprehensive Formal Assessment" (CFA) on 25th March 2026 (REF). These findings supersede the previous evidence gaps published by the HSE in 2020.

The submissions by LTS Futures for the CFA provide evidence for the broader policy discussion on hydrogen heating, but do not constitute the critical evidence on which the final hydrogen for heating decision depends. The transmission networks (NTS and LTS) are not included in, nor contingent upon, the government's decision on the future of hydrogen heating as they may transport hydrogen for other industries, including power generation, grid balancing, industrial feedstocks, or transport.

8.2.1 LTS Futures Submitted Evidence to HSE

As detailed within the CFA, a collection of evidence produced by the LTS Futures Project was used to review the suitability of the LTS for hydrogen. Additional evidence was also submitted to the HSE pertaining specifically to completion of the live trial on the Grangemouth to Granton pipeline. The evidence reports below were submitted to the HSE as part of the evidence review process with some feeding into the wider CFA review:

Element 1 (Live Trial Design & Construction)

- Assessment of TD/1 compliance and hydrotest of the Grangemouth to Granton pipeline.
- Final design of the hydrogen supply pipeline for the live trial.

Element 2 (Laboratory Testing of Vintage LTS Material)

- Characterisation tests in air (hardness, microstructure, chemical composition).
- Charpy impact and transverse strip tensile tests in air.
- Diffusion and flux testing.
- Tensile testing in air and hydrogen.
- K_{IH} testing in hydrogen.
- Interim FCGR tests in air and hydrogen.

Element 3 (Offsite Testing)

- Live hot works on hydrogen pipelines.
- Burst tests on pipeline defects in hydrogen.
- Fatigue testing of small-bore connections.
- Venting and flaring of hydrogen.

Element 4 (Live Trial)

- Linepack and capacity assessment technical note.

Element 5 (QRA and Case for Safety)

- Safety Dossier (including Case for Safety, training and competency plan, and operational procedures – see Section 3.5).

Element 6 (Knowledge Dissemination)

- Pipeline and PRI repurposing case studies.

8.2.2 Comprehensive Formal Assessment Gaps

The CFA [82] was split into network pressure tiers (and production/storage sections). Regarding the LTS, it concluded:

> **"It is potentially feasible to convert the use of the LTS from the transportation of natural gas to hydrogen.**
>
> **However, while the evidence demonstration supports near-term potential use of the LTS, the longer-term impacts from hydrogen service remain to be determined.**
>
> **The level of assurance that can be gained from experimental data when considering potential long-term real-world exposure is limited. Operational learning, supported by further research, will be key to validating the evidence base provided. It is likely that current integrity management approaches should support this validation if adapted to hydrogen service.**
>
> **There are a range of outstanding issues that the gas network industry would need to address. These include gaps in knowledge relating to the suitability and condition of critical equipment such as pressure reduction installations that are integral to the pipeline network."**
>
> *HSE's assessment of the safety evidence for 100% Hydrogen Heating March 2026*

The LTS Futures Live Trial, small- and full-scale fatigue tests, fracture toughness tests and Blueprint [5] were completed after the September 2024 deadline for evidence and did not contribute to the CFA [82]. The live trial and testing provide significant operational learning and evaluation of longer-term exposure tests.

LTS Futures has reviewed the remaining CFA LTS gaps and identified where further work is underway that could provide evidence for closure of these gaps. A gap analysis has been produced in Table 28 on the following pages:

Table 28: CFA gap analysis.

CFA Gap: Conclusions on the LTS	**Identified evidence to support closure**
"LTS assets, as with the NTS assets, are considered to be relatively well documented with a good degree of confidence in the data on asset type and location. However, there remains the need to ensure individual pipelines are adequately assessed in relation to material properties, historic operating and process conditions, initial build quality assurance and condition before operating with 100% hydrogen. Acceptable operating parameters need to be confirmed and verified."	The LTS Futures Blueprint [5] provides an assessment methodology for repurposing individual pipelines, or several pipelines, to hydrogen. A breakdown of critical elements of data required within LTS records to undertake assessment on repurposing. Subsequent chapters of the Blueprint address design and operability assessment under natural gas for decisions on future operating parameters to be set under hydrogen service.

CFA Gap: Conclusions on the LTS	Identified evidence to support closure
"The output from the HyNTS Dataset study should enable a sound judgement to be made by the operator of LTS pipeline systems as to the suitability for repurposing to hydrogen service. This should allow identification of any necessary remediation or mitigation as well as identifying any requirement to limit maximum operating pressure or pressure cycling to limit fatigue."	The LTS Futures Blueprint [5], provides a methodology for determination of whether any remediation or additional mitigation measures need to be taken when repurposing a pipeline to hydrogen. The Blueprint also provides a methodology for determining pipeline operational limits in hydrogen (including MOP and pressure cycle limits/remaining fatigue life).
"The impact of higher flow rates within equipment items and filters has been studied at below 7 barg. No similar studies have been provided for the LTS (and NTS) at higher pressures. The FutureGrid flow trials that tested assets in hydrogen service did not address the peak increased flow rates that would be required through the LTS. Further study and conclusions are required to be addressed by the gas network industry on the tolerance of pipework to potentially higher velocities, and industry guidance should be updated accordingly. The National Hydrogen Safety Assessment (NHSA) has recognised the potential for increase in velocities to accelerate degradation, which could be via vibration erosion. Written schemes of examination should be reviewed and updated as required."	LTS Futures will be completing flow rate tests on an ex-natural gas PRI containing typical makes/models of regulators, safety devices, filters and isolation valves. The testing will encompass tests at flow rates up to 2.6x those seen with natural gas. The capacity of the existing system will be evaluated alongside functional checks on all components at higher flow rates with hydrogen. Noise and vibration during the tests will also be recorded. The SIF Velocity project is looking at erosional velocity limits.
"**For live gas operations HSE considers that:** further work is required to demonstrate that isolation techniques can be deployed to ensure that adequate isolation of a piping system is accomplished in a reliable and repeatable manner, and the various techniques suitably validated for the pipe material, line size, and process conditions accordingly."	The LTS Futures project successfully completed flow isolation on a live hydrogen pipeline using the STATS BISEP tool. Prior to deployment, a FAT was completed to demonstrate the efficacy of the tool before deployment in field. It is anticipated that similar FATs would be carried out pre-deployment for other pipe diameters, materials etc.
"**For live gas operations HSE considers that:** there are concerns over potential inadequate purges being carried out due to inefficiency of the equipment during purging activities. The issue of purge efficacy also extends to the potential loss of purge during drilling operations where a potential loss of purge within the hot tapping chamber during drilling operations would lead to increased risk. Such an occurrence would be considered within the operational risk assessment and method statement and suitably mitigated. The gas network industry has indicated that further work is being undertaken in this area."	The LTS Futures project completed six hot taps on hydrogen-containing systems (four during testing and two during the live trial) successfully without loss of purge in the hot tap chamber. A recommendation from the LTS Futures Blueprint is to develop a gas network management procedure for hot tapping and flow stopping in hydrogen.

