

Pipeline Installation Techniques for Net Zero

WP1A – Pipeline Construction Technologies

National Gas

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Abbreviations

AGI	Above Ground Installation
AI	Artificial Intelligence
BVLOS	Beyond Visual Line of Sight
CCUS	Carbon Capture, Utilisation and Storage
DAS	Distributed Acoustic Sensing
DfMA	Design for Manufacture and Assembly
E&I	Electrical and Instrumentation
FBE	Fusion Bonded Epoxy
FCAW	Flux Cored Arc Welding
GIS	Geographic Information System
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HDD	Horizontal Directional Drilling
HDPE	High Density Polyethylene
HFI/HFW	High Frequency Induction Welded
MAG	Metal Active Gas Welding
NDT	Non-Destructive Testing
NGT	National Gas Transmission
NTS	National Transmission System
NUAR	National Underground Asset Register
PA	Phased Array
PE	Polyethylene
PED	Pressure Equipment Directive
QA	Quality Assurance
RAMS	Risk Assessment and Method Statement
RTP	Reinforced Thermoplastic Pipe
SAWH	Submerged Arc Welded (Helical)
SAWL	Submerged Arc Welded (Longitudinal)
SMAW	Shielded Metal Arc Welding
SMLS	Seamless
SSSI	Sites of Special Scientific Interest
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TBM	Tunnel Boring Machine
TOFD	Time of Flight Diffraction
TPI	Third Party Interference
TRL	Technology Readiness Level
UHDPE	Ultra-High-Density Polyethylene
VSM	Vertical Shaft Sinking Machine

Executive Summary

This report provides a state-of-the-art review of pipeline construction practices and emerging technologies that could enhance efficiency, reduce costs, and support future network expansion to achieve Net Zero goals. Areas of focus include:

- Novel methods for optimisation of pipeline routing
- Trenching and trenchless methods for pipeline installation
- Automation of welding and non-destructive examination of welds
- Alternative fabrication methods, materials and coatings
- Modular construction methods
- Novel methods for pipeline risk mitigation

In many instances, use of state-of-the-art methods would not require any technology development but would still represent a change in practice relative to NG recent experience and may need to be described in relevant contracts with service providers to ensure adoption. Recent advances that offer the potential for significant impact include:

- Use of software tools for optimisation of pipeline routing during project engineering. Guidance on appropriate weighted scoring systems should be developed to ensure consistency across projects.
- Appropriate use of different trenchless installation techniques, including recent developments such as Direct Pipe and Pipe Express, depending on terrain, soil conditions and other requirements.
- Advanced automated internal and external multi-torch welding systems and line-up clamps. When used together with laser pipe end measurement systems and other digitalisation tools, these systems improve both production efficiency and weld quality.
- Factory-built modules, containerised systems, and 3-D-printed concrete foundations for AGI infrastructure elements reduce on-site labour and re-work, achieving substantial programme compression and embodied-carbon savings.
- Fibre-optic cables installed along the pipeline length to provide continuous monitoring capability for leak detection, third party interference and ground movement at high risk locations. There is a unique opportunity during construction to integrate this technology.
- Reinforced thermoplastic pipe for small diameter spurs / tie-ins.

In some instances, these methods are not covered by National Gas standards or specifications, so these will also need to be updated prior to use.

Where technologies are yet to have reached the level of maturity to be widely implemented in projects, an indication of Technology Readiness Level is provided. In some cases, where TRL is very low, and the amount of investment required would be high, it is considered unlikely that these technologies will be developed within the timescale needed for implementation on planned infrastructure projects in the next 10-15 years. However, in some cases, the necessary technology development is considered more feasible. Examples of the latter instance include:

- Autonomous excavation and lowering systems (where terrain and soil type is appropriate).
- Battery electric or hydrogen powered trenching equipment.
- MASiP pipe as an alternative to conventional carbon steel linepipe. At present the technology has only been demonstrated for small/medium pipeline diameters that would only be applicable for NGT spurs or tie-ins. However, the main potential benefit of significantly reduced cost would only be realised on longer pipelines, which for transmission infrastructure is likely to be of larger diameter. A significant technology development and demonstration programme would be needed in this instance.

1. Introduction

1.1. Project Background

National Gas Transmission (NGT) is committed to supporting the government and the broader industry in achieving the Net Zero target by 2050. Carbon Capture, Utilisation and Storage (CCUS), alongside hydrogen, will play a critical role in reaching this goal. Since existing infrastructure was originally designed for methane, adapting it to transport these new gases presents significant engineering challenges. To address this, an extensive research program has been launched to assess the technical feasibility of repurposing sections of the National Transmission System (NTS) for hydrogen and carbon dioxide transportation.

While repurposing existing pipelines will be an essential part of the transition, it will not be sufficient – new infrastructure will be required to support a scalable hydrogen and carbon network. Given the ambitious deployment timelines, meeting these targets will require not only innovative technical solutions but also a holistic strategy that integrates the supply chain and fosters collaboration across the industry.

The construction of new hydrogen and carbon dioxide pipeline sections presents several challenges, including selecting the most effective construction methods and managing commissioning risks. Establishing a standardised process to connect future producers, emitters, and users is also a challenge. The lack of a formalised approach can lead to inefficiencies and potential delays. Through this project, NGT aims to investigate new construction practices, identify technical requirements and compliance, and address commissioning challenges. The project also aims to identify a conceptual connection design that will enhance efficiency, reduce costs, and support future network expansion.

The project is divided into four work packages as follows:

- Work Package 1 - Pipeline Construction and Commissioning Techniques for Net Zero
- Work Package 2 - Procurement and Supply Chain Management
- Work Package 3 - Connections Process for Net Zero NTS Customers
- Work Package 4 – Reporting

There are two deliverables within Work Package 1 as follows:

- Technical Report 1A – Pipeline Construction Technologies
- Technical Report 1B – Pipeline Commissioning and Decommissioning

This document is Technical Report 1A and is described in further detail below.

1.2. Document Purpose and Scope

Work Package 1 includes a number of market reviews of technologies associated with pipeline construction and recommendations for potential improvements to current practices. Areas of focus include:

- Novel methods for optimisation of pipeline routing
- Trenching and trenchless methods for pipeline installation
- Automation of welding and non-destructive examination of welds
- Alternative fabrication methods, materials and coatings
- Modular construction methods
- Novel methods for pipeline risk mitigation

As these reviews were carried out, reference was made to relevant NGT policies and standards related to pipeline construction. Where these standards do not cater for application to hydrogen or gas phase CO₂ pipelines, or they would require update to facilitate the use of different technologies, these instances were noted (see Section 9).

Where novel technologies are presented, an indication of technology readiness is included using the NASA scale of 1-9 as shown in the Table below.

An indication of the potential impact of the technology is also presented. This constitutes a judgement of the potential impact that the technology could have, if deployed on a large scale pipeline construction project. It is assumed that these construction projects would relate to pipelines carrying either hydrogen, natural gas or gas phase CO₂. Dense phase CO₂ is not considered.

Potential impacts could be related to:

- **Cost** – i.e. associated with materials or labour
- **Safety / integrity** – either during construction or later during operation of the pipeline
- **Environment** - in the form of either reduced carbon emissions or disruption to environmental habitat
- **Operability** – i.e. impact on other activities, during either construction or subsequent operation of the pipeline

A qualitative scale is used to describe the potential impact of the technology on each of these metrics, using the following scale.

Table 1 Technology Readiness Levels

TRL	Description
1	Basic principles observed and reported. This is the initial stage where scientific research begins to translate into applied research and development.
2	Technology concept and/or application formulated. At this stage, practical applications are identified, but they remain speculative with little experimental proof.
3	Analytical and experimental critical function and/or characteristic proof of concept. Active research and development are initiated, including laboratory studies to validate analytical predictions.
4	Component validation in a laboratory environment. Basic technological components are integrated to establish that they will work together.
5	Component validation in a relevant environment. This involves more rigorous testing, often in environments that simulate real-world conditions.
6	System/subsystem model or prototype demonstration in a relevant environment. A fully functional prototype is developed and tested.
7	System prototype demonstration in an operational environment. The technology is demonstrated in a real-world setting.
8	Actual system completed and qualified through test and demonstration. The technology is fully operational and has been proven in its intended environment.
9	Actual system proven through successful mission operations. This is the highest level of maturity, indicating that the technology has been successfully used in operational conditions.

Table 2 Technology Impact

Impact	Description
-3	Large negative impact
-2	Moderate negative impact
-1	Small negative impact
0	No impact (baseline for comparison described in each instance)
+1	Small positive impact
+2	Moderate positive impact
+3	Large positive impact

2. Optimisation of Pipeline Routing

2.1. Overview

Software tools, some incorporating elements of AI, have been developed to assist the power, utility and renewables industries in visualising and assessing different routing and siting options for various infrastructure projects. These tools automate the route corridor optimisation process using GIS datasets and specially designed weighted scoring algorithms to determine the “optimum” route, subject to multiple constraints such as cost, safety or environmental impact. Workshops are typically held to agree weighting factors for each scoring criteria.

Tools can be tailored to incorporate a variety of different datasets such as:

- Existing infrastructure (pipelines, roads and railways, power lines etc.)
- Terrain information and geological data
- Social and population data
- Ecological or special cultural heritage sites
- Hydrology and flood risk areas

GIS datasets are available from a number of sources and can be accessed from the example platforms below, [redacted] initiative could also provide suitable datasets.

A large number of potential routes can then be considered, and where the route interacts with features defined in these datasets, a cost or impact can be ascribed (per km or per instance).

This provides the following benefits:

- Improved efficiency / reduction in timescale during project engineering, while maintaining a thorough consideration of all potential routing options.
- Use of a robust and transparent evaluation criteria to balance potentially competing interests, and assurance that all possible routes have been evaluated.
- Provide demonstration that a robust process has been followed to select the preferred route to support processes such as submissions for Development Consent Orders (DCO)
- For a selected route, subsequent activities such as producing drawings or other reports can be automated.

2.2. Example Platforms

Kent has identified a number of pipeline routing tools:

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

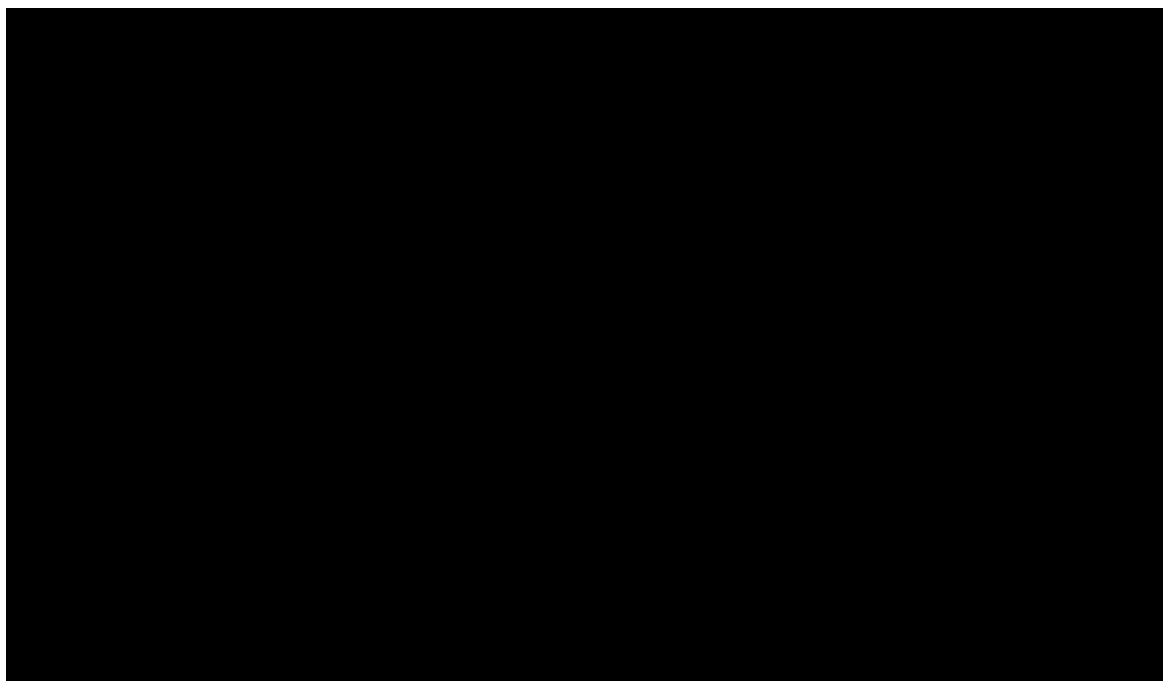
All of these tools have a similar functionality, based on publicly available information. Some are in-house tools designed for use within the engineering teams of the companies concerned, while others are commercially available software products. Kent has not had detailed discussions with potential vendors to facilitate a detailed

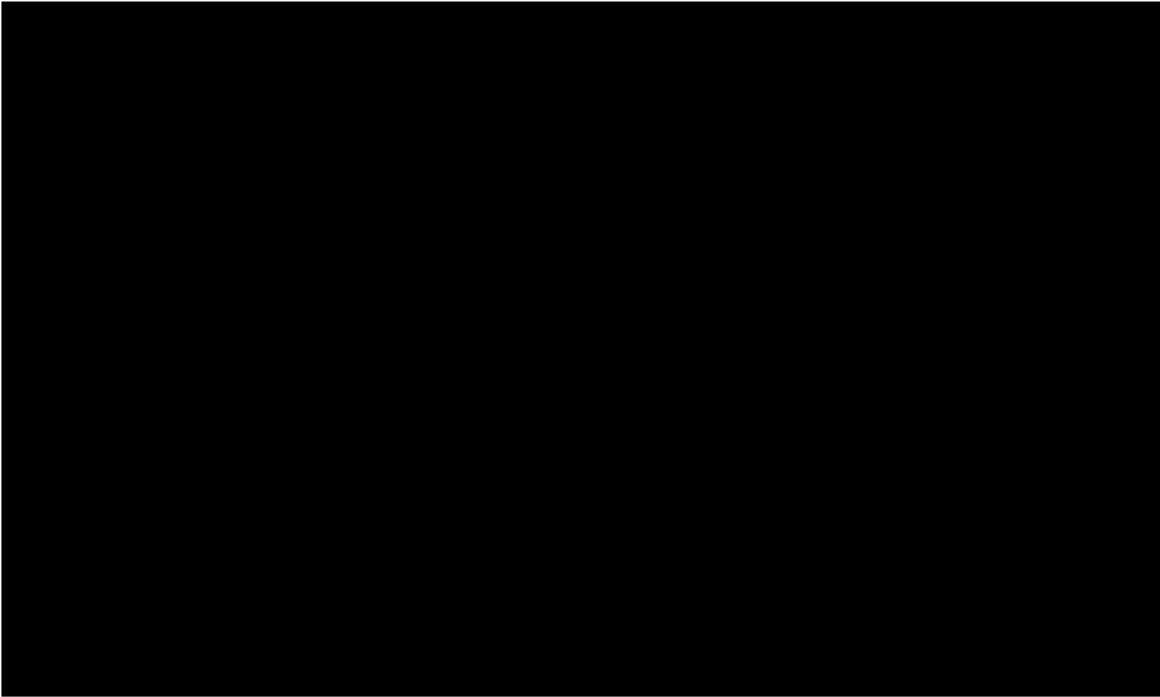
comparison, as it is understood that NG is in discussion with these vendors as part of a separate study, and Kent was instructed to hold on this activity while this dialogue was ongoing.

2.3. Technology Readiness

The above platforms are available today, so engineering contractors should be ready to use them within engineering projects to support the construction of new H₂ or CO₂ pipelines.

Guidance on the development of appropriate weighted scoring systems for each pipeline type would be needed to ensure consistency across projects. Minimum requirements with respect to applicable datasets could also be defined for this purpose.





3. Open-Cut Installation Techniques

3.1. Overview of Open-Cut Installation

Open-cut excavation remains the predominant and most established method for large diameter high-pressure pipeline installation in the UK. The process involves the following sequential activities: soil investigation, survey and setting-out, trench excavation, pipe stringing and welding, lowering-in, coating of field joints, hydrostatic pressure testing, backfilling, and final reinstatement. Typical working corridor have a minimum width of 40 m depending on pipe diameter, soil type, environmental constraints, temporary storage requirements and construction equipment.

National Gas Transmission (NGT) and the wider gas industry apply comprehensive standards (e.g. IGEM/TD/1 [1] for hydrogen pipelines; PD 8010-1 [2] addresses the design, construction, and operation considerations for CO₂ pipelines), supported by company engineering specifications and procedures (e.g. T/SP/CE/1 [3], CE/2 [4], etc), to ensure safety, quality and long-term performance of open-cut installations of large diameter high pressure pipelines. These standards are evolving to accommodate hydrogen and carbon dioxide transport, incorporating Net Zero targets such as reduced emissions and recycled materials for future transmission systems.

3.2. Trenching Equipment and Excavation Practice

Standard 360° hydraulic excavators remain the most widely used equipment for pipeline trenching in the UK, due to their flexibility, availability of skilled operators, and adaptability to diverse ground conditions. Quick-change buckets and specialised attachments allow adaptation to a variety of soils and reinstatement needs.

Dedicated mechanised trenchers are increasingly adopted on major pipeline projects, offering enhanced productivity, consistent trench profiles, and improved safety by reduced manual labour. These machines are best suited to long, rural sections with uniform soil profiles and minimal obstructions. As of 2025, advancements include electric-hybrid models (e.g., Vermeer's e-series) that reduce carbon emissions by up to 40%, aligning with NGT's Net Zero strategy.

Examples of suitable trenching machines include:

- Vermeer T1255 Commander® 3 Terrain Leveller – widely used for rock trenching and utility corridors; capable of cutting trenches wider than 1.2 m.



Figure 3 Vermeer T1255III pipeline trencher (Image from www.vermeer.com)

- Tesmec 1475 EVO Rock Hawg – used in Europe for large diameter pipelines in mixed soils and rock; offers GPS machine control and automatic depth regulation.



Figure 4 Tesmec 1475XL EVO trencher (Image from www.tesmec.com)

- Trenchor T14 / T16 – heavy-duty chain trencher, effective in both soft ground and moderately hard rock.



Figure 5 Trenchor T16 trencher (Image from trenchor.com)

Table 3 summarises the suitability of key trenching machines for different soil conditions. Modern machines are commonly fitted with GPS depth sensors and automated grade assistance, providing the basis for the more advanced digital automation described in Section 3.3.

Table 3 Suitability of open-cut and trenching machines for different soil types

Soil Type	360° Excavator (Open-Cut)	Chain Trencher	Rock Wheel Trencher	Comments
Soft soils (clay, silt)	Excellent – flexible and efficient	Excellent – high productivity	Not required	Excavators are flexible, but chain trenchers improve consistency.
Sandy soils	Good, but sidewall stability may be an issue	Excellent – uniform trench profile	Limited	Shoring may be needed for excavator trenches; chain trenchers cut clean walls.
Gravelly / mixed soils	Moderate – bucket wear, sidewall collapse risk	Good – productivity depends on stone content	Good	Chain and wheel trenchers maintain shape; excavators may require benching.
Weak rock (chalk, marl)	Moderate – slow progress, high tool wear	Limited – chain wear increases	Good – effective with rock wheels	Rock wheels often used for chalk geology in SE England.
Hard rock (sandstone, granite, basalt)	Poor – requires breakers, very slow	Not suitable	Good – but slower, high power demand	HDD or trenchless methods often preferred in long stretches of competent rock.
Peat / organic soils	Excellent – light equipment required	Good – specialised chain trenchers available	Not suitable	Stability and dewatering are critical; chain trenchers useful in consistent peatland.

3.3. Bedding, Padding and Backfilling

Bedding and padding must provide uniform pipe support and protect the pipeline from point loads. Engineered imported materials or processed native soils are used according to IGEM/TD/1. Imported fill is substituted with processed spoil materials when possible to reduce carbon footprint.

Backfilling includes careful lift and compaction, typically using vibratory or plate compactors with density testing for compliance. GPS-enabled compaction techniques now offer digital tracking and quality assurance, with AI analytics for real-time density verification in the future.

3.4. Pipe Express® Semi-Trenchless Methods

Pipe Express® (Herrenknecht) integrates narrow trench excavation / spoil removal, pipeline installation, and initial backfilling into one continuous operation with a narrow (~10 m) corridor width. This reduces land take, spoil removal, reinstatement, and overall construction time, particularly effective in long rural sections with soft soils and low groundwater levels.

Although its applicability is limited in areas with deeper cover depth or variable soil conditions, Pipe Express® presents a hybrid approach bridging conventional open-cut and fully trenchless methods. As of October 2025, it has not been deployed in the UK for gas pipelines but has seen success in European projects. Further discussion is provided in Section 4.7.

3.5. Emerging and Future Technologies

Recent innovations in machine control and automation include GPS-guided excavators and trenchers with automatic grade control and digital data capture for excavation precision and construction quality. AI-driven

systems are reported to improve fuel efficiency and reduce emissions by up to ~30% in specific industrial applications [5], and similar gains may be achievable for trench excavation operations.

Benefits of automation include improved efficiency, reduced operator fatigue, reduced environmental footprint, and more accurate as-built documentation. Emerging technologies promise future AI-driven autonomous trenching, robotic pipe lowering, and integrated digital twin monitoring enabling high productivity and low-carbon construction. Table 4 summarises the shift from current to future trenching practices.