CFA Gap: Conclusions on the LTS	Identified evidence to support closure
"In relation to barrier coatings as a method for limiting the impact of hydrogen on material properties of higher strength steels, HSE concludes that, although it may be feasible to apply a suitable barrier coating to the critical locations within pipelines to reduce exposure of the substrate to hydrogen, at present suitable technologies have not been demonstrated or proven as described. Therefore, currently there are limited means of practically limiting the impact of potential hydrogen embrittlement within high-strength pipeline steels."	LTS Futures did not include barrier coatings as part of its scope.
"HSE's assessment of the Hydrogen Ready Components studies concluded that the approach provided a robust means of assessing and ranking components and materials for suitability with hydrogen within the limits and scope of the study. **The following gaps and concerns remain to be addressed, however:** Limiting the scope of the studies to 7 barg and below presented knowledge gaps relating to equipment and materials operating within the higher pressure systems, namely the LTS and NTS. There were other programmes, Page 70 of 194 HSE Assessment of the evidence for 100 Percent Hydrogen Heating, intended to determine suitability of equipment items such as pressure regulation, filtration, and metering skids for use in hydrogen service with variable results and, in one instance, awaiting commencement of testing."	An Asset Compatibility Tool (ACT) for above 7 barg assets has been developed in partnership with the HSE Science Division (post CFA deadline). There is further work to be done to ensure this tool includes equipment from all installations. The ACT forms a critical part of the Blueprint when assessing the repurposing of LTS installations to hydrogen.
"HSE's assessment of the Hydrogen Ready Components studies concluded that the approach provided a robust means of assessing and ranking components and materials for suitability with hydrogen within the limits and scope of the study. **The following gaps and concerns remain to be addressed, however:** The outstanding data submission for the assessment of sealants was of particular concern as this impacts a number of assemblies and piping systems, particularly considering degradation over time. Further studies on sealants applied to pipework screwed fittings had provided variable results. Further testing of sealants should be undertaken for use in hydrogen service and especially with screwed fittings. The findings should be developed to provide appropriate guidance on use of suitable products and application, including any restrictions."	LTS Futures did not include evaluation of sealants as part of its scope.

CFA Gap: Conclusions on the LTS	Identified evidence to support closure
"The justification for use of spring steels within a hydrogen environment was considered to be dependent on the service conditions of a particular asset. Therefore, each asset type will need to be further assessed prior to conversion."	An Asset Compatibility Tool (ACT) for above 7 barg assets has been developed in partnership with the HSE Science Division (post CFA deadline). The ACT forms a critical part of the Blueprint when assessing the repurposing of LTS installations to hydrogen. The ACT includes evaluation of spring steels.
"Some used assets or asset types had not performed well during initial integrity testing and following hydrogen leak testing. Although potentially not specifically related to material compatibility, this raises questions over the level of maintenance and inspection required for such assets for use within a hydrogen environment."	The LTS Futures Blueprint [5] recognizes that a different level of maintenance and inspection may be required for assets repurposed from natural gas to hydrogen.
"The gas network industry recognises the need to develop a management process that includes the condition assessment of above-ground network assets. The development of IGEM standard TD/22 supports this approach for ensuring such assets are maintained in an acceptable condition, being leak tight and compatible for operation in hydrogen service at the defined process conditions. However, HSE notes that the scope of this standard was limited to trials. Therefore, this standard may need to be developed to support any wider rollout."	Note IGEM/TD/22 is for below 7 barg assets only. The project developed Operation and Maintenance procedures and an Audit Inspection Plan for all above-ground sites during the live trial. These would need to be expanded and updated when moving from short-term trial to operational service.
"The evidence from WP2B Alpha Phase reporting the risk of failure due to vibration of intrusive flow elements (e.g. thermowells), showed a significant increase to the risk of vibration-induced failure with hydrogen at an equivalent energy delivery rate to natural gas. This will need to be considered in conjunction with any conversion and roll-out strategy based upon the anticipated energy demand at 100% hydrogen. If the original intrusive elements are to be potentially re-utilised, the energy demand would have to be reduced by a factor of 3 to 4 times that of natural gas. If the velocity of the gas flow was to increase to give parity in energy transition to that of natural gas, then such devices will likely require reengineering and replacement."	SIF Velocity Project is assessing thermowell/ protrusions as part of their vibration testing.

8.2.3 Modifications

As per NZASP LTS Futures Direction Annex 2 [7]: Project Deliverables and additional governance on the notification of any project change to Ofgem, the project notified Ofgem of changes experienced during completion of the project. The changes listed below on LTS Futures had no impact to completion of project deliverables in line with Annex 2 of the project direction.