Table 4 Future Trenching Practice

Aspect	Current Practice (2025)	Future State (3–10 Years)
Excavation and Level Control	Manual grade control; limited 2D/3D guidance	Fully autonomous AI-driven excavation with real-time control
Trench Stability	Visual inspection and reactive shoring	Real-time sensors, predictive modelling of trench stability
Bedding & Padding	Manual placement or padder with fixed rate	Automated padding with spoil re-processing
Pipe Handling & Lower-In	Manual side boom coordination	Robotic multi-boom automated lowering
Backfill & Compaction	Visual lift control; spot tests	GPS-mapped intelligent compaction
As-Built Data	Digital records; sporadic drone survey	Integrated digital twin with real-time data capture
Emissions	Mainly diesel with some hybrid plant; limited HVO fuel	Battery-electric/hydrogen plant for zero emission operation
Programme Certainty	Experience-based planning; weather-dependent	AI-assisted dynamic scheduling with real-time optimisation and risk mitigation
Safety	Operator-assisted	Remote/no-operator with hazard prediction
Sustainability	Spoil recycling (50-70%)	90%+ recycling with AI material sorting

The first UK trial of an autonomous excavator integrating AI control, a 3D digital ground model and real-time LiDAR sensing was undertaken at Manchester Airport in 2025, demonstrating the feasibility of automated earthworks in a live infrastructure environment. In parallel, major pilot projects such as National Grid’s 2024–2025 pipeline demonstration in Southeast England, Gasunie’s hydrogen pipeline initiatives in the Netherlands, and the Trans Adriatic Pipeline (TAP) in Europe have been exploring the use of low-impact construction technologies, including automated trenching systems, modular trench boxes, and enhanced digital QA tools, to reduce construction duration, improve safety, and lower carbon emissions. While full deployment details are still emerging, these early initiatives highlight the direction of development for sustainable, technology-enabled pipeline construction in the UK.

Anticipated developments for trenching include fully autonomous excavation and lowering systems, and low-carbon battery or hydrogen-powered machinery to meet NGT’s Net Zero emission targets. Embedded soil and pipeline sensors for health monitoring, and digital twin integration for real-time project management are also in development.

Table 5 below summarises the Technology Readiness Level and potential impact of different technologies.

Table 5 TRL and Impact Summary for Emerging Trenching Technologies

Technology	TRL	Impact				Comments
		Cost	Safety	Env.	Ops.	
Autonomous excavation and lowering systems	7	+1	+2	+1	0	Magnitude of impact very dependent on route complexity and soil conditions
Battery or hydrogen powered machinery	8	0	0	+2	-1	Battery powered construction plant are widely adopted. Limited hydrogen fell-cell and hydrogen combustion engine powered construction plant are available.
Embedded pipe and soil sensors	8	+1	+2	0	+1	Typical sensing technologies include: Fibre-optic strain; temperature; moisture pore-pressure; acoustic; vibration; gas leakage
Digital twin integration	7	+1	+1	0	+2	Digital twin integration can provide real-time project management at construction phase, and integrity management during normal operation.

4. Trenchless Techniques

Trenchless construction techniques are widely adopted for installing pipelines beneath highways, railways, infrastructure, water courses and environmentally sensitive areas where open-cut methods are not practical or would cause significant disruption. These methods minimize surface impact, reduce spoil generation, and lower reinstatement costs. Each technique has its own operational envelope, risks, and cost implications, requiring careful selection during design. IGEM has a standard covering all trenchless techniques suitable for the gas industry (IGEM/SR/28 [6]), and NGT has an engineering specification for HDD (T/SP/CE/14 [7]).

The following sections summarise the principal trenchless techniques currently available. More detailed descriptions of some of the trenchless techniques and case studies are available in NIA_NGGTO069 project report for Pipeline Installation Techniques [8] and IGEM/SR/28.

4.1. Horizontal Directional Drilling (HDD)

HDD is the most prevalent trenchless technique for long, curved pipeline crossings beneath rivers, canals, roads, or environmentally sensitive areas. It involves three stages: a steerable pilot bore, successive back reaming to enlarge the borehole, and product pipe pullback. Modern rigs with walk-over or wireline guidance achieve high accuracy for lengths up to 2 km+ and diameters up to 1.5 m. HDD performs best in cohesive or fine-grained soils but faces challenges in coarse gravels or fractured rock where steering and fluid return are more difficult. The method's versatility and cost-effectiveness make it the default trenchless choice for medium to large scale pipeline projects. Industry surveys and contractor data consistently show HDD accounting for the majority of trenchless pipeline crossings, with project numbers several times higher than those completed using other methods.



Figure 6 HDD Rig (Image from prime-drilling.de)

For very long crossings or to reduce overall construction time, the intersect method (drilling simultaneously from both sides of the crossing) can be used. The two pilot bores are drilled and accurately steered using radar, GPS tracking or Gyro Steering Tool to meet in the middle of the drill path, after which the bore is reamed, and the pipeline is pulled from one side. This technique has been used successfully on major river crossings for large diameter pipeline projects worldwide and in the UK.

Advantages:

- Capable of long crossings (>1,500 m, record cases >4,000 m).
- Minimal surface disruption to land and watercourses.
- Intersect method reduces pullback force, programme duration, or allows longer crossing.
- Avoids direct disturbance to sensitive habitats.

Limitations:

- Risk of drilling fluid loss (frac-out), especially in fractured rock or gravels.
- Reduced performance in mixed soils or gravels with boulders.
- Requires long, straight pipe strings and large laydown areas.
- May be uneconomical for short crossings due to high mobilisation cost.

Applications:

- Major watercourse, highway and railway crossings.
- Crossings of SSSIs or wetlands where open-cut is not acceptable.
- Long spans where shafts are undesirable.
- Intersect method allows very long crossings or shortens programme time.

Case studies:

- River Eden HP Gas Pipeline Diversion, Carlisle, UK – 914 mm steel gas main, ~498 m drilled HDD crossing under River Eden.
- Solent Gas Pipeline Replacement, Isle of Wight, UK - Two × 324 mm steel gas pipelines, HDD crossings of 3,926 m and 3,930 m beneath the Solent.
- Lake Sakakawea / Missouri River Crossing, USA – Long-range HDD for transmission pipeline; single drive ~4,702 m (24–30" class).

4.2. Microtunnelling

Microtunnelling uses remotely controlled, slurry-supported tunnel boring machines that advance pre-fabricated pipes with jacking forces from a launch shaft or pit. Laser guidance ensures millimetric accuracy, making it suitable for high-precision pipeline installation. Drives up to 2000 m and diameters exceeding 3 m are common. Although capital intensive, microtunnelling machines have continuous face support which provides exceptional ground control and minimal surface disturbance in urban or sensitive environments.

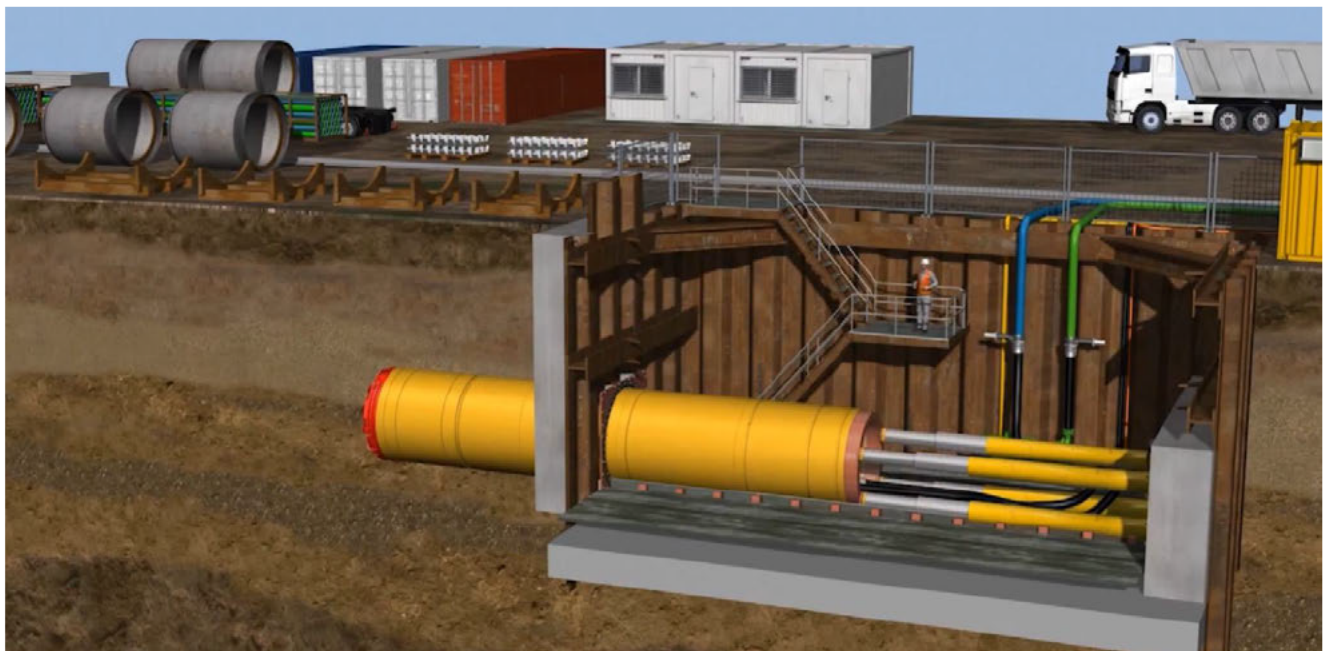


Figure 7 Microtunnelling (Image from www.herrenknecht.com)

Advantages:

- High alignment accuracy with laser guidance.
- Minimal settlement / ground movements risk with closed-face machines.
- Can handle a variety of ground conditions and groundwater pressures.
- Can install large diameter pipe < 3 m diameter.

Limitations:

- Requires launch and reception shafts / pits and slurry plant.
- Best suited for drives <1.5 km.
- High mobilisation and shaft /pit construction costs.

Applications:

- Corridors with high utility density and settlement sensitivity.
- Urban road and railway undercrossing.
- Precise grade-controlled installations for multi-utility tunnels.
- Crossings where HDD frac-out risk is unacceptable.

Case studies:

- Blackpool South Strategy Sewer Tunnels, UK – Two microtunnels, 1,200 mm ID concrete pipe, total length >550 m in silty sand along Blackpool seafront.
- Pannal to Asselby Gas Pipeline Rail Crossings, UK – Three microtunnel / pipe-jacked sleeves for 1,220 mm gas pipeline; 1,500 mm OD jacking pipes; crossing lengths 50 m, 60 m and 100 m under railways.
- Rotterdam Metro Extension, Netherlands – 1,000 mm diameter microtunnelling of 450 m length for utility corridors
- Northern Pipeline Interconnector Microtunnel, Queensland, Australia – 2,100 mm ID pressure pipeline installed by microtunnelling / pipe jacking over a 1,032 m drive between two shafts.

4.3. Pipe Jacking

Pipe jacking is a variant of microtunnelling typically used for larger diameters and shorter drives under roads or railways between shafts, and with semi or fully mechanised excavation at the face. The latest tunnelling technology can be incorporated into pipe jacking excavation systems, and a range of machines are available to suit most ground conditions from soft water bearing strata to hard rock.

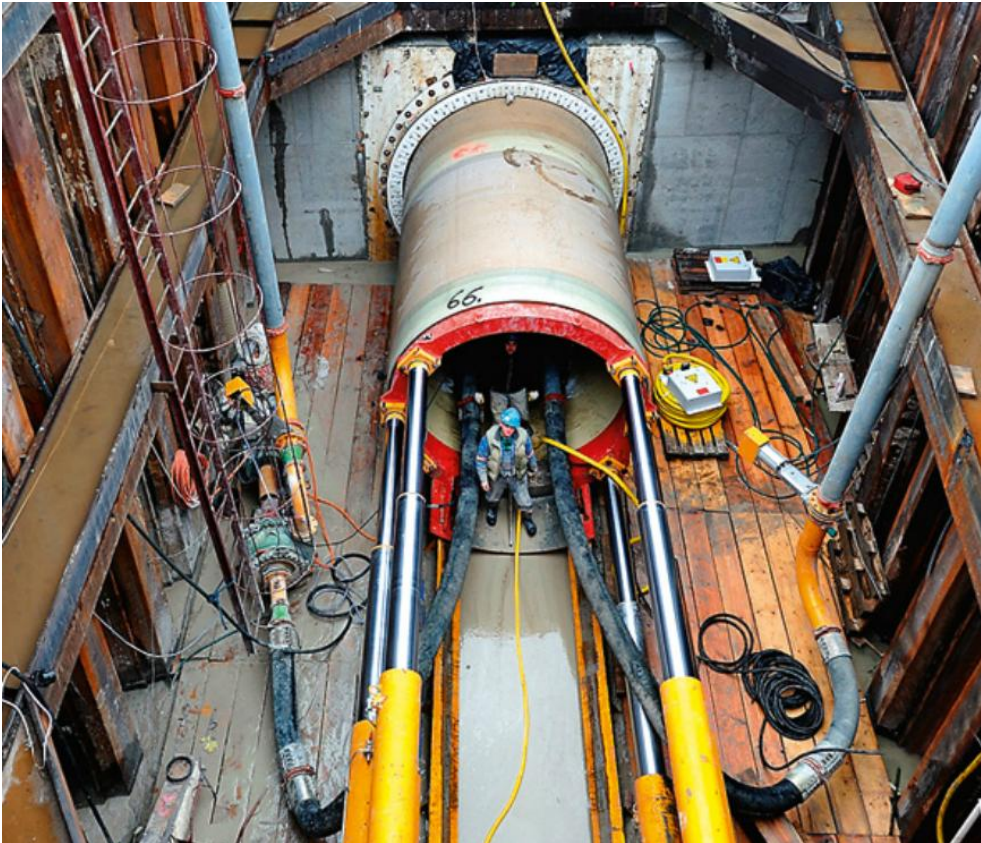


Figure 8 Pipe Jacking (Image from www.pipejacking.org)

Advantages:

- Simpler and lower cost than microtunnelling for short drives.
- Accurate line/level; minimal surface disruption.
- Effective beneath embankments from shafts.

Limitations:

- Limited to shorter lengths, typically <500 m, although up to 1000 m is possible.
- Requires groundwater control and face support in poor soils.
- Still requires shafts and jacking frame.

Applications:

- Short urban crossings, road/rail embankments.
- Where shafts are feasible and groundwater manageable.
- Utility corridors needing precise alignment over short distances.

4.4. Auger Boring

Auger boring is a semi-mechanised method using rotating augers within a steel casing to remove spoil while the casing is jacked forward. Once the bore is complete, a carrier pipe may be inserted within the casing or the casing itself can serve as the permanent conduit. It is suitable for short, straight crossings beneath roads, railways, and embankments up to 100 m in length and diameters from 300 to 1,200 mm. Best suited to cohesive soils such as stiff clay or dense sand, the method offers simplicity, low cost, and minimal surface impact but lacks steering capability and performs poorly in variable or saturated ground.



Figure 9 Auger Boring (Image from www.ukstt.org.uk)

Advantages:

- Low mobilisation and setup cost compared with microtunnelling or HDD.
- Simple operation requiring compact launch and reception pits.
- Minimal surface disruption; suitable for road and rail crossings.
- Proven, robust technology for short, straight crossings with wide contractor availability.

Limitations:

- Limited steering capability; alignment corrections are possible with new systems.
- Unsuitable for long drives or where precise grade control is required.
- Performs poorly in boulder-bearing, unstable, or highly variable ground.
- Not suitable for high groundwater level and variable ground conditions.

Applications:

- Short crossings and local utility interfaces under roads, railways, and embankments.
- Small to medium diameter casing installations in stable soils.
- Cost effective when HDD and microtunnelling are uneconomical.

4.5. Pipe Ramming

Pipe ramming employs a percussive hammer to drive a steel pipe (or casing) through the ground. The leading edge of the pipe penetrates the soil, and spoil is subsequently removed using compressed air or mechanical methods. Guide rails may be used for line and grade, but the method is not steerable. It is ideal for short, shallow crossings under roads or railways, particularly where settlement must be avoided. Typical lengths are under 80 m with diameters up to 1.5 m.



Figure 10 Pipe Ramming (Image from www.ukstt.org.uk)

Advantages:

- Relatively low cost and simple equipment compared to more complex trenchless machinery.
- Effective in many soil types including mixed ground.
- Useful for short to moderate crossings under road or rail embankments where steering isn't critical.

Limitations:

- Poor control over grade, and alignment. Once launched, deviations are difficult to correct.
- High impact forces can cause noise and vibration, and potential damage to adjacent structures.
- Obstructions (large rocks, boulders) can stall or deflect the pipe; risk increases with depth.
- Due to defects and crack grown risks for hydrogen pipeline, this method is more suitable as a sleeve or casing.
- Typically limited in drive length <80 m.

Applications:

- Road/rail embankments where shallow installation and minimal surface disruption are needed.
- Locations where steering accuracy is less important.
- Temporary bypass or low-risk third-party interface crossings.

4.6. Direct Pipe®

The Direct Pipe® system from Herrenknecht (also referred to as Direct Steerable Pipe Thrusting) integrates microtunnelling and HDD. A Tunnel Boring Machine (TBM) with active face support is attached directly to a prefabricated pipeline that is thrust forward continuously by a pipe thruster. This eliminates pullback operations while maintaining pressure control. Typical applications include river or environmentally sensitive crossings up to 1500 m in length and diameters up to 1.4 m.



Figure 11 Direct Pipe® (Image from www.herrenknecht.com)

Advantages:

- Steerable with high alignment accuracy.
- High borehole stability, even in weak or saturated soils.
- Suitable for high groundwater pressures.
- Automated, continuous process with minimal surface disturbance.

Limitations:

- High mobilisation cost; specialist equipment and crews.
- Substantial launch setup and thrust capacity required.
- Herrenknecht is currently the sole equipment supplier with limited UK contractors purchased the system may affect programme.

Applications:

- River/wetland crossings with challenging geotechnical conditions with groundwater.
- Sensitive habitats where fluid loss must be avoided.
- Large diameter, high accuracy crossings.

Case studies:

- Beatrice Offshore Wind Farm landfalls, UK – Two Direct Pipe® sea-outfall ducts, each 48" diameter and ~440 m long for export cable / pipe landfalls at Portgordon.
- TANAP Gas Pipeline, Turkey/Europe – Large-scale cross-country 48" pipeline with Direct Pipe® for river and road crossings

4.7. Pipe Express® Semi-Trenchless Method

Pipe Express® from Herrenknecht integrates shallow trench excavation, pipe installation, and initial backfilling into one continuous process with a narrow footprint (~10 m wide). Unlike conventional open-cut, it minimises corridor width and environmental impact. Best suited in soft, homogeneous soils and long/straight alignment.

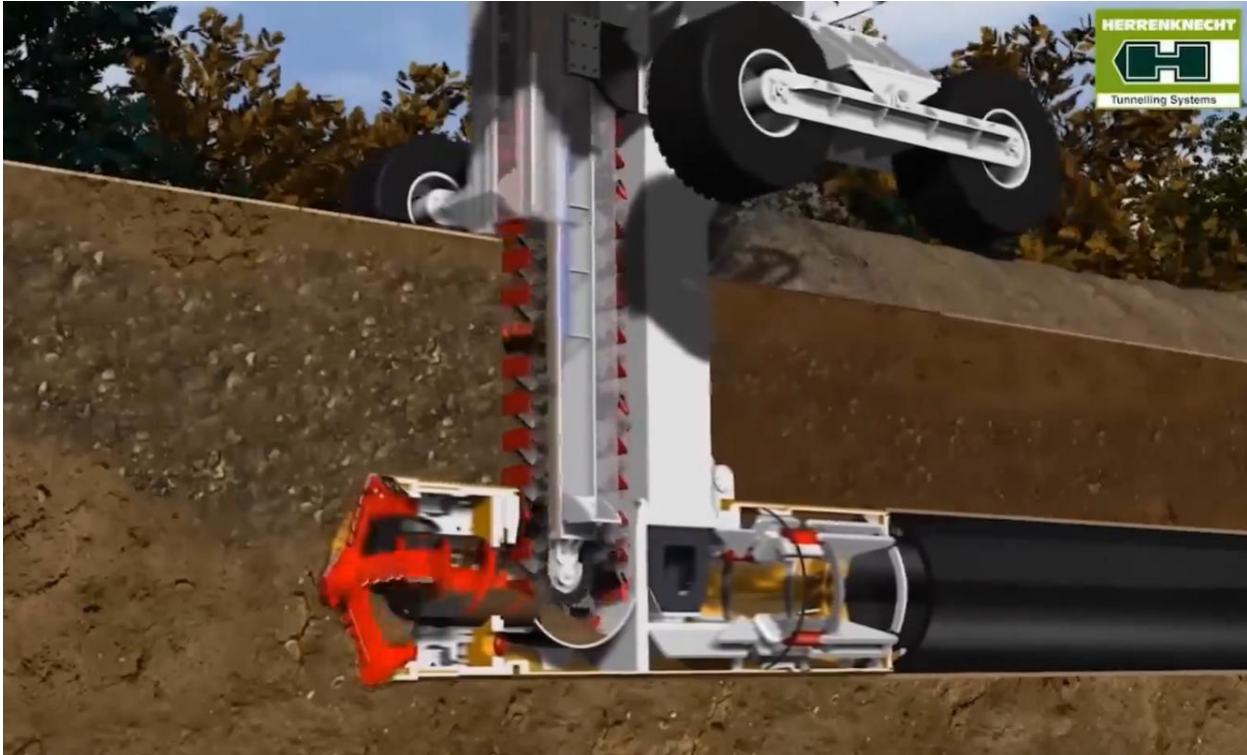


Figure 12 Pipe Express® (Image from www.herrenknecht.com)

Advantages:

- Reduced land-take, spoil and reinstatement compared with conventional open-cut.
- Continuous process reduces handling and rework.
- High production rate on long rural stretches than conventional open-cut in suitable soils.
- Lower environmental impact and carbon footprint.

Limitations:

- Limited to shallow cover depth (~2.5 m).
- Suited mainly to soft, homogeneous soils. Ground conditions must be fully understood to avoid coating damage.
- It will likely increase the number of golden welds.
- Herrenknecht is currently the sole equipment supplier with limited UK contractors purchased the system may affect programme
- Has not been used in the UK for gas pipeline installation as of 2025 (It has been used for installation of cable duct for Beatrice wind farm).
- Not suitable for crossing roads, railways, water courses, etc.

Applications:

- Long-distance pipelines in rural/agricultural land with suitable ground conditions.

- Environmentally sensitive areas where corridor width is restricted or areas where NGT has limitations on the construction corridor.
- Projects targeting reduced emissions and programme.

Case studies:

- First Gas Pipeline Application, Sevenum, Netherlands – 48” gas pipeline, ~488 m length installed using Pipe Express® for near-surface installation with narrow footprint.

4.8. Tunnel Boring Machine (TBM)

Large-diameter TBMs are used to construct tunnels; the pipeline is installed within the tunnel after completion. Normally use for exceptional cases in which other trenchless techniques are not suitable, where surface access is severely constrained such as mountain passes, long subsea crossings, dense urban corridors. Capable of very long distances exceeding 5 km.

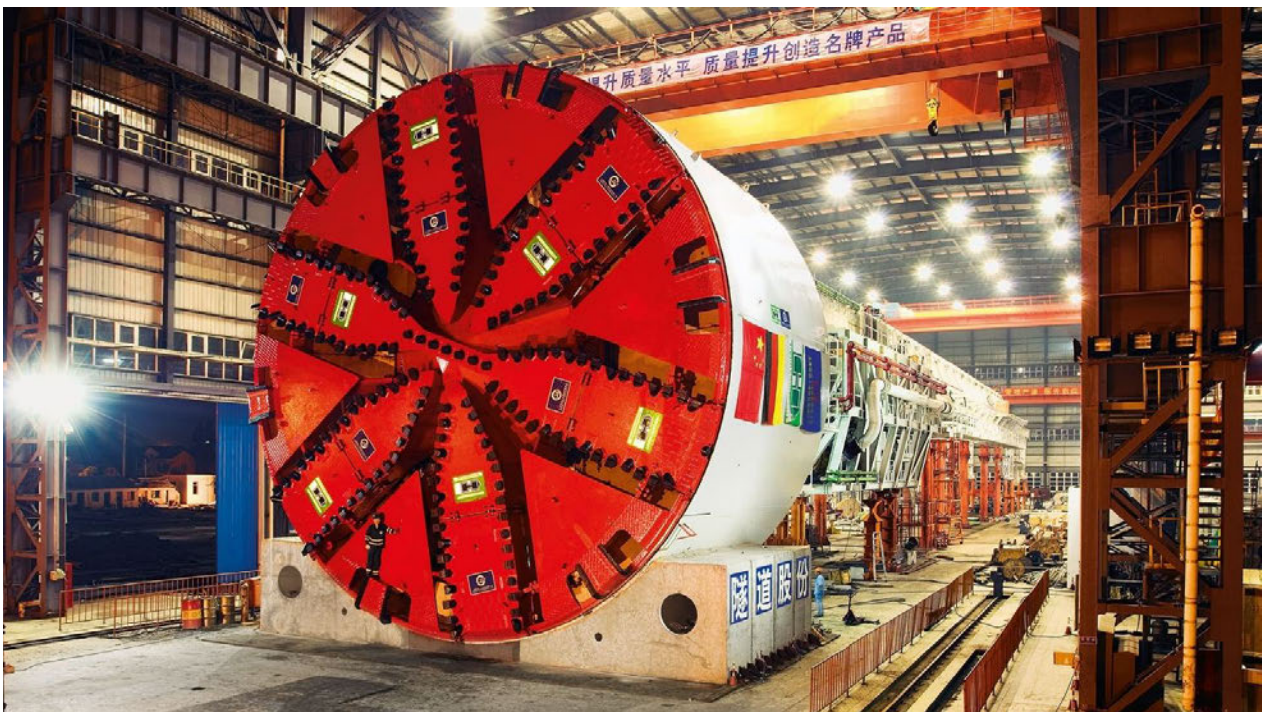


Figure 13 Tunnel Boring Machine (Image from www.herrenknecht.com)

Advantages:

- Very long crossings with negligible surface impact along alignment.
- Opportunity for multi-utility tunnels/future resilience.
- Excellent control of ground movements with suitable TBM/lining.

Limitations:

- Very high capital cost and long programme durations.
- Requires large launch and reception shafts.
- Complex logistics and spoil management.
- High commercial risk if advance rates underperform.

Applications:

- Strategic urban or subsea/river crossings (e.g. NGT Feeder 9 Humber crossing).
- Corridors requiring long-term multi-utility capacity.
- Mountainous terrain with steep gradients.
- High-consequence areas with strict settlement limits.

Case studies:

- Humber Crossing – Feeder 9 Replacement, UK – ~4.9 km long tunnel under the Humber Estuary; 4.38 m external diameter tunnel excavated by slurry TBM to house the 42" diameter high-pressure gas pipeline.

4.9. Vertical Shaft Sinking Machine (VSM)

Launching and reception shafts are normally required for TBM and other trenchless techniques such as microtunnelling. Common techniques for shaft construction include sinking or jacking precast concrete segments from the surface down. The excavation progresses in sections, with the extracted soil removed via cranes. Groundwater is managed through pumps or ground freezing, and spray-applied concrete (shotcrete) or other methods are used to permanently support the shaft walls as the excavation deepens.

The Vertical Shaft Sinking Machine (VSM) from Herrenknecht, is a mechanised system for sinking vertical shafts (4.5 – 18 m diameter, up to 250 m depth). Unlike conventional caisson sinking, the VSM uses a rotating cutting drum and slurry or water supported excavation, with precast segmental lining installed continuously. VSM is effective below groundwater.

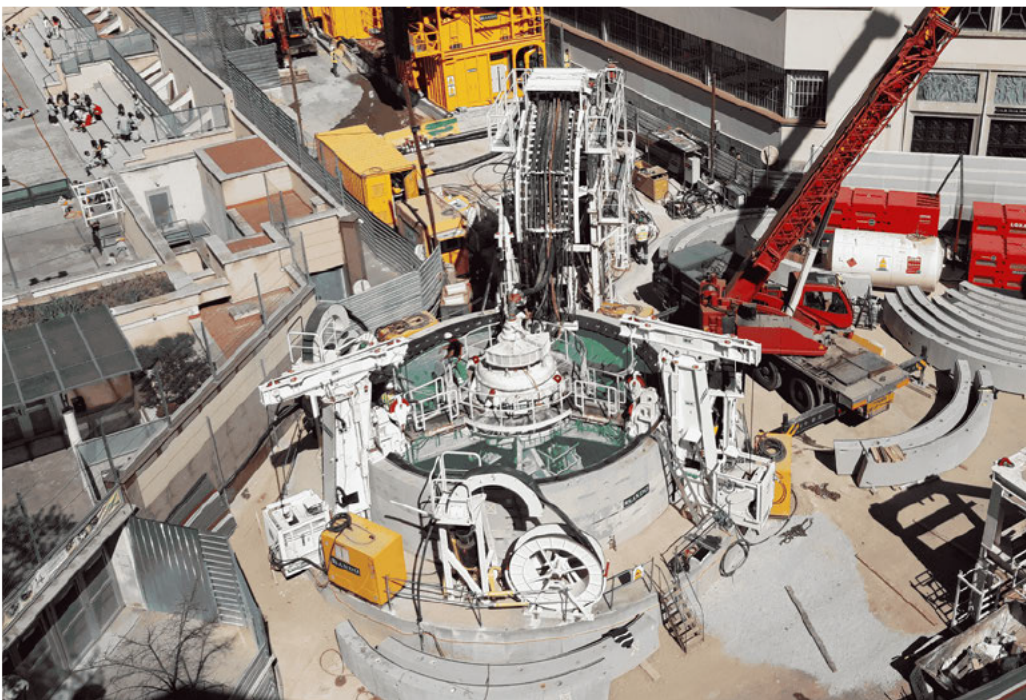


Figure 14 Vertical Shaft Sinking Machine (Image from www.herrenknecht.com)

Advantages:

- Mechanised, safer alternative to conventional shaft sinking.
- Designed for use below groundwater without extensive dewatering.
- Rapid and accurate construction of shafts.

Limitations:

- Specialist equipment, limited availability in the UK.
- High mobilisation and support costs, uneconomic for isolated/small projects.
- Shaft diameter constrained to machine design limits.

Applications:

- Launch/reception shafts for TBMs and other trenchless techniques.
- Access, ventilation and inspection shafts for deep utility tunnels.
- Sites with challenging hydrogeology.

4.10. Selection Guidance and Comparative Assessment

4.10.1. Trenchless Techniques Selection Guidelines

The trenchless techniques described in Sections 4.1 to 4.9 vary significantly in terms of suitability for ground conditions, environmental impact, cost and technology maturity. Selection of the most appropriate method requires consideration of advantages, limitations and technology readiness, and project-specific factors such as crossing length, soil conditions, third-party constraints and risks.

Table 6 below may be used for early screening / optioneering. Relative costs assume large diameter pipelines ($\approx$ 900–1200 mm) in the UK.

4.10.2. Technology Readiness Levels (TRL)

Table 7 below assesses the Technology Readiness Level and potential impact of different techniques.

Most trenchless methods are TRL 9, i.e. fully proven. Direct Pipe[®], Pipe Express[®], and VSM are TRL 8-9 in the UK (proven internationally but limited UK deployments as of 2025).

4.10.3. SWOT Highlights by Method

A summary of key strengths and risks is provided in Table 8 below. Full SWOT tables are given in Appendix A.

4.10.4. Discussion

A wide range of trenchless techniques is available, each suited to specific crossing requirements and ground conditions. Although no major step-change innovations have emerged in recent years, incremental advances in equipment design, guidance systems, and digital control have substantially improved reliability, achievable drive length and installation accuracy. Modern systems can now accommodate a broader range of soil types and geotechnical conditions than was previously possible. The use of biodegradable drill fluids and electric rigs can help achieve Net Zero compliance.

The selection of an appropriate method should follow a structured option appraisal, considering the technical feasibility, cost, environmental impact, and socio-economic factors of each viable alternative. A detailed assessment of site constraints, ground conditions, groundwater regime, and environmental sensitivities must be undertaken to determine the most suitable technique for each crossing.

To minimise the risk of failure, high-quality ground investigation along the proposed alignment is essential. In areas of complex or variable geology, horizontal boreholes following the intended drill path should be considered to provide continuous subsurface information which allows for the collection of core samples and perform in-situ testing along the borehole's path, providing a clearer picture of the subsurface conditions than a small number of vertical boreholes. Early engagement with experienced trenchless contractors is strongly recommended to validate constructability, confirm method suitability and optimise design prior to mobilisation.

Table 6 Comparison of Trenchless Techniques

Method	Advantages	Limitations	Maximum Length / Diameter (m)	Relative Cost
HDD	Long crossings (>1,500 m), minimal surface impact; widely available contractors	Risk of frac-out; geology dependent; requires laydown area	1,500–2,000 / 1.5	Moderate
HDD (intersect)	Extends crossing length (>3,000 m possible); reduced pullback forces; shorter programme	Risk of frac-out; geology dependent; requires laydown areas; requires two rigs/shafts; precise bore alignment required	2,000–4,000+ / 1.5	Moderate–High
Microtunnelling	Accurate, urban-suitable; minimal settlement risk	High mobilisation cost; shafts required	<2,000 / 3+	High
Pipe Jacking	Low cost for short drives; minimal surface disruption	Limited length; dewatering often needed	<500 / 3	Moderate–High
Auger Boring	Low cost for short drives; minimal surface disruption	Non-steerable; Limited length	<100 / 1.2	Low
Pipe Ramming	Low cost, simple, robust in many soils	Non-steerable; vibration; obstruction risk; suitable as a sleeve/casing	<80 / 1.5	Low
Direct Pipe®	Bore stability; continuous install; handles groundwater	High mobilisation cost; limited suppliers	1,000–1,500 / 1.4	High
Pipe Express®	Narrow corridor, continuous laying, lower spoil volumes	Limited cover depth (~2.5 m); soil-dependent; limited suppliers	1,000–2,000 m/ 1.5	Moderate
TBM	Very long crossings (>5 km); multi-utility potential	Very high cost, long programme duration	2,000–>5,000 / Unlimited	Very High
VSM	Safe, mechanised shaft construction under groundwater	Specialist, high mobilisation cost	Depth up to 250 / 4.5 - 18	High

Category	Sub-category	Item 1	Item 2	Item 3	Item 4	Item 5
Category 1	Sub-category 1	Item 1.1	Item 1.2	Item 1.3	Item 1.4	Item 1.5
Category 2	Sub-category 2	Item 2.1	Item 2.2	Item 2.3	Item 2.4	Item 2.5
Category 3	Sub-category 3	Item 3.1	Item 3.2	Item 3.3	Item 3.4	Item 3.5
Category 4	Sub-category 4	Item 4.1	Item 4.2	Item 4.3	Item 4.4	Item 4.5
Category 5	Sub-category 5	Item 5.1	Item 5.2	Item 5.3	Item 5.4	Item 5.5
Category 6	Sub-category 6	Item 6.1	Item 6.2	Item 6.3	Item 6.4	Item 6.5
Category 7	Sub-category 7	Item 7.1	Item 7.2	Item 7.3	Item 7.4	Item 7.5
Category 8	Sub-category 8	Item 8.1	Item 8.2	Item 8.3	Item 8.4	Item 8.5
Category 9	Sub-category 9	Item 9.1	Item 9.2	Item 9.3	Item 9.4	Item 9.5
Category 10	Sub-category 10	Item 10.1	Item 10.2	Item 10.3	Item 10.4	Item 10.5
Category 11	Sub-category 11	Item 11.1	Item 11.2	Item 11.3	Item 11.4	Item 11.5
Category 12	Sub-category 12	Item 12.1	Item 12.2	Item 12.3	Item 12.4	Item 12.5
Category 13	Sub-category 13	Item 13.1	Item 13.2	Item 13.3	Item 13.4	Item 13.5
Category 14	Sub-category 14	Item 14.1	Item 14.2	Item 14.3	Item 14.4	Item 14.5
Category 15	Sub-category 15	Item 15.1	Item 15.2	Item 15.3	Item 15.4	Item 15.5
Category 16	Sub-category 16	Item 16.1	Item 16.2	Item 16.3	Item 16.4	Item 16.5
Category 17	Sub-category 17	Item 17.1	Item 17.2	Item 17.3	Item 17.4	Item 17.5
Category 18	Sub-category 18	Item 18.1	Item 18.2	Item 18.3	Item 18.4	Item 18.5
Category 19	Sub-category 19	Item 19.1	Item 19.2	Item 19.3	Item 19.4	Item 19.5
Category 20	Sub-category 20	Item 20.1	Item 20.2	Item 20.3	Item 20.4	Item 20.5

Table 8 SWOT Highlights For Different Trenchless Techniques

Method	Strengths	Weaknesses	Opportunities	Threats
HDD	Minimal surface impact, intersect reduces pullback and time and allow longer crossings	Risk of drilling fluid loss (frac-out); requires long straight strings & large laydown area	Intersect method increases length capability (>3 km); innovation in drilling fluids	Geology sensitivity; public concern over frac-outs; limited contractor capacity
Microtunnelling	Very high accuracy; minimal settlement; good for urban sites	Requires shafts; high mobilisation cost; limited to ~1.5 km	Growth in congested cities; integration with digital monitoring	Groundwater inflow or mixed face can cause delays; limited UK capacity
Pipe Jacking	Simpler/cheaper than microtunnelling for short drives; robust	Limited to short lengths (<500 m); requires dewatering in poor soils	Modular shaft techniques to improve efficiency	Obstructions or poor face support can lead to settlement/ground loss
Auger Boring	Low-cost, proven method for short crossings; simple setup	limited steering capability; limited to short drives and stable ground	Guided or slurry-assisted heads could extend range and improve control	Outcompeted by HDD and microtunnelling for longer or high-accuracy crossings
Pipe Ramming	Simple, low-cost; effective for shallow road/rail embankments	Non-steerable; vibration risk; length limited; suitable as a sleeve/casing	Useful for temporary/low-risk crossings	Obstructions can stall progress; vibration may affect adjacent assets
Direct Pipe®	Continuous installation; bore stability; good in groundwater	High mobilisation; limited supplier market	Ideal for rivers/wetlands; avoids frac-out	Equipment failure or contractor shortage carries high consequence
Pipe Express®	Narrow corridor (~10 m); reduced spoil haulage; faster in soft soils	Limited cover depth (~2.5 m); requires homogeneous ground; limited supplier market; not suitable for road/river crossings	Good fit for Net Zero – lower carbon footprint in long rural sections	Few UK deployments; learning curve for contractors
TBM	Very long tunnels (>5 km); minimal surface disturbance; multi-utility	Very high capital cost; long mobilisation/programme	Strategic long-term tunnels; subsea & urban resilience	TBM breakdowns cause major delays; cost overruns common
VSM	Safe mechanised shaft sinking; effective under groundwater	High mobilisation; shaft size constrained	Enables deep launch/reception shafts in difficult hydrogeology	Limited UK contractor base; high mobilisation for small projects

5. Pipe Welding and Inspection

5.1. Overview

Pipe welding and subsequent inspection and coating can account for a significant fraction of total pipeline construction costs. This includes both materials/consumables for the welding operations as well as associated labour. A reduction in the time taken to complete each girth weld has a significant impact on the associated cost, so welding contractors have developed narrow gap welding processes that improve efficiency. There has also been research carried out to develop novel welding processes that complete a girth weld joint in a single shot, rather than employing multiple passes, using techniques such as laser, friction or electron beam welding. This research is often focussed on application to offshore pipeline installation where the time/cost incentives are very high, but the techniques could also be applicable onshore. Section 5.2 below reviews these alternative welding processes, as well as the automation systems that welding contractors have developed to improve the efficiency of conventional arc welding processes.

Welding efficiency and quality can also be improved by using data management tools to make best use of pipe geometry and other data, e.g. to assist in ensuring optimum fit-up of pipe joints prior to welding. Other data such as welding process parameters and NDT results can also be logged and viewed in near real time, which provides a valuable assurance tool during construction to enable an efficient response to any observed trends. Example tools and systems are reviewed in Section 5.3 below.

Automated methods for non-destructive testing have also been developed to enable similar efficiencies, rather than relying on manual methods that are typically employed in smaller construction or fabrication projects. Methods include both digital radiography and automated ultrasonic techniques. The latter are likely to be needed for construction of hydrogen pipelines, as they provide a means of sizing detected flaws (height and length) which is critical to ensure that welds have sufficient fracture capacity for this application. Systems for non-destructive testing are reviewed in Section 5.4.

Field coating methods are reviewed along with other coating technologies in Section 6.2.

5.2. Welding Processes and Equipment

5.2.1. Arc Welding Processes

IGEM/TD/1 states that pipe and fittings shall be prepared, welded and inspected in accordance with BS 4515-1. This British Standard applies to the welding of carbon steel pipelines and is specific to arc welding processes only.

Arc welding processes covered by BS 4515-1 and commonly used during onshore pipeline construction include SMAW, GTAW, GMAW, MAG and FCAW. For large scale construction projects, welding contractors use automated systems that incorporate multiple torches and associated robotics and sensors to complete the weld. As noted above, narrow gap bevels provide a means of improving efficiency, due to the reduced consumable requirements and shorter welding times. Specialised equipment is needed however, because of the limited access to the root area. Bevel angles are typically in the range 2-6° per side, with a 2-3mm root face / land.

Critical welding parameters include the consumable chemistry (e.g. low hydrogen), pre-heat and interpass temperatures, welding current / voltage, travel speed etc. and these are all defined in a welding procedure specification, which may be tailored depending on the material grade to be welded and qualified in accordance with Section 8 of BS 4515-1.

T/SP/P2 states that welding should be carried out in accordance with BS 4515-1 but also describes some additional requirements, which would in most cases be equally applicable to hydrogen or CO₂ pipelines. Supplement 2 to IGEM/TD/1 (for hydrogen pipelines) also includes some minor additional requirements associated with hardness limits and use of low-hydrogen electrodes. These requirements are considered to be

readily achievable, using welding procedures very similar to those already used by contractors for natural gas and other pipelines.

The automated robotic systems used by welding contractors should also be suitable for welding hydrogen or CO₂ pipelines with no significant modifications. Welding process parameters will need to be selected to suit the application and base material, but this should not pose any difficulty. Some example systems are illustrated in Figure 15 and Figure 16 below.



Figure 15 CRC Evans (a) P625 External Welding System and (b) Internal Welding Machine

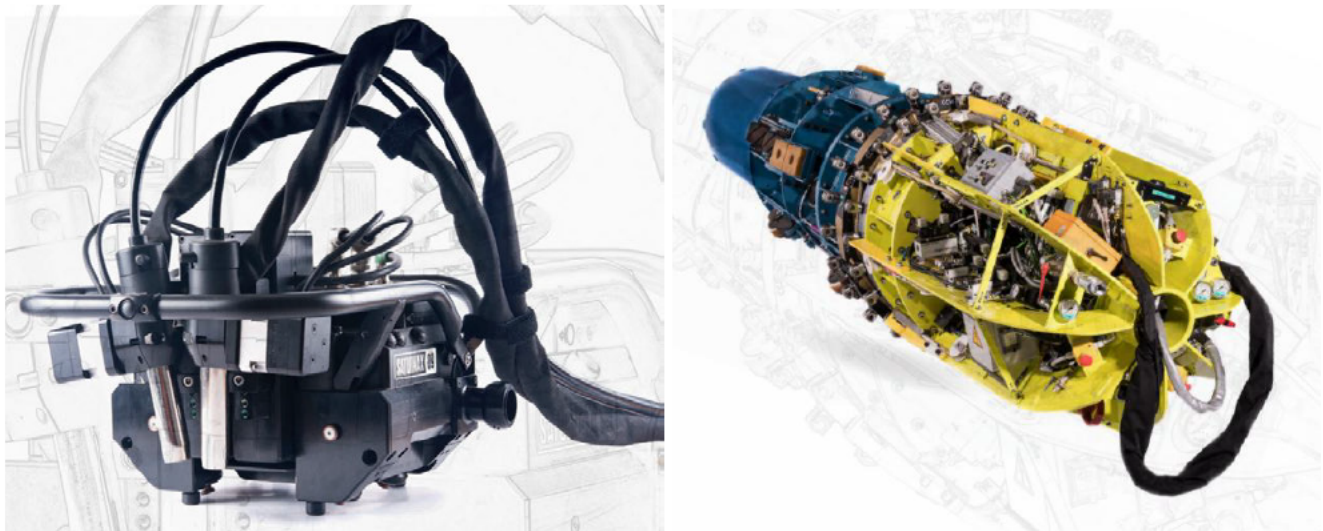


Figure 16 Serimax (a) Saturnax 09 welding system and (b) Internax Welding Machine

Internal welding machines incorporating multiple welding heads provide an efficient means of producing a high quality root pass. Internal clamps provide a pipe re-rounding capability to ensure better fit-up with reduced hi-lo and give a high quality root profile. This would be particularly useful for hydrogen pipeline applications where the stress concentration associated with axial misalignment caused by hi-lo is a significant factor in determining the girth weld's fracture capacity. The CRC Evans internal welding machine is available in sizes ranging from 24" to 60" with 4 to 8 heads depending on diameter.