UNC derogation

The project wrote to Ofgem on 17th October 2022, requesting disapplication of SSC A7 (Requirement to enter into transportation arrangements in conformity with the Network Code) [32] of SGN's transporter licence for completion of the project live trial. As the Grangemouth to Granton pipeline was an isolated system that did not connect to any other part of the SGN or wider GB LTS system, did not supply any customers, and did not require booking capacity, the UNC was not an appropriate commercial document for the introduction of hydrogen. Therefore, SGN requested that SSC A7.1 should be disapplied for the purposes of completion of the live trial only. Ofgem provided a response on the 20th January 2023 that this request was accepted for the project.

Project completion date extension

Annex 2: Project Deliverables of the LTS Futures Project direction detailed key dates for the deliverables. 31st March 2025 was stated as the completion date of the live trial and 30th June 2025 for delivery of the closedown report and project close. Due to delays in the construction phase of the works for the new hydrogen supply line, the project completed the live trial element in August of 2025. The completion date was updated to 30th June 2026 for the closedown report and project closure with Ofgem receiving notification of this change on the 7th April 2025. The amendment allowed for data processing and review following the completion of the trial. The extension to the completion of the project falls within the year gratis for research and development projects; however, formal notification was still given to Ofgem.

Subsequent to the above notification, LTS Futures informed Ofgem on 10th April 2026 of remaining testing activities that would exceed the June 2026 date due to delays outside of SGN control. These activities included:

- Outstanding small-scale material testing.
- Pressure reduction installation testing.

Ofgem have been notified that delays will not cause any additional cost and remain aligned with original direction deliverables. Discontinuing the testing element on 30th June 2026 would risk a missed opportunity to close current industry gaps. These programmes are to be completed by the end of 2026. Ofgem approved the extension to the project timescales on 13th May 2026.

Burst and Fatigue Testing: Oxide Layer Removal

A project change notification was submitted to Ofgem detailing change in Work Package 2: Burst and Fatigue testing within Element 3-Offsite testing of the project. Oxide layer formation within vessels planned for burst testing during fabrication could potentially impacting hydrogen permeation into the pipe wall steel, meaning the test may not represent a worst-case scenario. As a result, a test change was proposed to Ofgem including heating of vessels in order to break down the oxide layer within the vessel. It was decided for the work package to heat vessels for up to 96 hours (4 days) at 100°C to promote breakdown of the oxide layer an allow hydrogen to permeate into the pipe wall.

PRI Testing

As detailed within the LTS Futures NZASP reopener submission document [4], PRI operability and functionality assessments were to be completed to understand if a representative PRI can be repurposed to hydrogen under varied hydrogen flow rates and pressures. The project encountered challenges with completion of the work package due to costs for purchase of a compressor. The project implemented a robust procurement process for compressor purchase; however, costs exceeded the budget. PRI testing with a compressor element would not be value for money or in the best interest of customers and therefore an alternative plan was implemented that would still meet deliverables set out within the LTS Futures Direction [7].

9. Overall Deliverables Conclusion

The LTS Futures Project has successfully delivered a first-of-a-kind programme that provides a robust and credible evidence base for the repurposing of Great Britain's Local Transmission System (LTS) for hydrogen. Through the integration of laboratory and full-scale testing, and a live demonstration on the Grangemouth to Granton pipeline, the project has addressed critical technical, safety and operational uncertainties and demonstrated that existing LTS pipelines and installations could be safely and effectively repurposed for hydrogen service under defined conditions.

The project achieved all of its core objectives, including the safe and successful repurposing and operation of a 30 km pipeline. The trial incorporated purging, commissioning, pressurisation, and complex hot works including welding, hot tapping, and flow stopping. This was delivered following the development of a comprehensive safety, regulatory, and commercial framework. Extensive testing programmes have generated new evidence on material performance, defect behaviour, fatigue, and operability, while new procedures, training, and emergency response arrangements have demonstrated that hydrogen networks can be operated safely by upskilled existing personnel. All Ofgem approved deliverables under Annex 2 [7] have been successfully delivered, with structured stage gates ensuring that progression only occurred when proportionate, independently assured evidence was in place.

The LTS Futures Project has therefore met its NZASP objectives and provided enduring value through evidence, learning and a useable Blueprint for future hydrogen network transition.

Overall, LTS Futures can be considered a strong success. The programme not only met its intended deliverables but exceeded them by substantially reducing uncertainty for future hydrogen deployment through a structured, evidence-led approach. The use of gated governance, independent technical assurance and close collaboration with regulators and industry ensured that risks were well managed and that outputs are credible, transferable, and aligned with national requirements. The project also demonstrated that repurposing existing infrastructure offers a clear value-for-money proposition, with significantly lower cost and carbon impact than full network replacement.

A key legacy of the project is the LTS Futures Blueprint [5], which provides a scalable and repeatable methodology for uprating and repurposing LTS pipelines and installations across the GB network. The Blueprint brings together technical evidence, engineering requirements and safety principles into a coherent framework that could be applied nationally. It directly addresses regulatory evidence needs, supports the evolution of industry standards and provides a practical pathway for network operators to progress hydrogen conversion with confidence. As such, it represents a critical piece of evidence to enable future decision-making and investment.

In conclusion, LTS Futures has provided evidence showing the potential capability and confidence for hydrogen transmission in Great Britain. It has shown that repurposing the LTS is technically feasible, operationally safe and economically advantageous, while the Blueprint [5] provides a clear and actionable route for future deployment. Together, these outputs meaningfully de-risk future investment and policy decisions and position the LTS as a central enabler of the UK's transition to a low-carbon energy system.