In addition to the advanced automated welding systems described above, efficiency gains can also be realised by reducing the time needed to apply pre-heat. Induction heating provides a number of advantages compared to conventional flame preheating, such as improved safety and reduced labour requirement, but can also significantly improve productivity. Heat can be applied to a selected area rather than just in front of a torch, so this can give higher heating speeds. Power outputs depend on the system used but are sufficient for application to large diameter transmission pipelines.

5.2.2. Other Welding Processes

Aside from the conventional arc welding processes described above, research has been carried out to investigate other types of welding process such as:

- Laser or hybrid laser-arc welding
- Friction stir welding
- Electron beam welding

Hybrid laser arc welding [9] [10] [11] is a joining process that combines both arc and laser welding in the same weld pool. It has found use in the ship building industry and is well suited to the welding of thick steel plates in a single pass. This provides significant productivity gains by reducing the welding time in comparison to conventional arc welding processes. However, for circumferential welding of pipes, there is a limitation associated with the formation of weld defects during the closing of the weld as the laser power is ramped down. Achieving a high toughness in the weld metal and heat affected zone can also be a challenge. Although research is ongoing and there may be solutions to these problems, the technology has not been applied in this industry sector, so some significant development work would be needed to qualify this technique. Given the criticality of weld defects and fracture toughness for a hydrogen pipeline application, it is unlikely that this would be an area where the technology is developed and demonstrated. The technology may be better suited to natural gas or CO₂ pipelines.

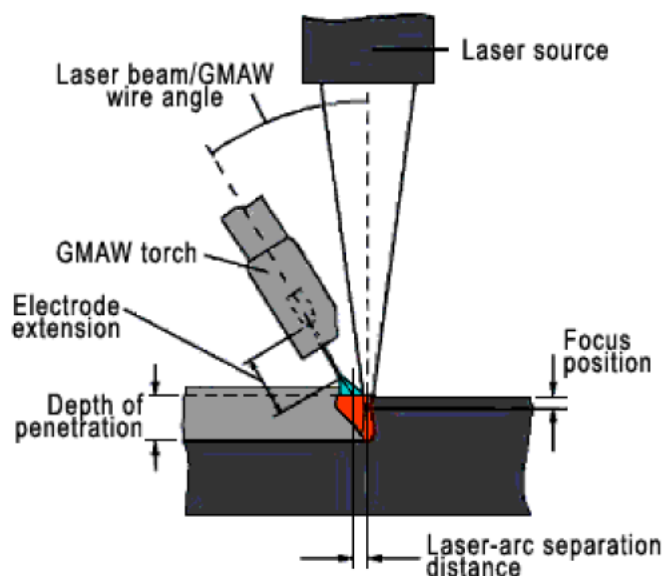


Figure 17 hybrid laser-MAG welding schematic from [10]

Friction stir welding is widely used within the aerospace and automotive sectors, particularly for welding of aluminium sheet and similar applications, but has also been considered as a potential process for welding steel pipelines [12] [13]. This is a solid-state process that uses a rotating tool to generate frictional heat between the parts to be welded. Its adaptation to steel pipelines presents several challenges, including high rates of tool wear and difficulty in achieving welds in the thicknesses of interest for transmission pipelines. Local heating can be applied to improve the performance of the process for higher wall thicknesses and advanced ceramic tooling materials can be used to improve wear characteristics. However, significant further development work and qualification activity would be needed before the technique could be used in this industry. The machinery associated with applying a force to the rotating tool would also need to be developed into field deployable units. These would also need to be transported along the line as work progresses, which is a disadvantage relative to its use on an offshore lay barge, for which most of the technology development has been focussed.

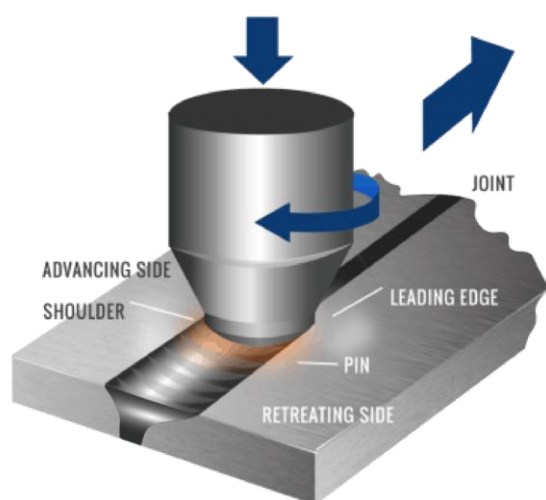


Figure 18 Schematic of friction stir welding process from [13]

Electron beam welding has a number of application areas but has historically been restricted by the need to carry out the welding operations within a vacuum chamber. However, recent advances have been made in the development of "Reduced Pressure Electron Beam Welding" where local sealing and pumping is used to provide greater flexibility [14] [15] [16]. The process is able to penetrate high wall thicknesses in a single pass and can produce high quality welds. However, significant investment would be needed to develop and qualify equipment and procedures for application to gas transmission pipelines. The bulky nature of equipment needed for this welding process is again a disadvantage.

As noted above, IGEM/TD/1 references BS 4515-1 which is specific to arc welding processes only. The use of other methods would therefore require an update to IGEM/TD/1 or the agreement of a project specific deviation, but as with any innovation, this does not preclude the development and use of new technologies. A qualification program would however be needed to demonstrate the effectiveness of alternative technologies in producing welds of equivalent or better quality. The advantages and disadvantages of different technologies is summarised in the Table below. The baseline in this instance is taken to be the manual welding systems commonly used by NGT and associated contractors in smaller construction projects. Use of state-of-the-art automated multi-torch arc welding systems would provide a significant benefit in terms of reduced time and cost, as would the use of advanced induction pre-heat systems, rather than conventional torches.

However, novel processes such as laser, friction or EB welding would require significant investment to develop the technology, and for application to onshore pipeline construction, there are significant challenges relating to both weld quality / toughness and the logistics of transporting associated machinery.

Table 9 TRL and impact summary for alternative welding technologies

Technology	TRL	Impact				Comments
		Cost	Safety	Env.	Ops.	
Automated multi-torch arc welding systems	9	+3	+1	0	+1	Internal systems can provide high quality for hydrogen applications
Advanced induction preheat	9	+2	+1	+1	0	Compared to conventional torches
Hybrid laser arc welding	5	+2	-2	0	0	Would have significant impact on cost, but doubts on weld quality and toughness, and low TRL
Friction stir welding	4	+2	-1	0	-1	
Electron beam welding	4	+2	-1	0	-2	

5.3. Digitalisation

In addition to the welding hardware systems described in the sub-section above, there are some improvements that can be realised by digitalisation and efficient use of pipeline data. One example of this is in relation to pipe end measurement and optimisation of fit-up prior to welding.

Laser pipe end measurement systems provide a means of recording detailed geometry data such as wall thickness and ovality for each pipe end. This is most efficient when applied in the pipe mill but can also be used in the field. The data can be used to calculate the optimum pipe rotation to be applied when fitting up selected pipe ends to minimise hi-lo, thus reducing the setup time and improving productivity.

In theory the technology could also be used to determine an optimum sequence of pipes to feed into the construction line. However, there are logistical limits on the extent to which this would be feasible. One specific application could be in the selection of pipes for a crossing, where a limited number of pipes would be needed, and potential delays associated with the discovery of unacceptable hi-lo immediately prior to welding would be most harmful (e.g. to productivity and project schedule).

Data from laser pipe end measurement systems can be combined with other welding data in digital platforms such as the CRC Evans DATA360 and Serimax CleverWeld. These systems allow the collation of information such as material data, geometry data, welding process variables, NDT data and coating data. This can be viewed in near real time, which provides a valuable assurance tool during construction to enable an efficient response to any observed trends, e.g. in the occurrence rate of defects or weld repairs.

Hi-lo data could also be used by NDT personnel carrying out inspection later in the construction sequence, where weld defect acceptance criteria could be optimised according to different levels of weld misalignment. For hydrogen pipelines where critical defect sizes are likely to be very small if conservative assumptions are made regarding all analysis inputs, this could be particularly useful (to avoid unnecessary weld repairs which have an impact on productivity and are of potentially lower quality).

Data will also be of great value to engineers involved in managing the integrity of the pipeline during subsequent operation, as detailed information on pipe geometry and weld defects are likely to be of use should the pipeline experience any damage, or if the pipeline is considered for pressure uprating or life extension.

Table 10 TRL and impact summary for digitalisation technologies

Technology	TRL	Impact				Comments
		Cost	Safety	Env.	Ops.	
Laser pipe end measurement systems	9	+1	+1	0	0	Reduces time for pipe fit-up. Minimises hi-lo and improves weld quality.
Welding and NDT data management systems	9	0	+1	0	+1	Improved technical assurance during construction and operations.

5.4. Non-Destructive Testing

Non-destructive testing of welds is carried out to ensure that welds are of the required quality level and do not contain defects that are larger than an established acceptance criterion. For hydrogen pipelines, this criterion is likely to be more stringent than for conventional natural gas pipelines, due to the detrimental effect that hydrogen has on the pipe material fracture toughness. Advanced methods for ensuring reliable detection and accurate sizing of weld defects are therefore of particular interest. For CO₂ pipelines acceptance criteria are expected to be similar to Natural Gas pipelines.

Automated methods for non-destructive testing have also been developed to provide time-saving efficiencies, rather than relying on manual methods that are typically employed in smaller construction or fabrication projects. These efficiencies mean that automated methods will be favoured on all large scale construction projects.

T/SP/NDT/2 describes procedures for non-destructive testing of welded joints in steel pipelines and pipework. It states that all butt welds should be inspected by radiography or manual phased array ultrasonic inspection. It does not cover automated ultrasonic inspection techniques or digital radiography. Therefore, although it is adequate for describing requirements for small construction projects, it is not well suited for large scale construction projects where automated techniques would be the norm. Some updates would therefore be needed if this document were to be used to specify requirements for NDT in major construction projects.

Digital radiography provides an alternative to conventional radiographic methods and this can be carried out in real time to enable rapid assessment. High quality digital images can be stored and viewed remotely to provide an efficient means of quality assurance. The technology also has environmental benefits associated with reduced use of chemicals and other consumables, as well as safety benefit associated with reduced radiation requirement. Systems such as Applus Rayscan real time radiography can be used for either double wall or single wall imaging and can inspect pipes of up to 56 inches in diameter.



Figure 19 Applus Rayscan real time radiography

Automated ultrasonic inspection systems often incorporate a range of different sensor types to allow detection of critical defects in different areas of the weld and in different orientations. Similar to the automated welding technologies described above, these often incorporate robotics and numerous sensors to reduce scan time. The Applus Rotoscan system can incorporate phased array (PA) and time of flight diffraction (TOFD) techniques as well as conventional ultrasonics. The Eddyfi Technologies WeldXprt system incorporates a similar range of methods, with simultaneous acquisition to improve efficiency.

The use of these systems is usually accompanied by a project specific qualification or validation activity to demonstrate adequate detection and sizing capability. As these systems were originally developed for use offshore, DNV recommended practice DNV-RP-F118 was developed for this purpose. This describes a process of performance verification using a project specific calibration block and test welds containing deliberately induced defects which are inspected and subsequently sectioned. It is suggested that this document could be used as a basis for determining appropriate assurance measures for onshore construction projects and included in an updated Appendix to T/SP/NDT/2.



Figure 20 Applus Rotoscan Automated Ultrasonic Inspection

The advantages and disadvantages of these technologies are again summarised in the Table below. In this instance, the baseline is taken to be conventional radiography and manual phased array, as currently described in T/SP/NDT/2. Both technologies would provide a significant benefit in terms of reduced time/cost relative to their manual counterparts. Improved reliability is the other main advantage.

Table 11 TRL and impact summary for digitalisation technologies

Technology	TRL	Impact				Comments
		Cost	Safety	Env.	Ops.	
Digital radiography (compared to conventional film)	9	+2	+1	+1	0	Quicker, real time data. Less radiation. Reduced use of chemicals / film.
Automated Ultrasonics (compared to manual)	9	+3	+1	0	0	Quicker, improved reliability of detection and flaw sizing.

6. Materials

6.1. Pipeline Materials

6.1.1. Carbon Steel

Gas transmission infrastructure is predominantly manufactured from carbon steel pipe and fittings. These are typically specified in accordance with material standards such as API 5L or ISO 3183. Depending on the pipe diameter, wall thickness and grade, a number of different manufacturing technologies are used to make the pipe, i.e. from steel plate or billet, such as:

- Seamless (SMLS)
- Longitudinal submerged arc welded (SAWL)
- Helical submerged arc welded (SAWH)
- High frequency induction welded (HFI or HFW)

All of these methods are described in IGEM/TD/1 although the majority of the UK National Transmission System (NTS) is manufactured from SAWL pipe (or SMLS for smaller diameter spurs or AGI piping). However, T/SP/PIP/1 and T/SP/DAT/6 allow all of the above techniques, as summarised in the table below.

Table 12 Typical pipe diameter, wall thickness and grade combinations given in T/SP/DAT/6

Diameter (mm)	Grade	Typical Wall Thicknesses as per T/SP/DAT/6 (mm)			
		SMLS	SAWL	SAWH	HFW
15-100	B	All	-	-	-
150-200	X42	All	-	-	All
250-300	X52	All	-	-	All
400	X52	All	All	-	All
450	X52	9.5, 11.9	9.5, 11.9	-	9.5, 11.9
	X60	15.9	15.9	-	15.9 (f=0.3 only)
600	X52	-	9.5, 14.3	9.5, 14.3	9.5, 14.3
	X60	-	19.1	19.1	-
750	X52	-	11.9	11.9	-
	X60	-	15.9, 19.1, 22.2	15.9, 19.1	-
900	X60	-	12.7, 19.1	12.7, 19.1	-
	X65	-	15.9, 25.4	15.9	-
1050	X60	-	14.3	14.3	-
	X65	-	17.5, 19.1, 28.7	17.5, 19.1	-
1200	X65	-	15.9, 19.1, 22.4, 25.4	15.9, 19.1	-
	X70	-	17.5, 25.4	17.5	-
	X80	-	14.3, 15.9, 20.6, 22.9	-	-

For large diameter pipe, of most relevance for the majority of a transmission network, SAWL or SAWH will be the most relevant manufacturing methods, although HFW may be considered for 600 mm diameter pipe.

For new build hydrogen pipelines mechanical design will likely incorporate lower design factors to satisfy more stringent allowable stress limits, so pipe wall thicknesses may tend to be towards the higher end of those illustrated above. This may mean that the SAWH process is less able to manufacture pipe with the desired wall

100" Two - step SAWH pipe mill Product Range																
Outside Diameter		Wall Thickness														
Inches		0.250	0.281	0.312	0.344	0.406	0.438	0.500	0.562	0.625	0.688	0.750	0.812	0.875	1.000	
	mm	6.35	7.14	7.92	9.53	10.31	11.13	12.70	14.27	15.88	17.48	19.05	20.62	22.23	25.40	
24	609.6															
26	660.4															
28	711.2															
30	762.0															
32	812.8															
36	914.4															
40	1,016.0															
44	1,117.6															
48	1,219.2															

Figure 22 Product range for SAWH pipe at Corinth Pipe Works

Table 13 TRL and impact summary for carbon steel pipe

Technology	TRL	Impact				Comments
		Cost	Safety	Env.	Ops.	
SAWH steel pipe *	9	+1	0*	0	0	Less suitable for H ₂ but could widen supply chain for CO ₂ pipelines
HFW steel pipe *	9	+1				Fracture toughness testing needed to demonstrate applicability for H ₂ . Could widen supply chain for H ₂ or CO ₂ pipelines.

* Diameters or wall thicknesses beyond those already described in DAT/6

6.1.2. Composite Materials

The use of reinforced thermoplastic pipes (RTP) or Flexible Composite Pipe (FCP) for high pressure gas transmission is described in IGEM/TR/19. These pipes typically consist of a thermoplastic liner such as PE, reinforcement layers added to improve pressure containment capacity, which may be aramid, glass or carbon fibres, or steel wires or strips, and then an outer layer to provide external protection.

IGEM/TR/19 permits RTP pipe in rural ("R") area types but not in more populated areas ("S" or "T" area types). Crossings of high density traffic routes, A or B roads, railways or watercourses conveying traffic are also not permitted. For minor roads RTP pipe may be used but impact protection measures need to be applied.

Products such as SoluForce (illustrated below) are available for a variety of different pressure ratings and operating temperatures, but only in pipe sizes of 4 or 6 inches. SoluForce pipes are manufactured in the Netherlands. They are also supplied as spools which can provide an advantage with respect to installation (e.g. avoidance of welding) for short tie-in connections. A variant suited to hydrogen applications for pressure of up to 42 bar is also available and 4km of this has been used at Groningen Seaports to distribute green hydrogen to local industry. This variant incorporates a bonded aluminium layer to act as a barrier to hydrogen permeation.

SoluForce products have also been used at NTS Somerset farm biomethane connection and installed by HDD at NTS Theddlethorpe.

	TYPE:	Ø	PRESSURE*	DESIGN	RECOMMENDED USE:		
					TEMPERATURE:	Water	Hydrocarbon Offshore
		Inch	BAR / psi	°C / °F			
SoluForce Light							
	ST	L450 ST	4 45 / 653	85 / 185	○	○	
	GT	L540 ST	6 36 / 522	85 / 185	○	○	
	ST	L450 GT	4 45 / 653	85 / 185	○	○	
	GT	L540 GT	6 36 / 522	85 / 185	○	○	
SoluForce Classic							
	ST	M480 ST	4 113 / 1639	85 / 185	○	○	○
	GT	M570 ST	6 90 / 1305	85 / 185	○	○	○
	ST	M480 GT	4 113 / 1639	85 / 185		○	○
	GT	M570 GT	6 90 / 1305	85 / 185		○	○
SoluForce Heavy							
	ST	H415 ST	4 466 / 6759	85 / 185	○	○	○
	GT	H515 ST	6 388 / 5627	85 / 185	○	○	○
	ST	H415 GT	4 466 / 6759	85 / 185		○	○
	GT	H515 GT	6 388 / 5627	85 / 185		○	○
	HT	H415 HT	4 466 / 6759	105 / 225	○	○	○
	HT	H515 HT	6 388 / 5627	105 / 225	○	○	○
ST	Standard: Standard high performance FCP						
GT	Gas Tight: The industry's only true permeation tight FCP						
HT	High Temperature: Available with SoluForce Heavy with design temperatures of 105°C / 220°F						

Figure 23 Product range (SoluForce)

Other suppliers include Strohm (previously Airborne) and Future Pipe Industries also based in The Netherlands, PES.TEC based in Germany, and TUFFPIPE based in UK. Product ranges vary a little, as summarised in the tables below. Strohm supply flowlines up to 7.5" diameter in various grades and pressure / temperature ratings. Each supplier also provides a range of fittings or couplings that allow connection of pipe reels to each other or adjoining infrastructure.

Overall, these systems are limited to applications where relatively small diameter pipelines are needed, such as local tie-in points or connections between nearby industrial sites. In these instances, the technology provides a means of reducing installation costs, as reels of 1-4 km can be procured, with no need for welding or associated NDT.

Where some installation methods (such as HDD) may involve the application of significant axial stresses, analysis would be needed to ensure that the product has sufficient axial strength. However, the SoluForce product was installed by HDD at NTS Theddlethorp in Lincolnshire, so there is some track record in this respect. For very long HDD runs, where the length may exceed the length of pipe on a reel, the connector would also need to withstand axial forces, so some additional analysis or design may be needed in this instance.

Table 14 Product range (PES.TEC)

Type	Materials	Diameter	Pressure
RTP LP HDPE	PE 100, synthetic fibre	75-160 mm	40 bar
RTP LF HDPE	PE 100, aramid fibre	50-315 mm	25 bar
RTP LS HDPE	PE 100, steel	90-400 mm	30 bar
RTP MF HDPE	PE 100, synthetic fibre	75-150 mm	40-80 bar
RTP HF HDPE	PE 100, synthetic fibre	75-150 mm	64-120 bar
RTP HS HDPE	PE 100, steel	75-150 mm	64-120 bar

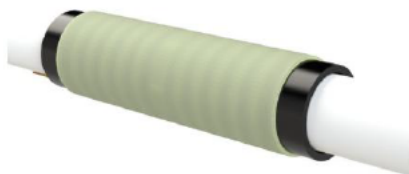
RTP US HDPE	PE 100, steel	75-150 mm	100-150 bar
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Table 15 Product range (TUFFPIPE)

Type	Materials	Diameter	Pressure
TUFFPIPE SC	HDPE, steel wire	50-150 mm	50-150 bar
TUFFPIPE FR	HDPE, polyester wire	50-150 mm	50-150 bar
TUFFPIPE GF	HDPE, glass fibre	50-150 mm	50-150 bar



End Fitting Flange



Inline Coupling



Inline Coupling Pipe-to-Pipe

Figure 24 Example end fittings and couplings (SoluForce)

A summary of the potential impact of this technology is given in the Table below. The baseline in this instance is taken as a carbon steel pipe of similar diameter. For short spurs or tie-ins, the cost benefit of reinforced thermoplastic pipe would be significant. However, as products are only available in relatively small diameters, and most of the network requirement for NGT will be for much larger pipe diameters, overall impact would be more limited.

Category	Sub-category	Material				Notes
		Steel	PE 100	PE 100	PE 100	
Category 1	Sub-category 1	Blue	Green	Yellow	Green	Notes 1
Category 2	Sub-category 2	Green	Green	Yellow	Green	Notes 2
Category 3	Sub-category 3	Green	Red	Yellow	Green	Notes 3

pipes have an integrity advantage compared to steel as they do not suffer from corrosion or hydrogen embrittlement. However, they can be susceptible to long term degradation in the form of swelling or thermal degradation, and may need additional protection against third party impact

** Polymer materials may be non-renewable but are less energy intensive during production compared to steel. They are also lighter, so will have less environmental impact during transportation and do not require welding.

Some of the suppliers described above also manufacture larger diameter composite pipe sections that are not reeled. A number of material types are available to suit different operating conditions. In this instance the advantage of reduced installation cost is diminished, and the higher material costs would be unfavourable, although reduced susceptibility to corrosion would still provide some operational advantage.

6.1.3. MASiP Pipe

Sustainable Pipeline Systems have developed a Mobile Automated Spiral Intelligent Pipe (MASiP) that consists of a polymer liner and a spirally wound overlapping high strength steel strip with a patented interlock. Environmental coatings are then wound over the steel reinforcement to provide corrosion and mechanical protection.

A fibre optic cable is also incorporated in order to allow in-service monitoring, e.g. for detection of pipeline movement or deformation



Figure 25 MASiP pipe structure

The end product is similar to some of the steel reinforced composite pipes described in the section above. However, the system is designed to be manufactured on site, rather than being delivered on reels, and this would potentially make it feasible to construct larger diameter pipelines where reels would become impractical.

SGN and Lloyd's Register have carried out a technology assessment for a 12-inch diameter pipeline system with two reinforcement layers [17] [18]. Stress analysis and burst testing have also been carried out for this diameter pipe, which was rated at 35 bar if unconstrained. Some analysis work was carried out to establish the extent to which pressure rating could be increased by using additional layers of steel strip, but this variant has not been manufactured and the results are yet to be validated by full scale testing.



Figure 26 MASiP pipe mobile fabrication concept

In addition to the uncertainties surrounding the ability to manufacture pipe with larger pressure capacity and diameter, there are also other aspects of pipeline that may need further work before the technology could be considered suitable for use. These include:

- The long term corrosion protection performance of the external wrap / coating system. Although these products are not novel, it is questionable whether they would provide adequate protection over an extended service life. For a conventional pipe, cathodic protection would be used to provide secondary protection and regular surveys and inspection carried out to identify areas of coating degradation and/or corrosion. It is not clear how the integrity of a MASiP pipe would be managed in service.
- Some analysis has been carried out to consider the impact resistance of MASiP pipe, e.g. with respect to excavator damage. The results appear promising, but it is likely that more work will be needed, i.e. if the intention is to use pipe in location types where RTP is currently precluded (see section 6.1.2 above).
- Some permeation of hydrogen through the polymer liner would be expected and this would lead to hydrogen being present in the annulus between the liner and subsequent outer layers. The pressure would be low, but the potential impact of hydrogen on the mechanical properties of the high strength steel strip would still need to be investigated. For higher pressure and higher diameter applications, the potential for liner collapse would also need to be considered.

Overall, it is considered that this system incorporates a unique combination of technologies that would potentially allow the construction of composite pipes of moderate diameter, somewhat larger than the more conventional RTP products described in section 6.1.2 above. However, the novel onsite manufacturing process has not been fully validated in the field, and it would take significant time and investment before it could be widely deployed to install significant lengths of pipeline infrastructure. The technology readiness assessment carried out with SGN and Lloyds Register [17] assigned a TRL of 7 for the 12" system capable of operating at 35 bar, but a lower score for higher diameter or higher pressure variants. It is also noted that, from the documents made available for review, qualification activities seem to be very focussed on demonstrating mechanical performance of the composite pipe and fittings. A wider consideration of other potential threats during all phases of life from construction to operations should be considered, i.e. in the form of a HAZID and/or FMECA, to ensure that all credible failure modes have been identified and addressed.

Before deploying this technology on large scale hydrogen infrastructure, it would be better to demonstrate its performance on a short length of pipeline within the natural gas network. Localised replacement of short pipe sections or installation of new branch connections could provide a suitable opportunity. However, some of the concerns described above would need to be resolved before this could be considered.

The technology may be well suited to new build CO₂ pipeline infrastructure, where gas phase transportation could involve relatively modest operating pressures, and the polymer liner would not be susceptible to corrosion if water were unexpectedly present in the gas stream.

A summary of the potential impact of this technology is given in the Table below. Similar to RTP pipe above, the baseline is taken as a carbon steel pipe of similar diameter. For short spurs or tie-ins, the cost benefit could be significant. However, as most of the network requirement for NGT will be for much larger pipe diameters, overall impact would be more limited unless higher pressure and higher diameter variants can be developed.

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6.2. Coatings

IGEM/TD/1 makes reference to BS EN ISO 21809 for factory applied coatings on buried pipelines and T/SP/CW/6 Part 2 describes additional requirements. Fusion bonded epoxy (FBE) coatings are the most commonly applied, and in general these have exhibited good long term performance within the NTS in conjunction with cathodic protection.

For field applied coatings, IGEM/TD/1 makes reference to BS EN ISO 21809-3 and T/SP/CW/5 describes additional requirements for a range of different products. Field joint coating systems applied during onshore pipeline installation are typically:

- Heat-shrink sleeves - Prefabricated cross-linked polyethylene sleeves with a heat-activated adhesive backing. The sleeve is wrapped around the field joint and heated to shrink tightly and bond to the adjacent mainline coating. Has the advantage of fast application and good mechanical strength and chemical resistance.
- Liquid epoxy systems – Two-component epoxy applied by brush, roller, or spray on the prepared steel joint area. Has the advantage of excellent adhesion and corrosion protection performance and continuity with the pipe FBE coating.
- Polyurethane systems - Two-component polyurethane applied by spray or pour. Has the advantage of high abrasion resistance and strong adhesion, e.g. for HDD crossings or rocky backfill.
- Cold applied tapes - Bitumen or viscoelastic compound tapes wrapped around the joint. Simple application with no heating required, but lower performance.

Transportation of hydrogen or CO₂ inside the pipe is not expected to influence the performance of external coatings. There is a potential influence of hydrogen permeation through the pipe wall, resulting in blistering and increased demand on the CP system, but it is likely that rates of permeation will be too low to have a significant influence. Where venting of CO₂ could lead to a local reduction in temperature, this may need to be considered, but this would only be very localised.

Historical performance of established coatings such as FBE has also been generally good, so there is not a strong incentive to explore novel alternatives. However, some relevant research activities are noted as follows

- Graphene enhanced coatings – These have been investigated, with enhancement of anticorrosion properties being attributed to increased mass diffusion resistance, improved adhesion or improved charge transfer for cathodic protection. However, in some instances a detrimental effect has been reported due to increased porosity and galvanic interaction between the graphene and steel [19]. The amount of graphene and its dispersion within the coating have been shown to be important parameters, with a well dispersed 0.01wt% coating performing better than a reference red oxide coating. However, this research is at a relatively early stage and the performance benefit does not appear to be significant.
- Self-healing coatings that incorporate inhibitors or other healing agents that are activated when coatings are damaged or environmental conditions change [20] [21] [22] [23]. These types of coating have been available for a number of years but have not found wide application in the pipeline sector. In theory, use of these coatings could lead to a reduction in the number of external corrosion defects that need to be repaired. However, this long term performance benefit has not been proven, so a demonstrator programme would be needed before coating suppliers would be interested in providing a solution at scale.

These new technologies would be better suited to above ground pipework at AGIs, where corrosion is more prevalent, rather than on buried pipeline sections where cathodic protection is usually very effective.

Table 18 TRL and impact summary for enhanced coating technologies

Technology	TRL	Impact				Comments
		Cost	Safety	Env.	Ops.	

Graphene coatings	3	0	0	0	0	Potential long term integrity benefits have not been proven or demonstrated
Self-healing coatings	5	0	+1	0	+1	Performance demonstrated in other sectors, but uncertain whether impact would be significant for this application.

7. Modular Construction Methods

7.1. Overview

Modular construction and off-site fabrication are increasingly adopted in UK energy and utility infrastructure. For pipeline and Above Ground Installation (AGI) projects, modularisation provides an opportunity to reduce on-site construction duration, improve quality control, and lower safety risks. These methods align with NGT's Net Zero strategy by enabling low-carbon, high-efficiency delivery and facilitating repeatable, standardised designs.

7.2. Drivers for Modularisation

The primary drivers for modular construction adoption include improved safety performance, reduced carbon emissions, shorter project schedules, and enhanced constructability in constrained environments. Factory-based fabrication enables work under controlled conditions, reducing weather dependency and re-work. Typical modular delivery programmes demonstrate 20–50% schedule compression and cut construction costs by 20% [24], and approximately 20% embodied-carbon savings [25] compared with conventional builds for the specific assemblies. For hydrogen and CO₂ projects, prequalification and pretesting of materials within modules will ensure compatibility with future transmission requirements. The demand for prefabricated and modular pipeline solutions is expected to grow annually by approximately 8% [26] globally as industries move towards more sustainable, faster, and cost-effective construction methods.

7.3. Current and Emerging Modular Approaches

Recent progress in modular pipeline delivery has focused on integrating prefabricated structural, mechanical, and electrical assemblies to reduce site labour, improve quality assurance, and shorten construction schedules. Across the UK and European gas sectors, a range of modularisation strategies are being implemented, from factory-built skids and containerised systems to precast and 3-D-printed civil components.

Skid-based AGI pipework modules allow repetitive assemblies of various components to be fully fabricated and pre-tested off-site. This reduces on-site welding, non-destructive testing, and permit durations. Containerised E&I (Electrical and Instrumentation) systems, are now common within AGIs and compressor stations, providing plug-and-play functionality and simplified commissioning.

At the civil and structural interface, precast trench and cover modules offer repeatable protection systems that minimise excavation, spoil disposal, and reinstatement effort. 3-D-printed reinforced concrete elements, such as foundations, valve plinths, and AGI bases, are emerging as sustainable alternatives to traditional formwork, achieving significant material and carbon savings. The convergence of these technologies supports a scalable, standardised approach to pipeline infrastructure delivery, enhancing safety, constructability, and long-term maintainability.

Table 19 below illustrates some examples of modularisation currently being deployed or trialled across the UK and European gas sectors.

7.4. Integration with Hydrogen and CO₂ Networks

For hydrogen and CO₂ transmission systems, modular pre-assembled units can incorporate pre-qualified materials such as hydrogen-compatible steel components, polymer-lined valves, and CO₂-resistant elastomers. Standardised module libraries and DfMA (Design for Manufacture and Assembly) principles will accelerate network replication across multiple sites. These modular designs support rapid deployment of compressor stations, pressure reduction installations, and hydrogen blending facilities, as seen in 2025 HyNet trials.

7.5. Cost, Risk and Logistics Considerations

Initial capital expenditure may be 5–10 % higher due to factory setup and transportation costs. However, overall project lifecycle costs are reduced through improved productivity, reduced weather delays, lower site labour

requirements, and decreased re-work. Modular construction also reduces exposure to high-risk construction activities, minimising personnel hours on live operational sites. Transport, cramage planning, and access routes must be carefully designed to accommodate large module movements, particularly within rural or constrained AGI locations.

- Logistics – Transport and lifting limits for large spools or skids (width, weight, route permits).
- Interfaces – Requires precise civil tolerances and early digital survey integration.
- Supply Chain – Limited UK fabrication capacity for large-diameter spools; may require international modular yards.
- Design Flexibility – Modularisation can constrain bespoke designs or late-stage route adjustments.
- Standards and Certification – Must align with IGEM/TD/1, PED, and ISO 3834 welding quality systems.

7.6. Digital Integration and Future Outlook

Future modular construction will be increasingly integrated with digital engineering and data-driven quality management. Digital twins linked to NGT's SAP/Maximo systems will enable real-time module tracking and lifecycle management. Automated QA using RFID or QR-coded components will provide transparent as-built traceability. Design standardization through DfMA libraries, combined with collaborative frameworks under ISO 44001, will allow replication of modular AGIs and pipeline components across the national network. Emerging trends include hydrogen-ready modular compressors, robotic pipe alignment tools, and low-carbon hybrid concrete-steel or 3-D printed foundation systems.

7.7. Summary

Modular and off-site construction offers a strategic pathway to achieve Net Zero delivery targets for future pipeline and AGI projects. When combined with digital engineering, automated welding, and low-carbon materials, modularization can deliver up to 50% shorter build times, 20% cost reduction in total installed scope, and measurable reductions in carbon and health-and-safety exposure. The key enablers are early integration of DfMA during design, adoption of standardized component libraries, and investment in UK fabrication and logistics capacity. For hydrogen and CO₂ transition networks, modularization will be essential to achieve rapid, replicable deployment with assured quality, traceability, and sustainability.

Table 19 Emerging technologies and methods in modularization

Technology / Method	Description	UK Examples (2024-2025)	TRL	Impact				Comments
				Cost	Safety	Env.	Ops	
Prefabricated Pipe Spools	Off-site welded sections transported and assembled on-site.	HyNet North West hydrogen tie-ins (2025).	9	0	+1	+2	0	≈ 20% emission reduction.
Skid-Mounted AGI Units	Pre-assembled compressor/regulation skids.	NGT FutureGrid blending facilities (2024).	9	+2	0	0	+2	≈ 30% schedule compression; improved quality and repeatability.
Modular Foundations	Modular supports for AGIs or pipelines; 3D-printed reinforced concrete bases (e.g. Hyperion Robotics)	Somerset biomethane connections (2025).	7	0	0	+2	0	≈ 20% carbon savings.
DfMA Libraries	Standardised component designs for replication.	National Underground Asset Register pilots.	8	+1	0	0	0	Enhanced scalability.
Containerised E&I systems	Pre-fabricated electrical and instrumentation modules in containers for plug-and-play AGI control and monitoring.	NGT upgrades (e.g., HyNet hydrogen storage facilities (2024 pilots).	8	+2	0	+2	+2	25-35% faster installation; reduced on-site wiring emissions by 40%; improved safety with factory-tested systems.
Pre-cast trench and cover modules	Pre-fabricated trench segments with integrated covers for rapid assembly in open-cut or hybrid installations.	NGT pipeline reinforcements in Midlands (2024-2025).	9	+2	+1	+2	0	20-30% quicker reinstatement; ≈ 25% lower material waste and carbon footprint through off-site production; enhanced protection against third-party interference.

8. Third Party Interference – Monitoring and Mitigation

8.1. Overview

Third-party interference (TPI) remains one of the predominant residual threats to the integrity of buried high-pressure gas pipelines. While the intrinsic reliability of the UK gas transmission network is high, historical incident data demonstrate that external interference such as excavation and construction activities by third-parties represents the majority of recorded pipeline failure incidents.

A comprehensive mitigation strategy is required which integrates design, construction, operation, and stakeholder engagement to ensure early prevention, rapid detection, and timely intervention throughout the asset lifecycle.

8.2. Third-Party Interference

Typical third-party interference incidents include:

- Unauthorised or accidental excavation within pipeline easements.
- Loading or compaction from construction plant or abnormal loading.
- Vibrations from piling or heavy compaction adjacent to the pipeline.
- Ground movement from construction activities adjacent to or underneath the pipeline.
- Land-use changes, reduced cover depth, or increased corridor access frequency.

Mitigation requires both engineering and procedural controls, combining physical protection, surveillance, real-time monitoring, and proactive stakeholder engagement with landowners, contractors, and local authorities. AI-enhanced systems have reduced detection times by 50% in recent trials [27].

8.3. Construction-Phase Mitigation

Effective control of third-party risks during construction depends on early engagement, physical safeguards, and active supervision.

Before any works near NGT assets, project teams should coordinate with developers, authorities, and adjacent utilities to confirm alignment clearances, access routes, and protection measures. If deemed necessary, soil/pipe interaction analysis and surface loading assessment should be carried out to demonstrate that pipeline integrity will not be adversely affected. Early coordination ensures haul routes, earthworks, and foundation designs fully account for pipeline location and integrity.

During construction, temporary protection may be required wherever heavy plant or cranes operate over pipelines. Common solutions include bog mats, steel road plates, reinforced concrete slabs, or engineered load-spreading layers to prevent overstressing and mechanical impact. Clearly marked pipeline alignment, fencing, and signage along the easement reinforce boundaries and reduce accidental encroachment.

Direct supervision is essential. NGT's representative should be present whenever third-party works occur near high-risk assets to monitor compliance with agreed RAMS (Risk Assessment and Method Statement) and intervene immediately if unsafe practices arise. Combined, these procedural and engineering measures provide a strong first line of defence against mechanical interference during third-party construction activities.

8.4. Post-Construction Monitoring and Surveillance

Traditional bi-weekly aerial surveys and line-walking, though effective, offer only snapshot visibility. Modern pipeline integrity programmes combine digital surveillance systems and manual patrols to improve the efficiency in detecting unauthorised activity within the easement and geohazard risks. Table 20 summarizes the latest

technologies and practices for continuous monitoring and surveillance of pipeline corridors, with most technologies at TRL 9, i.e. fully proven.

Table 20 Monitoring and surveillance technologies for pipeline corridors

Technology / Practice	Description	Maturity / TRL	Benefit & Key Constraints
Aerial & Satellite Monitoring	Use of UAVs or satellite imagery to detect ground disturbance, third-party encroachment, or vegetation anomalies.	9	Provides broad corridor coverage especially at remote areas. Limited by revisit frequency, image resolution, and weather conditions.
Centralised Autonomous Drone Inspections (BVLOS)	Drones operate Beyond Visual Line of Sight (BVLOS) from a central control room, following programmed routes to inspect infrastructure. Recently implemented by National Grid across its network of overhead power lines.	8-9	High-resolution imagery and frequent inspection without on-site pilots; reduces labour and exposure. AI-enabled image analysis Requires airspace approval, obstacle avoidance, and reliable communications.
Stationary Acoustic monitoring and visual surveillance	Acoustic and vibration sensing, surveillance camera integrated into a pipeline marker post. NGT has trialed the iDetect365 system.	8-9	Continuous monitoring and surveillance. Onboard AI to determine credible threats. Risk of vandalism; directional image capture within the Line of Sight only.
Fibre-Optic Distributed Acoustic Sensing (DAS)	Fibre-Optic cables installed along the pipeline or bonded to pipe coating, senses vibrations from excavation or heavy plant, ground movement, gas leak, etc. and raises real-time alerts.	8-9	Continuous monitoring over long distances; detects third-party activity and ground movement within minutes. Sensitive to background noise and requires maintenance of fibre integrity. Most suitable for new pipelines with high risk from TPI or geohazards.
Patrol Apps & GIS Integration	Field inspection data collected via mobile devices, synchronised to GIS for analysis and record keeping.	9	Improves traceability, consistency, and speed of inspection reporting.
Permit-to-Dig / Easement Activity Permissions	Digital permit systems controlling and recording all works within pipeline corridors, integrated with digital twin for real-time project management.	9	Prevents many TPI events pre-emptively. Effectiveness depends on compliance and enforcement.

8.5. Physical Protection Measures

Physical protection provides a permanent barrier between buried pipelines and surface activities. Where pipelines lie at shallow depth or beneath high-load areas such as haul roads or crane pads, reinforced concrete or composite protection slabs are typically installed to distribute loads and prevent overstressing.

In high-risk locations, such as road crossings, NGT routinely specifies heavy-wall pipes and installation of Ultra-High-Density Polyethylene (UHDPE) protection plates to guard against direct mechanical strike.

Surface awareness measures complement these structural defences. Marker posts, detectable warning tapes or PET mesh, and clearly defined wayleaves at field boundaries and crossings provide low-cost but essential visual indicators of pipeline presence. These features must, however, be inspected and renewed periodically to remain effective.

Where encroachment risks persist despite such measures, for example, within expanding industrial zones or where ground cover has been reduced, more substantial mitigation may be required. In these situations, the pipeline may need to be deepened or diverted to maintain adequate protection and ensure long-term integrity as surrounding land use evolves.

8.6. Future Opportunities

Looking ahead, the next generation of third-party risk mitigation will be driven by digital integration and predictive analytics. AI applied to satellite imagery, drone surveillance, and fibre-optic acoustic sensing will enable automatic detection of surface disturbances, unauthorised access and ground movement. This could dramatically reduce the time between occurrence and operator response.

Integrated corridor management platforms are emerging that fuse multiple data streams: imagery, vibration signals, and GIS mapping, into a single cloud-based dashboard accessible to both field and control-centre personnel.

The full implementation of the National Underground Asset Register (NUAR) will further enhance prevention by providing designers and contractors with authoritative, location-accurate subsurface asset information before excavation begins.

Finally, linking these data sources with pipeline digital twins will allow predictive modelling of interference probability, enabling operators to plan targeted inspections and preventative maintenance in advance of risk escalation.

Collectively, these digital and predictive technologies could significantly reduce third-party interference, underpinning a hydrogen-ready transmission system with enhanced safety, reliability, and environmental performance.

8.7. Summary

Third-party interference remains the principal external threat to buried high-pressure pipelines. The introduction of continuous, AI-enabled surveillance is transforming how operators detect and prevent such risks. Traditional aerial and line-walking surveys provide only periodic visibility; integrating drone, satellite, and fibre-optic sensing delivers near real-time awareness of corridor conditions.