10. Key Learning Documents

For more information on the LTS Futures Project and progress throughout the project years, please visit the LTS Futures website. The website provides detail on project life, enabling works on the Grangemouth to Granton pipeline, full-scale and lab-scale testing and completion of our UK first live trial including live welding. You can also find a collection of blogs and videos from the project team detailing an overview of these project elements.

Click here for more.

You can also find further information on the project through SGN's yearly innovation reports by visiting the SGN website, and following direction to reports and publications for an annual innovation summary for the duration of the project.
https://www.sgn.co.uk/reports-publications

Innovation annual summary 2021/2022
https://www.sgn.co.uk/sites/default/files/media-entities/documents/2022-09/SGN-NIA-Annual-Summary-2021-22.pdf

Innovation annual summary 2022/2023
https://www.sgn.co.uk/sites/default/files/media-entities/documents/2023-08/SGN_NIA_Annual_Summary_Report_2023_FINAL.pdf

Innovation annual summary 2023/2024
https://www.sgn.co.uk/sites/default/files/media-entities/documents/2024-07/SGNInnovationAnnualSummary2023-24.pdf

Innovation annual summary 2024/2025
https://www.sgn.co.uk/sites/default/files/media-entities/documents/2025-07/innovationannualreport2025.pdf

11. Data Access Details

For further information, details of research testing, completion of the live trial or Blueprint, please contact the LTS Futures email address:

LTSFutures@sgn.co.uk

Interested parties may request information from the project; however, we reserve the right to redact information of a commercially sensitive nature.

12. Contact Details

For further information on the project and access to project learning, please get in touch with the project team:

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13. Abbreviations

ACT – Asset Compatibility Tool
AE – Authorising Engineer
AGIs – above ground installations
ALARP – as low as reasonably practicable
API – American Petroleum Institute
ASME – American Society of Mechanical Engineers
BCB – Baseline Change Board
BCR – Baseline Change Request
BEIS – Department for Business, Energy & Industrial Strategy
BIK – benefit in kind
CCUS – carbon capture, utilisation and storage
CDM – Construction Design and Management
CFA – Comprehensive Formal Assessment
CfS – Case for Safety
CIPS – Close Interval Potential Survey
CLP – Clean Pig
CMOD – Crack Mouth Opening Displacement
COMAH – Control of Major Accident Hazards
CP – cathodic protection
CP – Competent person
DCPD – Direct Current Potential Drop
DCVG – Direct Current Voltage Gradient
DESNZ – Department for Energy Security and Net Zero
DMS – Dimethyl Sulpide
DoC – depth of cover
DSEAR – Dangerous Substances and Explosive Atmospheres Regulations
E&I – Electrical and Instrumentation
EAC – Estimate at Completion
ECU – Environmental Consents Unit
EIA – Environmental Impact Assessment
ENA – Energy Networks Association
EPRG – European Pipeline Research Group
FAT – Factory Acceptance Test
FCGR – Fatigue Crack Growth Rate
FCO – first call operative
FoE – Future of Energy
FPS – Forties Pipeline System
GB LTS – Great Britain's Local Transmission System
GCC – Gas control centre
GDN – Gas Distribution Network
GS(M)R – Gas Safety (Management) Regulations
GW – Girth Weld
HAR – Hydrogen Allocation Round
HAZ – Heat affected zone
HAZCON – Hazards in Construction Study
HAZID – Hazard identification
HDD – Horizontal Directional Drilling
HGG – Hydrogen Governance Group
HPRT – Hydrogen Pipeline Response Team
HSAW – Helical Submerged Arc Welded
HSC – Hazardous Substance ConsentEla
HSE – Health and Safety Executive
ICCPS – Impressed Current Cathodic Protection System
IGEM – Institution of Gas Engineers and Managers
ILI – inline inspection
ISCC – internal stress corrosion cracking
IS – intrinsically safe
IVoR – Independent Verification of Readiness
LA – Local Authority
LEL – lower explosive limit
LMS – Learning Management System
LSBUD – Linesearch Before U Dig
LTS – Local Transmission System
LUP – Land Use Planning
MAH – Major Accident Hazard
MAPD – Major Accident Prevention Document
MEG – monoethylene glycol
MOP – maximum operating pressure
MPI – magnetic particle inspection
NB – new blend
NBV – Network Block Valve
NDT – Non-destructive Testing
NEA – Network Entry Agreement
NEP – Network Entry Point
NGT – National Gas Transmission
NHSA – The National Hydrogen Safety Assessment
NIA – Network Innovation Allowance
NOR – Network Operation Review
NPV – Net Present Value
NSIB – Network Safety and Impacts Board
NRO – Non-routine Operations
NRV – non-return valves
NZASP – Net Zero Pre-construction Work and Small Net Zero Projects Re-opener
O&P – olefins and polymers
OCC – Operational Control Centre
OD – outer diameter
OM – Optical Microscopy
PERO – Pipeline Emergency Response Officer
PHSER – Project Health Safety Environmental Review
PID – Perimeter Intrusion Detection
PIE – Pipeline Integrity Engineers
PM – Parent material