Advances such as Centralised Autonomous Drone Inspection and the relaxation of BVLOS operating rules now allow routine, automated patrols of the extensive NGT pipeline networks. Combined with predictive analytics and digital twin technology, these systems enable early detection, rapid intervention, and targeted maintenance.

For new-build pipelines, the construction phase provides an opportunity to embed smart monitoring systems from the outset. Fibre-optic sensing cables installed alongside the pipeline can continuously detect vibration, temperature, gas leakage or strain changes that signal interference or movement. Demonstrated applications of this technology include UK LNG importation plant leak detection [28], European long-distance monitoring on the 55 km Berlin brine pipeline [29], and large-scale DAS deployment along the TANAP gas transmission corridor

into Europe [30]. Geotechnical sensors placed in backfill or at critical slopes can track settlement or groundwater variation, while smart coatings and remote cathodic-protection sensors improve corrosion control. Including spare ducts or conduits for future sensors and communications ensures the asset remains upgradeable. Installing these systems during construction minimises future retrofit work and establishes a digital-ready pipeline from commissioning.

It is envisaged that these technologies can be operated within a simple monitor–analyse–respond cycle. Data from fibre-optic sensing, autonomous drones, satellite imagery, patrols and the permit-to-dig system is brought into a central digital platform and correlated with GIS and historical risk information. AI-driven analytics detect ground disturbance or third-party activity, filter false positives and prioritise alerts. Confirmed events trigger rapid response actions such as drone verification, landowner engagement or field team mobilisation. Each incident then feeds back into the AI model and risk database, enabling continuous learning and progressively improving third-party risk mitigation.

A coordinated defence, linking physical protection, digital monitoring, and stakeholder collaboration, offers the most resilient strategy. This integrated, data-driven approach moves pipeline protection from reactive inspection toward proactive, continuous assurance aligned with Net Zero and public-safety objectives.

9. Update of NGT Standards / Specifications

[REDACTED]

- [REDACTED]
- [REDACTED]
- [REDACTED]
- [REDACTED]

10. Conclusions

The technology reviews presented in the sections above have highlighted a number of areas where the implementation of new technologies related to pipeline construction could have a significant impact on upcoming infrastructure projects. Many of these innovations are designed to reduce cost, but may also have other advantages associated with safety, integrity, environment or operations.

The reviews present a description of what is considered state-of-the-art. In this instance, deployment on projects would not require technology development. However, the technologies may need to be discussed with service providers and described in relevant contracts to ensure adoption. In some cases, associated NGT standards / specifications would also need to be updated prior to use, as described in the section above. Specific recent advances that are judged to offer the most potential for significant impacts include:

- Use of software tools for optimisation of pipeline routing during project engineering.
- Appropriate use of different trenchless installation techniques, including recent developments such as Direct Pipe and Pipe Express, depending on terrain and soil conditions and other requirements.
- Advanced automated internal and external multi-torch welding systems and line-up clamps. When used together with laser pipe end measurement systems and other digitalisation tools, these systems improve both production efficiency and weld quality.
- Factory-built modules, containerised systems, and 3-D-printed concrete foundations for AGI infrastructure elements reduce on-site labour and re-work, achieving substantial programme compression and embodied-carbon savings.
- Fibre-optic cables installed along the pipeline length to provide continuous monitoring capability for leak detection, third party interference and ground movement at high risk locations. There is a unique opportunity during construction to integrate this technology.
- Reinforced thermoplastic pipe for small diameter spurs / tie-ins.

The reviews also highlight a number of technologies that are yet to have reached the level of maturity to be widely implemented in projects. An indication of Technology Readiness Level is provided in this instance. In some cases, where TRL is very low, and the amount of investment required would be high, it is considered unlikely that these technologies will be developed within the timescale needed for implementation on planned infrastructure projects in the next 10-15 years. However, in some cases, the necessary technology development is considered more feasible. Examples of the latter instance include:

- Autonomous excavation and lowering systems (where terrain and soil type is appropriate).
- Battery electric or hydrogen powered trenching equipment.
- MASiP pipe as an alternative to conventional carbon steel linepipe. At present the technology has only been demonstrated for small/medium pipeline diameters that would only be applicable for NGT spurs or tie-ins. However, the main potential benefit of significantly reduced cost would only be realised on longer pipelines, which for transmission infrastructure is likely to be of larger diameter. Significant technology development is needed in this instance.

11. Recommendations

Specific recommendations associated with the potential deployment of different technologies on forthcoming construction projects include:

- Guidance for the use of software tools for optimisation of pipeline routing during project engineering should be developed to advise on appropriate weighted scoring systems to ensure consistency across projects.
- Early engagement with experienced trenchless installation contractors is recommended to validate constructability, confirm method suitability and optimise design prior to mobilisation. T/SP/CE/14 should also be updated to cover the wider range of trenchless techniques now available.
- Early engagement with linepipe suppliers is also recommended with regards to potential supply of pipe for hydrogen projects, where additional Manufacturing Procedure Qualification Testing will be needed. Updates are also needed to T/SP/PIP/1 to capture relevant requirements.
- Early engagement with welding / NDT contractors is also recommended to ensure that automated techniques and digital tools can be deployed on projects. This is particularly important for hydrogen projects where weld defect acceptance criteria may be very tight (compared to conventional natural gas pipelines). A dialogue with relevant contractors would be useful to ensure that realistic limits can be set and innovative methods for optimisation are explored. Some updates to T/SP/P2 and T/SP/NDT/2 will also be needed.

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Appendices

Appendix A. Full SWOT Tables for Trenchless Techniques

Horizontal Directional Drilling (HDD)

Strengths • Steerable and accurate; ideal for long crossings (<1.5 km). • Minimal surface impact, suitable for rivers/roads. • Proven, mature method with well-developed contractor capability in UK. • Competitive costs for medium-long crossings.	Weaknesses • Risk of drilling fluid losses (frac-out). • Requires large laydown areas and long, straight pipe strings. • Reduced performance in mixed or boulder-rich soils. • High pullback forces for very large diameter pipelines of long crossings.
Opportunities • Wider adoption of intersect method for very long crossings to reduce construction time. • Optimise fluid design and reuse for carbon footprint reduction. • Innovation in monitoring systems for automation and improved accuracy. • Alignment with Net Zero through reduced corridor disturbance.	Threats • Public/environmental concern from inadvertent drilling fluid release. • Challenging geology may lead to programme delays due to borehole collapse or stuck pipeline. • Contractor capacity constraints in UK market at peak demand.

Microtunnelling

Strengths • High accuracy with laser guidance (<50 mm) - ideal for urban, congested areas. • Minimal surface settlement risk with closed-face slurry shields systems. • Effective across a wide range of soils and groundwater pressures.	Weaknesses • Requires launch/reception shafts. • High mobilisation costs. • Limited to ~ 1.5 km drives typically. • Specialist crews needed.
Opportunities • Growing use in congested UK cities for utilities. • Integration with remote monitoring for ground movement. • Alignment with Net Zero goals through minimal surface impact and footprint.	Threats • Groundwater inflow and mixed face conditions can cause delays. • Limited contractor fleet capacity in UK and Supply chain delays for equipment.

Pipe Jacking

Strengths - Proven method for short urban crossings. - Simpler and lower cost than microtunnelling for short drives. - Minimal surface disruption.	Weaknesses - Limited to <500 m drives (typical). - Requires dewatering and face support in poor soils. - Shafts would add cost.
Opportunities - Use of modular shafts and mechanised systems improves productivity. - Potential for integration with other utility corridor projects.	Threats - Ground obstructions or poor face support may cause settlement. - Programme delays in variable geology.

Auger Boring

Strengths - Proven and reliable trenchless method for short crossings. - Low setup cost and simple operation. - Minimal surface disruption; suitable for road and rail interfaces.	Weaknesses - limited steering capability; limited control over line and grade. - Restricted to short lengths ≤ 100 m and stable ground. - Poor performance in variable or waterlogged soils.
Opportunities - Adoption of guided or slurry-assisted systems to improve control and extend reach. - Rising demand for cost-efficient trenchless options in constrained sites. - Hybrid with ramming for mixed soils.	Threats - Competition from HDD and microtunnelling for longer or more complex crossings. - Reduced suitability in difficult ground or high groundwater conditions.

Pipe Ramming

Strengths - Simple, low-cost equipment and mobilisation. - Effective in mixed ground. - Useful for short, shallow crossings under embankments.	Weaknesses - Non-steerable with poor line/grade control. - Noise and vibration constraints, risk to adjacent assets. - Defects and crack grown risks for hydrogen pipeline, more suitable as a sleeve or casing. - Limited length (typically 60–120 m).
Opportunities - Cost-effective solution for temporary or low-risk crossings. - Useful for integrating short, low-risk crossings or casing installations at interfaces between trenchless and open-cut sections. - Hybrid use with other methods.	Threats - Large obstructions can stall or deflect pipe. - Increased risk with depth due to soil resistance. - Declining use due to limited control.

Direct Pipe®

Strengths - Combines HDD and microtunnelling advantages. - Continuous installation with controlled face pressure for high bore stability. - Ideal for river or sensitive crossings with high groundwater pressures. - Reduced frac-out risk compared to HDD.	Weaknesses - High mobilisation and equipment costs. - Limited supplier base, specialist crews required. - Less effective in highly abrasive rock.
Opportunities - Ideal for rivers, wetlands, and challenging geotechnical conditions. - Growing UK and European adoption for gas and hydrogen pipelines. - Reduced environmental footprint.	Threats - High consequence of equipment failure mid-drive. - Availability of suitable equipment and crews in UK market. - No UK track record for large diameter gas pipeline.

Pipe Express®

Strengths - Narrow corridor (~10 m) and reduced land-take. - Continuous excavation and pipe installation reduces spoil handling. - Lower reinstatement costs and environmental footprint.	Weaknesses - Limited cover depth (~2.5 m). - Most effective in soft, homogeneous soils. - Specialist equipment with limited availability.
Opportunities - Well aligned with Net Zero and carbon reduction targets. - Potential for long rural sections with reduced haulage emissions.	Threats - No UK deployments to date; limited contractor experience. - Performance risks in variable ground or groundwater conditions.

Tunnel Boring Machine (TBM)

Strengths • Capable of very long crossings (>5 km). • Minimal surface impact and surface settlement risk along alignment. • Multi-utility tunnels possible, futureproofing networks.	Weaknesses • Very high capital and operational cost. • Long mobilisation and programme durations. • Requires large shafts and complex logistics.
Opportunities • Strategic use for subsea tunnels (e.g. Humber Feeder 9). • Potential for resilient urban multi-utility corridors. • Digital twins for monitoring.	Threats • Breakdowns cause major programme delays. • High risk of cost escalation. • Unexpected Geological conditions

Vertical Shaft Sinking Machine (VSM)

Strengths • Safe mechanised shaft sinking under groundwater. • Rapid and accurate shaft construction. • Segmental lining reduces need for dewatering.	Weaknesses • High mobilisation cost and support plant requirements. • Uneconomical for small projects. • Limited to machine-defined shaft diameters (4.5–18 m).
Opportunities • Valuable enabler for TBM and microtunnelling projects. • Potential wider UK adoption for deep access shafts. • Net Zero: Reduced dewatering.	Threats • Limited UK availability and contractor expertise. • High mobilisation cost may not justify smaller projects.

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NIA NGT0267: Pipeline Installation Techniques for Net Zero

WP1B: Decommissioning, Testing and Commissioning

National Gas

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Abbreviations

Abbreviation	Description
AGI	Above ground installation
AI	Artificial intelligence
BTEX	Benzene, toluene, ethylbenzene and xylene aromatics
CCUS	Carbon capture, utilisation, and storage
CIPS	Close interval potential survey
CP	Cathodic protection
CPA	Cubic plus association
DCVG	Direct current voltage gradient
DP	Dye penetrant
ECV	Emergency control valve
F&G	Fire and gas
GPS	Global positioning system
HP	High pressure
HV	High voltage
IGEM	The Institution of Gas Engineers and Managers
ILI	In-line inspection
LED	Light emitting diode
LP	Low pressure
LOSH	Limits of system handover
LSM	Large stand-off magnetometry
LV	Low voltage
MPI	Magnetic particle inspection
MWC	Main Works Contractor
NCM	Non-contact magnetometric inspection
NIA	Network innovation allowance
NGT	National Gas Transmission PLC
NTS	National Transmission System
PAUT	Phase array ultrasonic
PE	Polyethylene
PRI	Pressure regulating installation
ROW	Right of way
SIMOPS	Simultaneous operations
UKOPA	United Kingdom Onshore Pipeline Operators' Association
UT	Ultrasonic
VCI	Vapour corrosion inhibitor
WP	Work package

Executive Summary

This report presents a high-level procedure and summary of the expected activities necessary to decommission an existing pipeline currently in natural gas service, and suitably prepare it for repurposing to either hydrogen or carbon dioxide service. Such a procedure is required since existing practices are typically focussed on decommissioning for short term repairs/maintenance, mothballing, or abandonment and not for a change of service. The report also outlines relevant considerations for testing and commissioning both new-build and repurposed pipelines for hydrogen or carbon dioxide service.

Decommissioning: Many of the activities and considerations during the decommissioning phase are similar for hydrogen and carbon dioxide. Before the existing natural gas system is taken out of service, it will be important to undertake surveys and condition assessments to gather the data necessary to underpin the re-qualification process and determine the nature and extent of repair and modification works required. All necessary pig runs should also be completed at this stage, if possible, while there is a ready source of motive fluid. Some of the techniques, emerging technologies, and challenges with conducting integrity assessments are presented as well as a suggested methodology/approach to the issue of contaminants and requirement to clean the pipeline.

Once the pipeline is taken out of service and disconnected from adjacent natural gas infrastructure, the necessary intrusive works to repair, modify / divert, replace equipment, and enact tie-ins can commence. A summary of the expected activities and considerations for the timing and phasing of tasks is presented. Getting the right systemisation boundaries and sequencing of tasks will be important to avoid unnecessary extra stages and temporary equipment. The requirement to put in place preservation measures to prevent degradation of the pipeline internals/externals during the shutdown period is also discussed.

Testing and Commissioning: The expectations for hydrostatic/pneumatic strength testing, pre-testing of pups/assemblies, and leak (tightness) testing for repurposed assets are set out. Strength testing repurposed pipelines will not be a mandatory requirement but may be deemed necessary as part of the requalification process, particularly for hydrogen pipelines, where a high level hydrotest could help in demonstrating adequate integrity of welds. If necessary, strength testing will generally be in accordance with current natural gas practices though for repurposed pipelines the selection of appropriate test envelopes will need careful consideration to take into account road/rail crossings, and modifications to the network since the original hydrotesting was completed.

A review of drying technologies is presented, where the threat of sweet corrosion of carbon dioxide pipelines may require both a more stringent dewpoint specification and procedural steps to give a high confidence there is no free water present in deadlegs, valve cavities, and similar hard-to-reach areas. Compressed, dried air and vacuum pump drying techniques will be most suitable, each with particular advantages and disadvantages. The equipment is readily available on the marketplace for both technologies however it is recommended that NGT engage with the UK supply chain to ensure suitable contractors / hire equipment vendors have sufficiently specified packaged units.

Aspects related to the safe introduction of fluids to the system during purging, startup, pressurisation, and the need to dispose of gas via venting / flaring are summarised. Much of the supporting engineering, modelling, and laboratory testing of these aspects for hydrogen have been covered by other studies and are summarised at a high level. For carbon dioxide, there were some gaps in knowledge around phase change / Joule Thomson cooling and purge velocities which were raised and these have been resolved by calculations presented herein.

Outputs: A summary of the key findings and recommendations from the study are presented in Section 5 on page 37. These include some assessments and procedures which are recommended to be developed, and where early engagement with the supply chain may be beneficial (see also Work Package 2). Ultimately it is hoped that the considerations and discussion within this report will be useful in updating NGT company standards and developing company / project-level procedures for repurposing assets.

1. Introduction

1.1. Project Background

National Gas Transmission (NGT) is committed to supporting the government and the broader industry in achieving the Net Zero target by 2050. Carbon Capture, Utilisation and Storage (CCUS), alongside hydrogen, will play a critical role in reaching this goal. Since existing infrastructure was originally designed for natural gas, adapting it to transport these new gases presents significant engineering challenges. To address this, an extensive research program has been launched to assess the technical feasibility of repurposing sections of the National Transmission System (NTS) for hydrogen and carbon dioxide transportation.

While repurposing existing pipelines will be an essential part of the transition, it will not be sufficient: new infrastructure will be required to support a scalable hydrogen and carbon network. Given the ambitious deployment timelines, meeting these targets will require not only innovative technical solutions but also a holistic strategy that integrates the supply chain and fosters collaboration across the industry. Nonetheless, the capacity to repurpose existing pipelines for hydrogen and carbon transportation is constrained by routing complexities, the geographical distribution of users, and the necessity to maintain the resilience of the natural gas network. Consequently, it will be imperative to construct new pipelines and customer connections efficiently and safely.

The construction of new hydrogen and carbon dioxide pipelines presents several challenges, including selecting the most effective construction methods and managing commissioning risks. Establishing a standardised process to connect future producers, emitters, and users is also a challenge. The lack of a formalised approach can lead to inefficiencies and potential delays. Through this project, NGT aims to investigate new construction practices, identify technical requirements and compliance, and address commissioning challenges. The project also aims to identify a conceptual connection design that will enhance efficiency, reduce costs, and support future network expansion.

The project is divided into four work packages:

- Work Package 1: Pipeline Construction and Commissioning Techniques for Net Zero
- Work Package 2: Procurement and Supply Chain Management
- Work Package 3: Connections Process for Net Zero NTS Customers
- Work Package 4: Reporting

There are two deliverables within Work Package 1:

- Technical Report 1A: Pipeline Construction Technologies
- Technical Report 1B: Pipeline Decommissioning, Testing and Commissioning

This document is Technical Report 1B.

1.2. Document Purpose

The objective for Work Package 1B was to develop a high-level, standardised approach for decommissioning existing natural gas pipelines due to be repurposed, and for testing and commissioning both new-build and repurposed pipelines for hydrogen, hydrogen blends, or carbon dioxide service. The brief for the study, as developed by NGT, identified several key topics to be given consideration and these are set out in the bullet points below and are summarised in Figure 1. The scope also included a review of existing NGT policies and procedures to determine where updates are required for hydrogen and carbon dioxide service.

Decommissioning approach for repurposed assets:

- Current decommissioning procedures may be unsuitable for assets which are to be re-purposed for hydrogen or carbon dioxide.
- Determine a high-level approach NGT should implement for the decommissioning of pipelines and assets for use in hydrogen or carbon networks, including the following topics: checks/inspections, cleaning, purging, excavation, dryness, and preservation.
- Consider the best approach to inspecting unspiggable sections prior to repurposing.

Testing and Commissioning:

- Recommend engineered solutions for hydrogen and carbon pipelines startup, including testing, pre-commissioning and commissioning stages.
- Confirm approach to hydrostatic strength testing.
- Identify any challenges in meeting dryness specifications and provide solutions.
- Determine how to safely introduce fluids to the system, e.g. flow rate requirements, temperature/pressure envelopes, and other parameters.
- Consider the implications of commissioning scenarios for different producer/emitter sites.

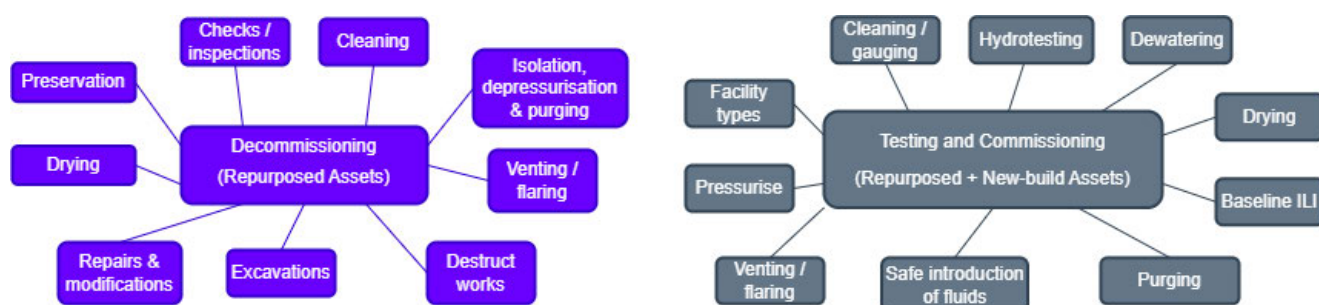


Figure 1: Work Package 1B Key Topics

A framing meeting was held on the 26th September 2025 to kick-off the Work Package 1B scope. This was a multi-disciplinary session with stakeholders from across the NGT technical teams and Project Union and SCO2T Connect project representatives in attendance. The purpose of the session was to discuss key aspects of the study brief and the approach being taken by NGT on current project (Project Union and SCO2T Connect), and agree priority areas for the study scope.

This report is structured to present a discussion of the key subject areas, referring to existing NGT policies and standards where appropriate. Much of the in-depth technical content for the topics covered has been studied as part of other innovation and research projects, so reference is also made to these completed studies or to upcoming/ongoing scopes. Where the findings of such studies are yet to be issued the content of this document may need to be revisited and updated. Recommendations are made where existing NGT standards may require updates, and where further research and trial work may be beneficial to reduce uncertainty/risk.

1.3. Study Scope

Within the scope of this document, the decommissioning activities for an asset to be repurposed encompass the steps necessary to inspect, shutdown, clean, repair/modify, preserve, and otherwise suitably prepare the pipeline system for subsequent construction, tie-in and commissioning stages. This is a broader definition than, for example, described in Section 12.10.2 of IGEM/TD/1 (Steel pipelines for high pressure gas transmission) or within the scope of the NGT's T/PM/TR/30 standard (Commissioning and decommissioning of above 7 bar pipelines and

AGIs), the latter of which only covers purging procedures. It is also recognised that, due to the wide variety of factors which will influence the procedure development, the phasing, extent and division of tasks across the decommissioning, construction and pre-commissioning/commissioning phases may vary between projects.