13. Abbreviations (continued)

PMB – Performance Measurement Baseline
PMO – Project Management Office
PMP – Project Management Plan
PPE – Personal Protective Equipment
ppm – parts per million
PRCI – Pipeline Research Council International
PRE – public reported escape
PRI – Pressure Reduction Installation
PRS – Pressure Reduction Station
PSR – Pipeline Safety Regulations
PSSR – Pre-Start Up Safety Review
QRA – Quantified Risk Assessment
RA – Reduction in Area
RAM – Responsibility Assignment Matrix
RAMS – Risk Assessments Method Statements
RTU – remote telemetry unit
SAT – site acceptance test
SCADA – Supervisory Control and Data Acquisition
SEM – Scanning Electron Microscope
SENB – Single Edge Notched Bend
SENT – Single Edge Notched Tension
SMAW – Shielded Metal Arc Welding
SME – Subject matter experts
SMLS – seamless
SMT – Swarf Management Tool
SOL – shift optimisation lead
SSRT – Slow Strain Rate Tensile
STEM – Science, Technology, Engineering and Mathematics
SW – seam weld
TAL – Technical Authority Level
TBM – Tetra Butyl Mercaptane
TCP – Town and Country Planning
TCP GPDO – Town and Country Planning General Permitted Development Order
TDU – Thermal dose unit
TIG – Tungsten inert gas
TRS – Transmission Reduction Station
UKOPA – United Kingdom Onshore Pipeline Operators' Association
UNC – Uniform Network Code
UT – ultrasonic testing
WI – work instruction
WSoE – Written Scheme of Examination
WT – wall thickness

14. References

Bibliography

[1] Department for Energy Security and Net Zero, "UK hydrogen strategy," December 2024. [Online]. Available: https://www.gov.uk/government/publications/uk-hydrogen-strategy. [Accessed June 2026].

[2] Scottish Government, "Hydrogen action plan," Decemeber 2022. [Online]. Available: https://www.gov.scot/publications/hydrogen-action-plan/pages/4/. [Accessed June 2026].

[3] Department for Energy Security and Net Zero, "Hydrogen Allocation Rounds," January 2024. [Online]. Available: https://www.gov.uk/government/collections/hydrogen-allocation-rounds#hydrogen-allocation-round-3-(har3). [Accessed June 2026].

[4] SGN, "SGN Local Transmission System (LTS) Futures Project," January 2022. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2022-01/Annex%20-%20SGN%20NZASP%20Application%20-%20Redacted.pdf. [Accessed June 2026].

[5] SGN, "LTS Futures Blueprint Pipeline and Installation Repurposing for Hydrogen Service," SGN, 2026.

[6] Institution of Gas Engineers & Managers, "Steel pipelines for high pressure gas transmission," IGEM/TD/1 Edition 6 Communication 1848, October 2021.

[7] Ofgem, "LTS Futures Funding Direction," April 2022. [Online]. Available: https://www.ofgem.gov.uk/sites/default/files/2022-04/Schedule%201%20Direction%20to%20SGN%20-%20LTS%20Futures.pdf. [Accessed June 2026].

[8] American Society of Mechanical Engineers, "Hydrogen Piping and Pipelines," ASME Code for Pressure Piping, B31, ASME B31.12-2023, New York, NY, USA, 2023.

[9] Institution of Gas Engineers & Managers, "Pressure regulating installations for Hydrogen at pressures exceeding 7 bar," IGEM/TD/13 Edition 2 Supplement 1 Communication 1850, November 2021.

[10] Institution of Gas Engineers & Managers, "High Pressure Hydrogen Pipelines," IGEM/TD/1 Edition 6 Supplement 2, Communication 1849, November 2021.

[11] SI 1996 No. 825, *The Pipelines Safety Regulations 1996*, as amended, legislation.gov.uk.

[12] Institution of Gas Engineers & Managers, "Recommendations on the installation of steel pipelines for high pressure gas," IGE/TD/1 Complete Edition 2, 1984.

[13] SGN, "Management Procedure for managing New Works, Modifications and Repairs," SGN/PM/PS/5 , 2025.

[14] J. Randall, "I.G.E. TD/1 Report, Pipeline Name: Grangemouth to Granton JCR/KLK/5096," British Gas Corporation, London, 1986.

[15] SGN, "Management Procedure for Cathodic Protection of Buried Steel Systems," SGN/PM/ECP/2, June 2023.

[16] Institution of Gas Engineers and Managers, "Pressure regulating installations for Natural Gas, Liquefied Petroleum Gas and Liquefied Petroleum Gas/Air," IGEM/TD/13 Edition 2 Communication 1755, September 2011.

[17] Institution of Gas Engineers & Managers, "Pressure regulating installations for Natural Gas, Liquified Petroleum Gas and Liquified Petroleum Gas/Air," IGEM/TD/13 Edition 3, Communication 1872, 2024.

[18] Institution of Gas Engineers & Managers, "Pressure regulating installations for Hydrogen at pressures exceeding 7 bar," IGEM/TD/13 Edition 3 Supplement 1, Communication 1889, March 2024.

[19] Institution of Gas Engineers & Managers, "Hazardous area classification of installations using Hydrogen or blends of up to and includng 20% by volume Hydrogen in Natural Gas," IGEM/SR/25 Edition 2 with amendments 2013 Hydrogen Supplement 1, Communication 1871, November 2022.

[20] Transco, "Work Procedure for Carrying Out Non-Destructive Testing of Plant and Equipment," T/PR/NDT/1, June 2004.

[21] SI 2002 No.2776, *The Dangerous Substances and Explosive Atmospheres Regulations 2002*, legislation.gov.uk.

[22] Institution of Gas Engineers & Managers, "Hazardous area classification of Natural Gas installations," IGM/SR/25 Edition 2 - with Amendments, Communication 1748, 2013.

[23] BSI, "Hazard and operability studies (HAZOP studies) - Application guide," BS EN 61882:2016, June 2016.

[24] F. Crawley and B. Tyler, HAZOP: Guide to Best Practice, 3rd ed., Elsevier, 2015.

[25] SGN, "Work Instruction for Managing High Risk New Works, Modifications and Repairs," SGN/WI/PS/6-1, November 2015.

[26] SI 2015 No. 483, *The Control of Major Accident Hazards Regulations*, legislation.gov.uk, 2015.

[27] UK Public General Acts, 1986 c.44, *Gas Act 1986*, legislation.gov.uk.

[28] SI 1996 No. 551, *Gas Safety (Management) Regulations 1996*, legislation.gov.uk.

[29] UK Public General Acts, 1974 c.37, *Health & Safety at Work etc.*, legislation.gov.uk.

[30] Scottish SI 2015 No.181, *The Town and Country Planning (Hazardous Substances) (Scotland) Regulations 2015*, legislation.gov.uk.

[31] SI, 1992 No. 223, *The Town and Country Planning (General Permitted Development) (Scotland) Order 1992*, legislation.go.uk.

[32] Joint Office of Gas Transporters, "Uniform Network Code," as of October 2022. [Online]. Available: https://www.gasgovernance.co.uk/UNC. [Accessed June 2026].

[33] Energy Networks Association (ENA), "Hydrogen Safety Case Framework," DNV Report No.: 10377759-02 Revision 2, 21/10/2022.

[34] SGN, "Management Procedure for Accident and Incident Reporting," SGN/PM/INV/1, October 2023.

[35] Institution of Gas Engineers & Managers, "Reference Standard for low pressure hydrogen utilisation," Communication 1877, IGEM/H/1 with amendments June 2022 and June 2023, June 2023.

[36] Institution of Gas Engineers & Managers, *Assessing the risks from high pressure natural gas pipelines*, Communication 1779, IGEM/TD/2 Edition 2 with amendments July 2015, 2015.

[37] Gas Council, "Instruction for 100% X radiography," 1969.

[38] Report for The Norwegian Directorate for Civil Protection (DSB), "Guidelines for Quantitative Risk Analysis of facilities handling Hazardous Substances," Report no: PRJ11100262033/R, 2021.

[39] HSE, "Modelling the economic impacts of an accident at major hazard sites," Report 1055, 2015.

[40] Institution of Gas Engineers & Managers, "Recommendations on the installation of steel pipelines for high pressure gas," IGEM/TD/1 Edition 1, 1977.

[41] SGN, "Management Procedure for Safe Control of Operations - Permits to Work on the Gas Network," SGN/PM/SCO/2, November 2022.

[42] SGN, "Management Procedure for Safe Control of Operations - Non Routine Gas Supply Operations," SGN/PM/SCO/4, November 2022.

[43] SGN, "Management Procedure for Managing Change Safely," SGN/PM/SHE/34, December 2021.

[44] SGN, "Management Procedure for the Management of Contractors," SGN/PM/SHE/76, July 2022.

[45] SGN, "Work Instruction for the Delivery of Plant Projects," SGN/WI/PLANT/1, January 2024.

[46] SGN, "Management Procedure for Quality Assurance of Suppliers of Scotia Gas Networks," SGN/PM/QA/1, November 2012.

[47] SI 2015 No. 51, *The Construction (Design and Management) Regulations 2015*, legislation.gov.uk.

[48] NPL, "Project Closure Report Hydrogen Odorant and Leak Detection Part 1, Hydrogen Odorant," Hy4Heat, November 2022.

[49] SGN, WWU, NGN, "The welding of fittings to pipelines operating under pressure," IDN/SP/P/9, 2018.

[50] British Standards, "Code of Practice for Welding on Steel Pipes Containing Process Fluids or Their Residuals," BS 6990, 1989.

[51] Health and Safety Executive, "The safe isolation of plant and equipment," HSG253 Edition 2 , 2006.

[52] SGN, "Work Instruction for the Installation of Grouted Tees on Transmission Pipelines in Service," SGN/WI/P/19, October 2024.

[53] National Gas Transmission, "Under pressure drilling and stoppling operations 7 to 100 barg inclusive," T/PM/P/24, August 2011.

[54] M. Koronka, G. Simpson, N. Thomson, M. Atkinson, A. El Kaabouni, L. Fabry, G. Senior and P. Boothby, "LTS Futures: Live Welding on Hydrogen Pipelines," 2026, PTC.

[55] A. Bruce, V. Li and R. Gitterberg, "PRCI Hot Tap 4.1: 'PRCI Thermal Analysis Model for Hot Tap Welding by EWI,'' PRCI Project PR-185-9632, L51837, May 2022.

[56] J. Moreton, F. R. C. and B. T, "Hydrogen movement in weld metals' Metal Construction," Vol.3 no.6, pp. 223-228, 1971.

[57] A. Cosham, G. Senior, J. Brass, M. Kroon, M. Koronka and N. Thomson, "Full-scale fatigue tests in hydrogen on grouted and welded split tees and small-bore connections," ICPVT, 2025.

[58] SGN, Cadent, GNI, NGT,NGN, WWU, "Specification for Welding of Steel Land Pipelines Designed To Operate At Pressures Greater Than 7 Bar," GIS/P2 (Supplementary to BS 4515-1:2009) , 2024.

[59] NGN, SGN, WWU, "The sampling and testing of steel pipe and fitting materials used in gas pipelines and pipework designed to operate at pressures above 2 bar," IDN/PM/Q/10, 2018.

[60] American Petroleum Institute, "Specification for High Test Line Pipe," API Spec 5LX Twentieth Edition, Washington, D.C., USA, 1975.

[61] American Petroleum Institute, "Specification for Spiral-Weld Line Pipe," API Spec 5LS API Eighth Edition, Washington, D.C., USA, March 1975.

[62] American Petroleum Institute, "API Specification for High Test Line Pipe," API STD 5LX Sixteenth Edition, Washington, D.C., USA, March 1968.

[63] British Standards Institution, "Metallic materials – Tensile testing Part 1: Method of test at room temperature," BS EN ISO 6892-1:2016, London, UK, 2016.

[64] American Society for Testing and Materials, "Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both," ASTM G142 – 98, West Conshohocken, PA, USA, Reapproved 2022.

[65] International Organization for Standardization, "Metallic materials — Unified method of test for the determination of quasistatic fracture toughness," ISO 12135:2021, 2021.