Similar to the WP1A scope, the focus of the study is on the repurposing of high pressure (HP) steel transmission pipeline sections which form the majority of the NTS. Many of the considerations will also be relevant to the repurposing of pipework within above ground installations (AGIs) and related sites (compressor stations, block valve stations, ECV compounds, etc.). However, based upon discussion with NGT, repurposing pipework and other equipment within AGIs is unlikely to be cost effective compared to replacing-with-new, due to the following:

- For a 100% hydrogen or carbon dioxide pipeline network, it is almost inevitable that intrusive construction works will be needed within AGIs to disconnect from the existing natural gas network, and to connect to new contributor/offtaker pipelines and distribution systems.
- Pipework within AGIs is much shorter, and easier to access compared to pipeline sections.
- AGIs may contain a variety of equipment such as valves, pig traps, metering packages, pressure reduction stations, odourisation systems, instrumentation, etc. In principle, it may be possible to repurpose such equipment however the effort to re-qualify/refurbish and the operational and maintenance risks from doing so will in most cases outweigh any potential cost savings compared to replacing with new. It is understood that NGT currently has no intent to reuse such equipment and all valves, instrumentation, etc. are generally expected to be fully replaced.
- Hazardous area zoning, purge rider sizing, vent facilities, metering / odorant packages, layout constraints, new 3rd party connections, and other related aspects within AGIs may not permit direct repurposing and require modification.

A key outcome of the above points is that a “direct repurposing” strategy of purging directly from natural gas to hydrogen or carbon dioxide will normally not be possible, and therefore the decommissioning approach should plan for a mothball phase where intrusive repair, modification, equipment replacement and tie-ins works can be enacted, prior to commissioning the system in the new service. From discussion with NGT a duration of up to two years is currently anticipated between decommissioning and commissioning, which is driven by the destruct and construction works within AGIs as well as the time required to undertake sequential excavation and repair works along the pipeline ROW.

The testing and commissioning scopes are similarly focussed on pipeline sections, with procedures well defined for current natural gas systems by Sections 8-9 of IGEM/TD/1 (and Sections 12-13 of IGEM/TD/13 for AGIs). The broader range of pre-commissioning and commissioning activities which will be necessary within AGIs, for example those covered by NGTs T/SP/COMP/36 standard (Testing and commissioning of plant and equipment on a compressor installation), are excluded from the scope. This would include activities such as factory acceptance testing, wider site pre-commissioning and commissioning activities (e.g. HV/LV electrical systems, instrumentation, cyber security, utilities, safety systems), performance and environmental testing, and so on, which in many cases will be in line with current practices.

2. Codes and Standards

NGT company and industry-wide codes and standards referred to within this report are listed in Table 1 and Table 2 respectively. These cover topics related to the decommissioning, testing and commissioning for existing natural gas infrastructure and hydrogen / carbon dioxide pipelines. In all cases the latest revision is referred to unless otherwise stated. Refer to the Section 6 for all other references.

Table 1: NGT Company Standards

Reference	Description
T/PM/G/35	Management of new works, modifications, and repairs on the NTS (including temporary modifications)
T/PM/P/11	Inspection, assessment and repair of damaged (non-leaking) steel pipelines above 150 mm nominal diameter and designed to operate at pressures greater than 2 bar
T/PM/PT/1	Pressure testing pipework, pipelines, small bore pipework and above ground austenitic stainless steel pipework
T/PM/RE/18	Management procedure for NTS commissioning, maintenance, operational and asset acceptance
T/PM/TR/17	Isolation of above 2 bar plant and equipment
T/PM/TR/30	Commissioning and decommissioning of above 7 bar pipelines and AGIs
T/PR/VA/3	Pre-commissioning of valves, actuators and associated gearboxes
T/SP/COMP/36	The testing and commissioning of plant and equipment on a compressor installation

Table 2: Industry Standards

Reference	Description
DNV-RP-F104	Design and operation of carbon dioxide pipelines
IGEM/SR/22	Purging operations for fuel gases in transmission, distribution and storage
IGEM/SR/23	Venting of natural gas
IGEM/TD/1	Steel pipelines for high pressure gas transmission
IGEM/TD/1 Supp. 2	High pressure hydrogen pipelines
IGEM/TD/3	Steel and PE pipelines for gas distribution
IGEM/TD/13	Pressure regulating pipeline installations exceeding 7 bar
IGEM/TD/13 Supp. 1	Pressure regulating installations for hydrogen at pressures exceeding 7 bar
IGEM/TD/13 Supp. 2	Pressure regulating installations for new and repurposing of existing PRIs for transmission of natural gas / hydrogen blends for pressures not exceeding 7 bar
ISO 13623	Petroleum and natural gas industries - pipeline transportation systems
ISO 27913	Carbon dioxide capture, transportation and geological storage: Pipeline transportation systems
PD 8010-1	Pipeline systems: steel pipelines on land

3. Decommissioning

3.1. Background, Current Practices & Guidance

To date there has been no widespread requirement to repurpose existing natural gas infrastructure for alternative service and therefore existing practices cover decommissioning for short term repair/maintenance works, temporary mothballing, or permanent abandonment. NGT's existing T/PM/TR/30 standard covers the purging practices for taking a system in/out of service however there are no other relevant company standards and decommissioning procedures, when needed, have typically been written on a project-level basis and/or relied on contractor (MWC) procedures.

Across the wider industry, the UKOPA Good Practice Guide to Pipeline Decommissioning and Abandonment [1] provides a useful overview of the requirements in UK legislation, standards, relevant technical and environmental issues, costs, and recommended approaches. The contained guidance on decommissioning and measures for temporary mothballing is a useful starting point for repurposing a pipeline for alternative service and background context. When repurposing a pipeline, it may also be necessary to abandon other parts of the network which become defunct. The guide outlines some high-level considerations from IGEN/TD/1 and PD-8010-1 standards:

Decommissioning for repair, modification, or temporary mothballing:

- Pipelines must be cleared and purged (or pigged) to remove flammable gases, vapours, and residues.
- Pipeline maintenance and surveillance must be continued.
- The cathodic protection system must be maintained.
- Pipelines should be abandoned where no further use is planned.

Decommissioning for abandonment:

- The choice between lift and removal or in-situ abandonment should be made with consideration to public safety, environmental protection, future land use, legal duties, practical difficulties / financial considerations, and maintenance requirements. The possibility of re-using recovered line pipe sections should also be considered (refer Section 3.7 later).
- Where pipelines/sections are to be left in-situ rather than lifted and removed:
 - Pipeline to be physically separated and isolated from other parts of the system.
 - Pipeline to be divided into sections, if necessary, with open ends capped and sealed.
 - Pipeline cleaned to ensure no toxic materials remain (consider any requirements for testing of contaminants/residues and pigging to clean the line prior to abandonment).
 - Pipeline sections to be filled with non-hazardous material (e.g. grout), especially for large diameter pipelines at crossings and other locations sensitive to subsidence.
 - If grout filling is impractical, pipeline to be charged with inert gas, sealed at vent/fill points, and leakage tests to be carried out as necessary.
 - Pipeline to be identified with suitable markers.
- Suitable precautions should be taken to prevent pipeline from becoming a source of danger or nuisance or having an undesirable effect on watercourses.
- Records of abandonment actions should be kept and plans showing the size, depth, and location of the abandoned pipeline should be prepared and shared with landowners and occupiers.

The above points should be taken into consideration when deciding whether to mothball, remove or abandon adjacent natural gas pipelines (for example, spur lines, LP distribution lines, etc.) made defunct during the repurposing process.

Existing guidance on repurposing natural gas pipelines to hydrogen or carbon dioxide service primarily covers the design re-qualification process. Relevant sections from design codes for repurposing to hydrogen or carbon dioxide service are outlined below:

Hydrogen:

- **IGEM/TD/1 Supplement 2:** Section 13 provides an overview of the process for repurposing a natural gas pipeline, stating that the following control stages shall be adopted:
 - **Viability:** obtain records, confirm accuracy and completeness, and identification of any fundamental characteristic which may prevent repurposing.
 - **Design and operability data assessment:** design review and identification of all modifications and specialist studies necessary for operation at the new MOP for hydrogen service (typically less than or equal to the current MOP) for future operation).
 - **Detailed technical assessments:** completion of specialist studies identified in the step above to confirm that the integrity and risk of the pipeline following the change of service is acceptable.
 - **Modification:** completion of all necessary modifications deemed required per steps above.
 - **Validation:** formal confirmation that the condition, integrity and risks posed by it are acceptable.
 - **Notify regulator and introduce new gas:** use appropriate purging procedures, gradual pressurisation stages, and undertake a leakage survey.
- **IGEM/TD/13 Supplements 1 and 2:** Section 16 covers repurposing an existing natural gas installation, with similar guidance and control stages as for the pipelines (above). Additional parts cover the different types of equipment within AGIs, integrity checks, and functionality and operability checks. Section 16.12 specifically covers the commissioning procedure for the change of service, setting out the requirement for a commissioning plan, survey, incremental pressure increase, leak detection survey, functional and operability tests, and metering equipment checks.

Carbon dioxide:

- **ISO-27913:** Section 10 covers requalification of existing pipelines, giving a series of twelve bullets points of key considerations for the process. These include consideration of the phase envelope and maintaining single phase operation, adaption of metering stations, potential reactions of the carbon dioxide stream with the previous fluid, venting arrangements and locations, and change of flow direction.
- **DNV-RP-F104:** Section 8 sets out high-level considerations for re-qualification of existing pipelines to carbon dioxide service (operating in the gaseous, liquid or supercritical phase). Data from the concept, design, construction and operation phase of the existing pipeline system provide the foundation for re-qualification, which covers an integrity assessment, hydraulic analysis, safety evaluation, transport premises (functional requirements), and re-assessment process.

The basis for any re-qualification process is data from the concept, design, construction, and operation phases of the existing pipeline, as shown in Figure 2 (adapted from DNV-RP-F104). This has been expanded to include the key stages which are expected to be required before shutdown and during the mothball period, prior to commissioning in the new service: these themes are developed further in this chapter. The “direct repurposing” path is shown for reference as a potential opportunity, though as noted in Section 1.3 this will not normally be possible.

In all cases there is a requirement for an integrity and condition assessment to underpin the requalification process, and this will generally be the first step of decommissioning an asset for repurposing and is discussed further next.

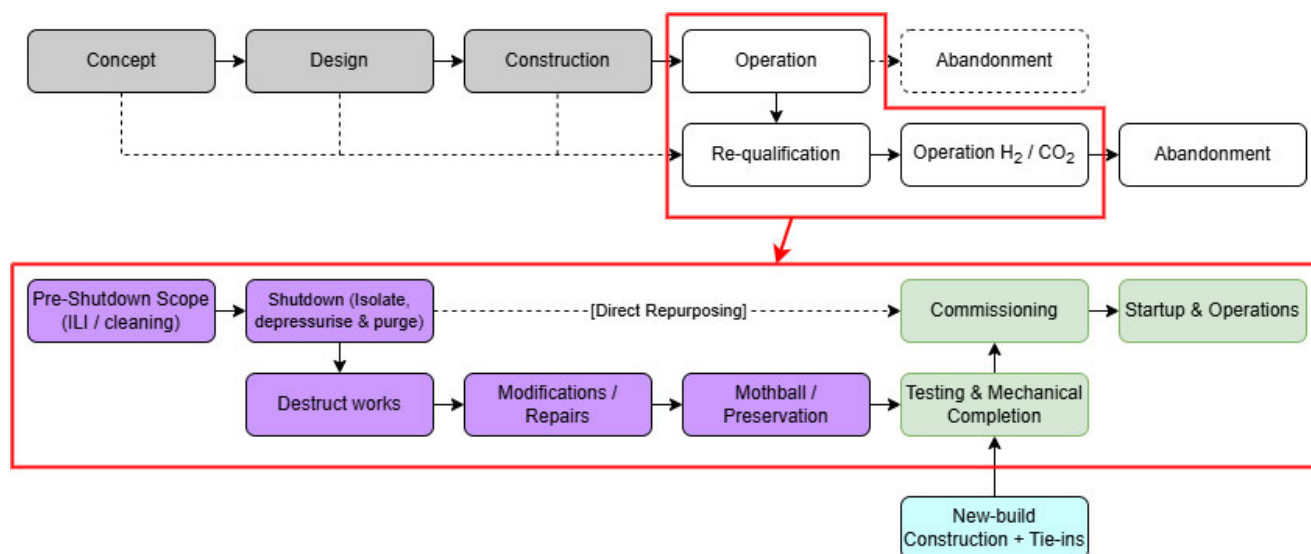


Figure 2: Decommissioning Process for Repurposed Asset

3.2. Checks / Inspections

During prior operation in natural gas service, the integrity of a pipeline will have been managed by carrying out periodic surveys and inspections to gather information on the pipeline condition. Monitoring data will also have been collected and periodically reviewed. Where necessary, repairs may have been carried out, either by replacing damaged sections of pipe, or installing repair clamps / sleeves per T/PM/P/11.

All of this information is critical when carrying out a repurposing assessment, as it will need to be demonstrated that the pipeline condition is suitable for its intended future purpose and extended life. Depending on the date of last inspection / survey, it may be appropriate to carry out additional inspections prior to decommissioning to ensure that sufficient data is available to facilitate the engineering analyses needed within a repurposing and re-qualification assessment. Such checks and inspections would typically include those listed below, all of which should be available from historical integrity records.

- Inline inspection (ILI) data:** usually from a magnetic flux leakage (MFL) tool. This data will confirm the pipeline wall thickness and highlight any areas of metal loss due to corrosion (either internal or external). Other defects such as dents or fabrication defects will also be reported. A pipeline is typically cleaned and gauged prior to sending through the intelligent pig (see Section 3.3).
 This will inform what repairs will be needed, if any, prior to repurposing, and this could influence the decision on whether it is suitable to be repurposed.
- Close Interval Potential Survey (CIPS):** will confirm the status of the cathodic protection system. Where anomalies are detected, other forms of survey such as Direct Current Voltage Gradient (DCVG) survey may provide additional information on the potential presence of coating defects. If the coating is in very poor condition, or there are significant challenges associated with the cathodic protection system, then upgrades may be needed, and this could influence the decision on repurposing. Cathodic protection monitoring data also provides a more continuous picture of system performance, alongside the CIPS / DCVG surveys.
- Right-of-way (visual) survey:** will provide useful information, in the form of potential infringements (which may impact safety assessment) as well as potential ground movement (which may impact pipeline integrity). Areas at risk of various geohazards should already be known and surveys carried out

periodically to confirm status of any protection measures. In some cases it may be appropriate to divert the pipeline to avoid such hazards when repurposing a pipeline, but the cost of this is obviously a factor in the decision making.

- **Historical pressure monitoring data:** will provide a means of establishing the remaining fatigue life of the pipeline. In most cases the consumed fatigue life from historical operations will be relatively low, but the information will be needed for a repurposing assessment [2].

[REDACTED]

The need for girth weld defect data will depend on what information is available from original construction (i.e. the welding standard adopted) as well as the proposed future operating conditions (i.e. operating pressure, and whether this would require a high stress or low stress design approach). Specialist advice should be sought on this matter. [REDACTED]

Where the above inspections indicate there may be a requirement to excavate and repair a defect, there will also be a requirement to undertake a site assessment of the repair location to allow the enabling works, excavation and civil works to be planned well in advance (refer Section 3.6).

3.2.1. Unpiggable Sections

[REDACTED]

Historically such pipeline sections have been managed by carrying out CIPS / DCVG surveys to confirm coating condition and CP system effectiveness, and as external corrosion is the main time dependent threat, this has been deemed sufficient. The pipeline will also have been hydrotested at a pressure higher than its operating pressure, so a margin to failure has been demonstrated. However, this philosophy is unlikely to be adequate for hydrogen service, as hydrogen will have an impact on pipeline pressure capacity (i.e. reduced in comparison to that seen at hydrotest) and also introduces additional degradation mechanisms not catered for in the original design (i.e. hydrogen embrittlement, leading to loss of toughness and accelerated fatigue).

While it is considered unlikely that unpiggable pipeline sections would be selected for a repurposing assessment, there are options available for providing the sort of inspection data needed, if so desired. Although pipelines may be described as “unpiggable” there are usually ways to overcome the associated difficulties. In some cases, sections may be considered unpiggable simply because there are no suitable facilities in place for launching and receiving the tools. Solutions to this could be engineered, albeit at significant cost, and these may require the system to be shutdown. Specialist internal tools could be employed, i.e. bidirectional tethered tools or crawlers that only require access at one end. The cost associated with this sort of campaign would be a significant factor in the decision to repurpose, particularly as most unpiggable pipeline sections are relatively short.

Novel inspection methods that use external tools have also been developed, such as non-contact magnetometric inspection (NCM) or Large Stand-off Magnetometry (LSM). These are based on the stress-magnetization mechanism and are non-invasive, above-ground, passive surveying techniques to detect anomalies/features and evaluate stress concentrations. They can also be mounted on unmanned aerial vehicles (drones) for efficient autonomous surveying of longer sections. [REDACTED]

Otherwise, where unpiggable pipe sections are above ground or buried but practicable to excavate for access, there are a wide array of conventional and emerging external inspection techniques available which may be considered such as ultrasonic testing (UT), phased array ultrasonic testing (PAUT), pulsed eddy current (PEC), magnetic flux leakage (MFL), and guided wave testing (GWT).

Table 3 provides a summary of the techniques discussed here.

Table 3: Summary of Potential Inspection Techniques for Unpiggable Pipe Sections

Technology	Main advantages / disadvantages
NCM / LSM	Non-invasive, no excavation needed, relatively quick for large pipe lengths
LRUT	Requires access at specific locations for probe placement, but can then inspect pipe between these locations, i.e. inaccessible locations under roads etc. Moderate / good defect detection capability
Tethered ILI tools, crawlers, etc.	Launcher still required at one end. Cleaning may be required prior to inspection. Good defect detection capability equivalent to ILI
Manual UT, PAUT, etc.	Requires access to pipe OD so excavation needed if buried. Good defect detection capability equivalent to ILI.

3.3. Cleaning

Confirming the cleanliness of the system internals and then maintaining and/or restoring it will be an important aspect throughout the decommissioning, testing and commissioning phases. This will ensure inspection tools and other pigs can be run successfully, avoids corrosion and debris damage to valves and other equipment, minimise problems with residues/contaminants when breaking into containment, and avoids product specification and contamination issues when the pipeline is brought into service with the new fluid. It is likely that a number of distinct cleaning stages, with associated acceptance testing, will be required (though it may be possible to combine some of these):

- 1. Pre-cleaning for ILI run (re-qualification):** Depending on the operational history this phase may involve an initial gauging run, followed by a progressive cleaning regime, before a dummy inspection pig and/or final ILI tool can be run. This will typically be undertaken prior to shutdown to inform the re-qualification process as discussed in Section 3.2.
- 2. Contaminant / residue removal:** A progressive cleaning campaign to remove existing residues and avoid problems associated with product specification and contamination issues after repurposing. The

extent of cleaning required will depend on the condition, type and nature of contaminants, and the required product purity specification for the new fluid. If a mechanical cleaning programme is not sufficient, a more comprehensive chemical cleaning programme will be necessary (and this may require to be done after shutdown).

3. **Post repair / construction (repurposing & new-build):** Depending on the nature of the repair and modification works required to be undertaken in the post-shutdown phase for repurposed assets, it will usually be necessary to prove system cleanliness prior to commissioning. This will ensure that the pipeline remains free of construction debris, free liquids, foreign objects, etc. and is suitable to run pigs during subsequent stages. This would also be done in advance of any gauging / baseline inspections using air or nitrogen as motive fluid. This requirement also applies to new-build pipelines prior to hydrotesting, for similar reasons, and ensures the system is fit to run the necessary pigs for hydrotesting, dewatering, and any gauging / baseline inspections.
4. **Post-hydrotest (new-build):** In some cases, further cleaning may be required after hydrostatic strength testing if there are any concerns with chemical residue from additives to the test water or organisms resulting from the test water.

The issue of contaminants in natural gas pipelines being repurposed for hydrogen service has been considered previously by the HyDelta study [3]. It is also understood that NGT has commissioned a separate study to investigate more specifically the existing contaminants in the NTS, and the potential interactions and impact on product quality following repurposing to hydrogen and carbon dioxide networks. The outcome of this study should help to confirm the extent of cleaning which will typically be required for different end-applications. In the meantime, it is recommended that the approach outlined in this section be adopted.

3.3.1. Pre-Cleaning Assessment

Prior to any cleaning, an assessment of existing records and history of the pipeline should be undertaken while in natural gas service. The range of information required will be similar to that for the re-qualification exercise, and should include gas analysis and dewpoint measurement history, pigging records (tight bends, free liquids, etc.), pigging debris analysis, chemical injection & corrosion management plans, ILI results, production history (e.g. changes in gas composition, equipment, operating conditions, etc.), operational history (faulty instruments, passing valves, etc.), and verification of the presence of, thickness, and type of internal flow coatings.

Efforts should be made to close any knowledge gaps or identified risks with regards to the current condition of the pipeline. Additional data gathering may be necessary, such as gathering samples for analysis, testing by chemical vendors, or site visits to confirm the serviceability of equipment (isolation valves, pig traps, etc.)



It is expected the ongoing studies mentioned above will allow specific guidance to be developed to set out the acceptance criteria (and appropriate test / inspection methods) for different types of contaminants. The cleanliness acceptance criteria should take into account the following:

- **Gas quality:** consider the potential to go out of specification.
 - For hydrogen, the ISO 14687 standard sets out different purity grades for different end-user applications. The lowest grade A purity is 98% molar, suitable for most combustion applications. CCUS projects typically require a minimum 95% purity. The relevant specifications may set component-specific limits.
 - Consideration should be given to the specific risks and likely persistence of contamination, for example a short period of off-specification fluid may be tolerable during the commissioning period if there is no impact to safety/integrity.
- **New contaminants / behaviour:** consider the potential for new contaminants to form, or existing contaminant behaviour to change, and cause problems with equipment downstream.
- **Network implications:** consider any impact to network operation and integrity.
- **Post-shutdown / construction phase:** consider whether residues may require additional purging or protection measures for personnel following breaking into containment for remedial works after the shutdown period.