[66] British Standards Institution, "Metallic materials. Method of test for determination of quasistatic fracture toughness of welds," BS EN ISO 15653:2018, 2018.

[67] ANSI/CSA, "Test Methods For Evaluating Material Compatibility In Compressed Hydro gen Applications – Metals," CHMC 1-2014, 2019.

[68] EPRG, "Draft best practice guidelines for small scale fracture toughness testing in hydrogen gas of carbon steel pipeline material," Rev4a, 2024.

[69] British Standards Institution, "Guide on methods for assessing the acceptability of flaws in metallic structures," BS 7910:2019, London, UK, 2019.

[70] British Standards Institution, "Guide to fatigue design and assessment of steel products," BS 7608:2014+A1:2015, London, UK, 2014.

[71] L. M. Haldorsen, X. Sun and J. Fonneland, "Perspectives and investigations on repurposing of large diameter offshore pipelines for H2 transport," in *Paper No. ISOPE-I-24-197. In Proceedings of the Thirty-Fourth (2024) International Ocean and Polar Engineering Conference*, Rhodes, Greece, 16-21 June 2024.

[72] Institution of Gas Engineers and Managers, "Pipework stress analysis for gas industry plant," IGEM/TD/12 Edition 3 Communication 1834, October 2021.

[73] American Society of Mechanical Engineers, "Boiler and Pressure Vessel Code. An International Code Boilers and Pressure Vessels," ASME BPVC. CC.BPV-2021 Code Cases , New York, NY, USA, 2021.

[74] National Grid, "Management Procedure for Inspection, Assessment and Repair of Damaged (Non-Leaking) Steel Pipelines above 150mm Nominal Diameter and Designed to Operate atPressures greater than 7 bar," T/PM/P/11, December 2019.

[75] G. Goodfellow, C. Lyons, S. Turner, F. Gray and S. Joyce, "An update to the recommended UKOPA external interference frequency prediction model & pipeline damage distributions," in *Paper No. IPC2018-78767. In Proceedings of the 2018 12th International Pipeline Conference. IPC2018. Calgary, Alberta,Canada, 24-28 September 2018*, New York, NY, USA, 2018.

[76] UKOPA, "Pipeline Fault Database Product Loss Incidents and Faults Report (1962 - 2022)," UKOPA/RP/24/001 Edition 1, November 2024.

[77] Pipeline Research Council International, *Full Scale Testing*, JEFI 04-08 CFER/PRCI EFI, Ongoing.

[78] Institution of Gas Engineers and Managers, "Venting of Natural Gas," IGE/SR/23 Communiciation 1623, 1995.

[79] American Petroleum Institute, "Pressure-relieving and Depressurising Systems," API Standard 521, 2014.

[80] Chemical Industries Association, "Guidance for the location and design of occupied buildings on chemical manufacturing sites," 2011.

[81] Ofgem, "Net Zero Pre-construction Work and Small Net Zero Projects Re," March 2021.

[82] Health and Safety Executive, "HSE's assessment of the safety evidence for 100% Hydrogen Heating," March 2026.

15. Meet the team

Nancy Thomson
Project Director

Nancy has led the LTS Futures project from its inception in 2020 through to its realisation and completion in 2026. With over 17 years' experience in pipeline integrity, working on onshore and offshore high-pressure pipelines, she has supported and guided her team to award-winning success. The project has achieved all its key deliverables, on time and on budget, and shown how the gas networks could play a role in net zero through repurposing the LTS to hydrogen.

Craig Henderson
Construction Project Manager

As Project Construction Manager with over 20 years of experience in the oil and gas industry, Craig was responsible for the delivery of all major works activities to facilitate the Live Trial. This included enabling works, the construction of the first pipeline to the IGEM/TD/1 Supplement 2 and supporting AGIs. Craig liaised with INEOS, project designers and managed contractors and suppliers to ensure that the project could be carried out safely, to budget, and on time.

Gemma Simpson
Live Trial Operations Manager/Project Director (maternity cover)/Research and development PM

With 13 years' experience in consultancy, testing and research in the energy sector, Gemma provided technical expertise across all elements of the project. This included research programmes, enabling works, design development and HAZOP, production of the Case for Safety and safety dossier. She developed and delivered training for trial personnel and provided expert technical support for emergency response. She was responsible for the design, procedures, and safe delivery of all live trial operations from purging and commissioning through to welding and depressurisation.

Courtney West
Project Manager

Courtney has been a member of the project team from the development of the bid, through its submission in 2021 and award of funding in 2022. His main responsibilities included management of the design of the new hydrogen supply pipeline and associated AGI's and the interface with hydrogen producers INEOS. Courtney managed commercial contracting and engineering assurance activities between INEOS and SGN for provision of hydrogen for the purposes of the live trial.

Steven Howells
Project Manager

Steve has over 25 years of experience in a variety of transmission engineering roles across Network Planning, Maintenance and Integrity Management. His role as overall project manager involved the development and monitoring of the project schedule, risk and issue tracking, change control and regulatory and internal compliance, including Management of Change. Steve also fulfilled the role of Network Controller for live trial operations.

Max Kornoka
Research and Development Project Manager

Max has a background in offshore oil & gas and renewables material development and testing. As part of the LTS Futures Team, Max was responsible for the design and delivery of small- and full-scale test programmes. In preparation for the live trial, he managed the development and creation of proven operational procedures for welding and hot tapping of hydrogen pipelines which were used during the live trial. Max has successfully delivered the LTS Futures Blueprint ensuring all knowledge and learning generated during the project was incorporated, providing industry-wide guidance for repurposing pipelines.

Sophie Bladon
Project Engineer

Sophie has a MEng in Chemical Engineering with oil and gas technology and has supported the project from its award of funding in 2022. She has contributed to the development of the Case for Safety and safety dossier as well as internal policies and procedures to support the safe and successful delivery of the trial. Sophie collaborated with contractors to ensure flow modelling was carried out for trial operations. She supported with the selection, procurement and distribution of specialist equipment for personnel and during the live trial ensured that essential data was captured for future analysis.

Temitayo Solanke
Project Engineer

Since joining the LTS Futures team, Temitayo has supported with the delivery of the small- and full-scale test programs. Temitayo delivered the equipment selection methodology, ensuring that equipment procured for the live trial was suitable for its intended use. During the live trial he supported hotworks operations and managed the gas sampling programme and onsite analysis by an external provider. He also supports on-going NIA projects which will develop further the understanding of hydrogen permeation and the parameters which affect this.

Craig Keating
Construction Project Engineer

With expertise in pipe fitting, hydrotesting, and fabrication, Craig managed the construction of the LTS Futures hydrogen supply pipeline. He ensured that the exacting requirements for this critical infrastructure met the highest quality standards and enabled the provision of hydrogen for the live trial.

Bernadette Ignatios
Project Analyst

Bernadette has supported the LTS Futures Project with administrative and financial tasks including project purchase order management and order tracking. She supported with records collation for training and issuing specialist equipment for the trial as part of the IVoR process and for routine operations during the trial.

16. Acknowledgements

The LTS Futures team would like to express their thanks to all the companies and individuals who supported the project and contributed to its success.

Advance were selected as the main works contractor for completion of the LTS Futures enabling works, construction of the hydrogen supply pipeline, fabrication and installation of the entry unit, Newton bypass and Granton site. Sonae (subcontractor) provided electrical and instrumentation installation across all sites.

Bell Ingram provided the project with critical landowner support throughout its duration. Bell Ingram supported on land access requirements and ensured landowners were updated with the project plans.

DNV provided services primarily in the delivery of the full-scale testing and research programme and facilitating off-site acceptance testing for operations which were conducted during the live trial. DNV also provided training packages for operational personnel and independent appraisal of design packages. In collaboration with STATS, DNV installed a grouted tee during the live trial.

INEOS located in Grangemouth were a critical partner in the delivery of hydrogen for the live trial. INEOS constructed hydrogen pipework to supply hydrogen to the trial through the supply pipeline and the entry unit was located within the INEOS FPS site.

PIE acted as the main expert technical service provider for the LTS Futures Project providing specialist engineering support across all elements of the project. They supported delivery of enabling works, design and equipment selection. PIE developed the Case for Safety and supported with development and delivery of training for the Live Trial. They provided onsite practical support for FATs and the Live Trial operations. PIE provided technical oversight of the research programmes and ensured all knowledge generated was incorporated into the Blueprint for repurposing LTS assets to hydrogen.

Premtech were the project's principal designer. Premtech successfully designed the hydrogen supply pipeline and associated network entry facility (Grangemouth), pressure control facility (Newton), and flare facility (Granton).

Rosen provided expert welding support throughout the development and execution of the hydrogen welding procedures. This included onsite support and independent weld inspection throughout the testing and research programme, attendance at FATs, and onsite support during the live trial.

RSK provided environmental support with the EIA screening assessments required due to project construction activities, including several watching briefs and supported with Local Authority applications to ensure environmental compliance.

Stats carried out drilling of a grouted tee and deployed the BISEP tool during the live trial achieving a 100% seal in hydrogen. Flow stopping was a critical element to test for the project under hydrogen service.

T.D. Williamson carried out live welding of a split tee welded to the Grangemouth to Granton pipeline in addition to drilling and installing a completion plug. This operation was a UK first under flowing hydrogen conditions.

TWI completed a suite of lab-scale tests in hydrogen and air to provide comparative data sets to improve understanding of the compatibility of LTS in hydrogen service.

Zeeco were selected as flare supplier for the Granton site. Zeeco provided the project with a 15 m high enclosed flare stack to ensure minimal disruption within the Granton region. Zeeco also supplied the project with a temporary flare stack at Newton and provided onsite training and support for commissioning.

16.1 Further Acknowledgements

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Bartec
Barton Firtop Engineering Co Ltd
Bauer Radio Ltd
Blackwater Ltd
Brightwell Systems Ltd
Cathodic Protection Ltd
Ceres Energy Ltd
City of Edinburgh Council
Computacenter UK Ltd
Core Cut Ltd
Costain Ltd
Crown Engineering Services Ltd
CT Construction Ltd
Dave Lander Consulting Ltd
Davidson and Robertson Ltd
Dentons UK Ltd
Department of Energy Security and Net Zero (DESNZ)
Dresser Ltd
East of Scotland Regional Resilience Partnership
Element Ltd
Emerson Electric UK Ltd
Falkirk Council
Flow and Process Solutions Ltd
Flowhire Ltd
Forsyth of Denny Ltd
GAP Group Ltd
GCM Services Ltd
GFSA Ltd
GRANFAB Ltd
H&B Sensors Ltd
HSE
Hydrotechnik UK Test Engineering Ltd
IACS Ltd
ID Verde UK ltd
Inspection Eccose Ltd
Instromec Ltd
Kinder Janes Ltd
LEWA Ltd
LFF Scotland Ltd
Luddon Construction Ltd
Malcolm Hughes Land Surveyors Ltd
Marsh Ltd
Mokveld Ltd
Natural Gas Solutions Ltd
NHS Forth Valley
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Safer Scotland Ltd
Scottish Ambulance Service
Scottish Fire and Rescue
SEPA
Simplify Ltd
Specialized Signs Limited
Steer Energy
Swagelok
Sweeney Drainage
Teemans Ltd
Teledyne Gas Measurement Instruments Ltd
TF Jackson Ltd
Thinking Hat Media Ltd
VXI Power Ltd
West Lothian Council
WPA Pinfold Ltd
WSG Energy Services Ltd