The pre-cleaning assessment should also take into account safety, integrity, and practicability issues, for example as set out below:

- **Side branches, dead legs, and bypasses:** May be difficult to inspect while in-service, and require inspection post shutdown.
- **Isolation standard and integrity:** Cleaning can require a significant number of pig runs (and associated breaking into containment, exposure to pig returns and chemicals, etc.), risks to personnel should be considered.
- **Temporary equipment:** Temporary and non-routine operations may be higher risk – need to ensure suitable staff training, equipment testing and qualification, proper design processes (HAZOP, risk assessments).
- **SIMOPS / space constraints:** Consider the working space for sending / receiving pigs, cleaning out traps, siting temporary equipment, and other works in the vicinity.
- **Contingencies:** Consider how stuck pigs will be recovered, and how cleaning operations may adversely impact the existing network.

3.3.2. Mechanical Cleaning

Where practicable to undertake cleaning pigging prior to shutdown, it should be readily achievable to reach a minimum cleanliness level equivalent to that required to run an ILI tool (i.e. no bore restrictions, all major deposits removed, minimal residue layer on pipe walls). Achieving this standard should not incur excessive cost, and in most cases would be required in any case to run an ILI tool to support the re-qualification process.

Typically, the route should be pigged with a BiDi (bidirectional) pig and the amount of liquids and solids returned monitored. The flat face of the BiDi pig, with 99% guide discs, allows the majority of debris to be removed. This step should be repeated until a pig is received with minimal solid/liquid returns (e.g. less than 1 litre). For systems with significant gaps or limited pigging history, it may be necessary to start with a less aggressive gel/foam/gauging tool and gradually move up to more aggressive and efficient sealing pigs as confidence grows. This strategy should reduce the chance of a stuck pig or creating too large a debris pile ahead of the pig.

Later, brush pigs with magnets should help to remove harder adhered solids and remove filled depressions in the line. Effective magnets will remove any loose ferrous debris from the line. A typical programme might involve 4 to 6 pigs, run in succession.

Consideration may also be given to running a camera-integrated pig to provide a means of visually surveying the pipe interior, such as shown in Figure 3. Cameras with LED lighting systems can be incorporated within mandrel bodied cup and disc pigs or foam pigs, and can be used to both clean and inspect cleanliness levels. Running a camera pig may be particularly useful if the presence of free liquids within the line is suspected and where these

may be difficult to fully eliminate (e.g. where a branch line prevents complete removal). Visual survey may also be useful to identify areas which have persistent residues and contamination. Such tools can be incorporated with gyroscopes and GPS tracking to provide locatable video footage to inspect debris accumulation, physical damage, and joint conditions.

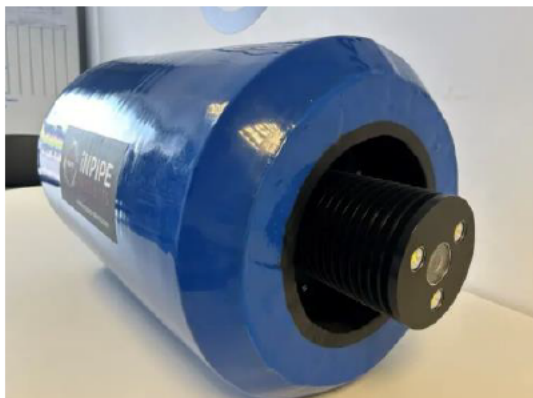


Figure 3: Camera / LED pig (www.inpipeproducts.com)

In most cases, a progressive mechanical cleaning pigging campaign, undertaken while the pipeline remains in natural gas service, is expected to be sufficient for hydrogen or carbon dioxide service (pending the outcome of specialist studies). In cases where it is not possible to pig the line while in natural gas service, for example due to lack of pig traps or inadequate isolations, the mechanical cleaning programme can be undertaken after shutdown using air or nitrogen as motive fluid.

Some indicative flowrates required for undertaking such cleaning operations after shutdown are given in Table 4 (N.B. requirements will however vary depending on types of cleaning pigs which require to be run, required pig velocity, any bypass ratio, etc.). Diesel-powered, trailer mounted mobile air compressors in the range 2,500 – 3,500 sm³/h with dimensions similar to that of a 20ft shipping container are readily available, with multiple units may be used in parallel and/or supplemented by the use of ejector systems to supply larger flowrates at lower pressures for pigging.

■ cases where a higher cleanliness specification is required, consideration may be given to running a more specialist mechanical cleaning tool (e.g. Reinhart type) which can remove harder residue deposits, internal weld seams, weld drops, and other construction debris. Such tools typically require to be propelled by water with significant bypass to clear out debris, however there are examples of running these in gas service.

The possibility of damage to the pipeline internal flow coating should be carefully evaluated when running any such tools. Liners used in natural gas pipelines are typically for pressure drop optimisation purposes rather than internal corrosion, so limited damage may not affect pipeline integrity though major delamination may cause significant issues for the pigging process (and impact on future flow capacity).

3.3.3. Chemical Cleaning

As an alternative to running any more aggressive mechanical pigs, a chemical cleaning programme may be considered, developed based on laboratory testing of debris returns and consultation with chemical solution suppliers. It may also be advantageous to conduct small scale trials with cut-out pipe sections, if available, to confirm effectiveness of the planned procedure.

It may be possible in limited cases to undertake chemical cleaning while the pipeline remains in natural gas service, by undertaking a batch pigging programme. This involves batching the cleaning agent / solvent solution between two pigs and running this as a train through the pipeline. Since the first pig is launched into the line, followed by the chemical solution, then a second pig, it is necessary to shut down the line temporarily while the batch is set up. Receiving the pig train is likely to also require shutting down the line, as well as the provision for temporary facilities to receive the gas-liquid returns from the pipeline. There are also likely to be restrictions on the types of chemical solution which can be used, and may require to be oil-based (diesel, xylene, toluene, etc.) or else contain sufficient hydrate inhibitor if aqueous to avoid issues with hydrate or ice formation. The operational risks to undertaking chemical cleaning while the pipeline remains in service should be considered.

If most cases it may be more appropriate to undertake chemical cleaning after shutdown, using either air or nitrogen as a motive fluid. This would mitigate the operational risks of cleaning when in-service and would allow a wider range of specialist cleaning products to be used, including aqueous based solutions which may include degreasers, alkaline washes, surfactants, etc. In all cases, consideration should be given to the possibility of chemical residues after cleaning which may require additional pig runs to remedy.

3.3.4. Unpiggable Sections

The considerations for cleaning unpigable sections of pipework will be similar to those for undertaking the checks and inspections already highlighted in Section 3.2.1. Where necessary (and justified, versus replacing relevant branch line / pipework sections) mechanical jetting tools or solvent / chemical washes may be practicable to use. Where necessary plugs could be installed to isolate sections from the mainline, and temporary connections installed to remedy problems associated with access from one end. The use of gel pigs could also be considered, in combination with chemical batching, to create an effective cleaning pig train in locations where conventional pigging is not possible.

3.3.5. Acceptance Criteria

The acceptance criteria for pipeline cleaning processes are typically based on the fluid or pig returns, for example minimal volume of debris returns, minimal concentration of contaminants in a solvent, minimal weight gain of a foam pig. While formal acceptance criteria can be set (and should be included in written procedures), a progressive cleaning programme should typically proceed until the most aggressive tool run sees diminishing returns such that further cleaning provides little further benefit.

If contamination in service is a concern, there may be merit taking gas samples for laboratory analysis for certain contaminants while purging (with air or nitrogen) during the decommissioning and/or preservation phase to confirm the effectiveness of the cleaning campaign. This could also be done after a "soak" test, similar to that undertaken to prove a dryness criterion is met (refer Section 4.4), where air or nitrogen is left in the pipeline at positive pressure for a period (e.g. 24 hours) before being sampled. This may be useful to give an indication of volatile contaminants which partition to the gas phase.

3.4. Isolation, Depressurisation, and Purging

Isolation, depressurisation, and purging to decommission the existing natural gas system is generally expected to be undertaken in line with current practice, in particular T/PM/TR/17 and Sections 10 and 11 of the existing NGT procedure T/PM/TR/30, and the IGEM/SR/22 standard.

To optimise the depressurisation stage (to evacuate natural gas from the system), the system pressure should first be lowered as far as normal operating limits allow. Then, to minimise the disposal of natural gas to

atmosphere, mobile compressors should be used as far as practicable to recompress gas from the pipeline sections to be repurposed to other parts of the network. In limited cases it may be also possible to depressurise via pressure reduction stations (e.g. where arrangements with customers can be made, or else where isolations allow a PRS to be supplied from the defunct line then switched back over to the remaining network).

The use of recompression equipment may be time consuming particularly for larger pipeline lengths / diameters, since the rate of evacuation reduces as pipeline pressure drops. A cost-benefit analysis may be used to compare the costs of recompression versus venting (and associated gas shrinkage). The optimal approach may require both methods, i.e. recompress gas into an adjacent inventory until no longer economical / practicable, and then finally venting to fully depressurise the system. Current NGT practices are to cold vent such quantities of gas, with flaring not a common approach. Mobile flare packages may be considered to reduce the environmental impact, if necessary, however the visual/thermal radiation impact would need consideration (unless enclosed flare packages are used).

Once the system has been depressurised, the decision to purge to air or nitrogen and evacuate any remaining natural gas should take the following points into account:

- Per IGEN/SR/22 direct purging to air is generally preferred unless there are constraints with meeting the necessary purge velocities, in which case indirect purging with nitrogen should be used.
- Where intrusive destruct, repair, and modification works are due to proceed imminently, purging to air will avoid the additional cost of purging to nitrogen and avoids asphyxiation risk. However, even when a system has been purged to air, irrespirable atmospheres or explosive mixtures can evolve from solid or liquid deposits or from leakage into the system. Therefore it is essential that post-purge atmospheres are checked regularly while works are being carried out (best efforts to clean the pipeline prior to shutdown will also help to minimise off-gassing of flammable components).
- Purging to nitrogen (or using dry, compressed air) may be advantageous if there will be a preservation period prior to intrusive works commencing, to remove oxygen and moisture from the pipeline.

Commissioning purges are discussed further in Section 4.6.

3.5. Destruct Scope

Once the system has been purged to evacuate natural gas, any necessary enabling and destruct works should be completed. These may include:

- Permanent disconnection (air-gapping) from adjacent natural gas systems which are to remain in service.
- Disconnections of defunct equipment/systems:
 - Equipment (compressor systems, odorant packages, metering packages, etc.) including air-gapping associated utilities connections
 - Instruments, valve actuators, etc.
 - SCADA, F&G / leak detection systems

As part of air-gapping works, it is expected that suitable environmental plugs / end caps / flange blinds would be installed. The exception is if any permanently decommissioned items are left in situ, they would be left open to allow natural ventilation (but full removal should be the first choice for such items).

Depending on the delivery strategy, the completion of the above activities may also correspond to handover of responsibilities from NGT control of work / permit processes to those of a contractor. However, operational activities to monitor and pipeline integrity should generally be maintained the same as for a live pipeline.

3.6. Repair & Modifications Work Scope (Excavations)

3.6.1. Pipeline Repairs

The T/PM/P/11 standard (Inspection, assessment and repair of damaged non-leaking steel pipelines above 150 mm nominal diameter and designed to operate at pressures greater than 2 bar) covers the current procedures for inspection, assessment and repair of pipelines, which includes categorisation of severity and corresponding requirements to reduce operating pressure in in-service pipelines until repairs are enacted. The standard covers remedial methods such as dressing, full encirclement repair (epoxy shell, snug-fit shell, stand-off shell, hot tap), replacement pipe pup, composite wrap, weld deposition, or the application of leak clamps for temporary repairs.

NGT's current operational experience is for between 20 to 50 encirclement repairs to be fitted per year across the network to fix all types of defects such as cracks, girth and seam weld defects, dents, gouges, corrosion and manufacturing defects. Replacement pipe sections are installed only when essential, requiring the system to be taken offline (or a bypass installed, the use of stopples). Plidco leak clamps are used rarely, and only for temporary (up to 12 months) repair until a more permanent repair can be enacted. In general, repairs to the NTS take months to plan, and weeks on site to execute.

For the repurposing of pipelines to hydrogen or carbon dioxide service, the categorisation and requirement to undertake such repair works will be informed by the re-qualification process (Section 3.1) and the checks and inspections process discussed in Section 3.2. Guidance in T/PM/P/11 will need to be updated for hydrogen service in particular, as defect severity will likely be influenced by the effects of hydrogen embrittlement. It is therefore likely that some defects previously accepted for continued natural gas service will need to be repaired / replaced prior to hydrogen service. The design of repair systems that have previously been used for natural gas service will also need to be reviewed to ensure that they are suitable for hydrogen service.

Some of the issues related to excavations on the NTS have been covered in a previous NIA project investigating technologies for lower cost excavation and repairs of hydrogen pipelines [4]. The extent and nature of excavations needed for mainline repairs on the ROW can vary significantly due to the depth, cover, remoteness, terrain, proximity of water and crossings, and other factors. It can take between 6 – 12 months to plan the whole process, though the physical repair may only take several days once the pipeline is exposed. The key problems are:

- Accurate location of the repair site.
- Size and cost of excavations.
- Safety of operators working in proximity to potentially defective live pipework.
- Remediation of excavation sites.

It is generally expected that all repair works will be done after the pipeline has been taken out of service, though where excavations are necessary while still in service (either to facilitate inspection works or to enact repairs), the existing procedures for mandatory pressure reductions would apply per T/PM/P/11.

3.6.2. Equipment Replacements

Excavations for valve and other replacements (adding construction valves, capping redundant connections, replacing small bore pipework, etc.) are likely to be more straightforward due to being located in more accessible areas, e.g. within AGI / block valve / ECV compounds.

One issue requiring consideration is the isolation standard, which may differ particularly for hydrogen service compared to natural gas service. The use of trunnion ball valves with two sealing surfaces and a cavity vent is common across the natural gas infrastructure (known as "double isolation and bleed" or DIB isolation), which has a lesser degree of isolation integrity compared to double valve block and bleed or DVBB isolation.

If DVBB requires to be retrofitted where DIB isolation currently exists, this may increase the space claim of existing sites beyond what is available and therefore need to be sited in new locations. Some of these aspects will be further developed within Work Package 3.

3.6.3. Pipeline Diversions

Where AGIs and block valve stations need to be relocated for hydrogen or carbon dioxide service, it will be necessary to install diversions to provide new approaches to these locations, and uplift (or abandon in place) the existing pipeline approach sections. It is generally expected that such new pipeline sections will be constructed with new line pipe (see Section 3.7) and hydrotested as a separate section prior to golden tie-in welds with the existing line, unless there is a requirement to re-hydrotest the pipeline to be repurposed as well (refer to Sections 4.1 and 4.2 later for strength testing requirements).

Given the relatively extensive planning requirements for all excavation works (but particularly mid-line repairs and complex AGI/block valve approach diversions) it may be necessary to begin enabling works prior to taking the pipeline out of service, and the sequential execution and resource limitations posed by these repairs are likely to be a significant driver to the duration of the mothball period.

3.7. Re-Use of Line Pipe

The option to excavate, lift, recover and process (inspect, clean, refit) line pipe sections from obsolete parts of the network and re-use these may be considered. This is unlikely to be practicable on a small-scale, ad-hoc or project-level basis (i.e. excavate pipe sections on an AGI approach and immediately re-use these for a diversion / alternative AGI approach), due to the requirement to undertake suitable inspections, cleaning, refitting (i.e. re-cutting bevels, internal and external coating fixes or removal and replacement) since the costs are likely to outweigh that of using new line pipe. There could be a potential benefit if realised as part of a wider strategic initiative within NGT to develop a strategic line pipe stock from recovered pipe, which can be assigned for use on projects, however this also presents significant challenges and risks.

Assessment of whether recovered line pipe is likely to be suitable for re-use should be considered as part of any pipeline decommissioning process (as outlined in Section 3.1). The potential requirement to re-use line pipe should be identified in advance of removal, to allow suitable preparations and procedures to be put in place for handling measures to preserve them, as a separate processing stream from those going to disposal / recycling.

Re-using line pipe would need to be considered at the design level (e.g. material properties, coating type / condition, etc.), as well as requiring a process and procedures to be developed for re-processing line pipe sections to be repurposed, which may include:

- Handling measures to ensure preservation during removal, transportation, and storage.
- An inspection process to identify defects and whether the pipe section is deemed salvageable.
- A cleaning process to remove residues on the interior and exterior.
- A means of assessing internal and external coating condition, and whether minor patching can be enacted or whether complete removal (with the use of coating removal machines) and recoating process is required.
- A process for re-beveling the pipe ends and preparing the cut-back area for welding.
- A quality assurance process, which tracks steel composition, material grade etc. Chemical composition would need to be established to ensure that proposed future welding operations are suitable and within qualified limits. Where records from original fabrication are lacking (which is considered likely) then additional testing / inspection would also be needed to confirm that mechanical properties, geometrical tolerances etc. are within specified limits.
- Previous operational history (pressure testing, fatigue etc.) would also need to be tracked. Although girth welds would effectively be “new” when sections of pipe are re-assembled, the seam weld (of welded pipe) would not, so the damage from historic operations would need to be assessed.

It is anticipated that the cost of these activities would likely outweigh the cost of new pipe, although a detailed assessment has not been carried out. The environmental benefit of re-use would also need to be assessed against the environmental impact of the above processes.

3.8. Dryness

Ensuring that the water content within a pipeline is within the specification limit is a key criterion which must be met prior to commissioning either a repurposed or new-build pipeline (refer Section 4.4). There will be no specific requirement to dry the pipeline during the decommissioning and mothball period except if deemed necessary for preservation purposes. Nevertheless, best efforts should be made to remove all liquids in the pipeline prior to shutdown, and to minimise the likelihood of water ingress while intrusive works are being undertaken:

- Existing NTS pipelines should be dry (gas is dewpointed) however based on past experience (e.g. during pigging operations) within NGT liquid accumulations or water or other fluids can be present in some systems. Therefore, consideration should be given to running foam pigs prior to shutdown to ensure free liquids are removed. For complex systems, additional measures may be required.
- General good hygiene measures should be followed during intrusive works:
 - Ensure excavations along the ROW can be suitably drained.
 - Use temporary shelters / ensure night caps fitted to prevent water ingress to pipeline.
 - Undertake checks to ensure water accumulation cannot enter the pipeline through open drain / vent valves, small bore connections, etc. during construction works.
 - Borescope inspections may be undertaken to confirm no free water in complex pipework.

The requirement for any further drying steps prior to commissioning would be strongly driven by the preservation requirements, next.

3.9. Preservation / Mothballing

A preservation management plan should be developed for the asset to be repurposed during the preservation period, which sets out the preservation measures and monitoring regime to be implemented. This should be tailored to the asset and take into consideration the condition assessments, remaining corrosion allowance, design life, the planned works locations, and system geometry (e.g. location of branches, spurs, terrain, vents/drain, etc.). Preservation should also be a fundamental consideration when setting the works sequencing: avoiding unnecessary additional pig runs and drying stages will come with a cost and schedule benefit.

For the pipeline externals, impressed current cathodic protection systems should be maintained energised throughout the mothball period and routine compliance checks undertaken. -Where pipelines are cut into sections for repairs/modifications, this will disrupt the CP system effectiveness. Temporary bridging may be possible, but a project specific preservation plan should take into account such considerations on a section-by-section basis. -The risk of corrosion associated with AC interference could also be influenced by modifications made during repairs or other decommissioning activities, so this should also be considered in the development of a preservation plan (e.g. where FBE and coal tar coatings are used on adjoining sections, and discharge of current through an adjoining section is disrupted). Specialist advice should be sought for any further requirements, for example for temporary sacrificial anodes or additional surveys.

To prevent degradation of the pipeline internals, the ideal preservation state is all free liquids removed, the pipeline dried to a suitable dewpoint (e.g. -20°C), and a positive pressure nitrogen blanket (0.5 – 1 barg) established and maintained. Where pipeline sections are open ended suitable low pressure environmental caps/plugs should be installed, and suitable pressure gauges installed to allow monitoring. Suitable fencing, valve locks, warning signs, and vent location should also be installed for pipeline sections in this preserved state to prevent 3rd party interference.

As an alternative to drying and the application of an inert gas blanket, the application of soluble corrosion inhibitor (SCI) via pigging may be considered. This could be applied immediately following shutdown while the pipeline remains mechanically complete. This would typically comprise an initial wiper pig and trailing filming pig to apply a thin layer of corrosion inhibitor. Compressed air may be used as the driving medium. Suitable bunding and measures to protect the environment from chemical spills should be in place. Elsewhere, corrosion inhibitor may

be injected to inhibit low-lying pipeline sections suspected of or susceptible to collecting residual water, via ports or other means.

Where intrusive works are being undertaken, preservation measures may include the fitment of night caps and corrosion inhibitor tape to protect cutback areas of the pipeline and bevelled pipe ends. Vapour corrosion inhibitor (VCI) packets, secured with string to night caps, may also be considered. These release inhibitor molecules which adsorb onto bare metal surfaces.

The use of all types of corrosion inhibitor would need to be confirmed as acceptable from a contamination point of view with the product fluid, and/or remediating these residues prior to commissioning may incur an additional cleaning stage. It is recommended that NGT develop a standardised preservation management plan. This should set out the expectations for measures which are required for certain timeframes (e.g. 1-2 weeks, 3+ months, 6+ months).

3.10. Sequencing and Systemisation

Figure 4 shows a schematic of an example pipeline section, to illustrate some of the considerations in sequencing the work scopes and in setting the limits of system handover (LOSH), comprising end-to-end pig traps with an intermediate AGI and block valve station.

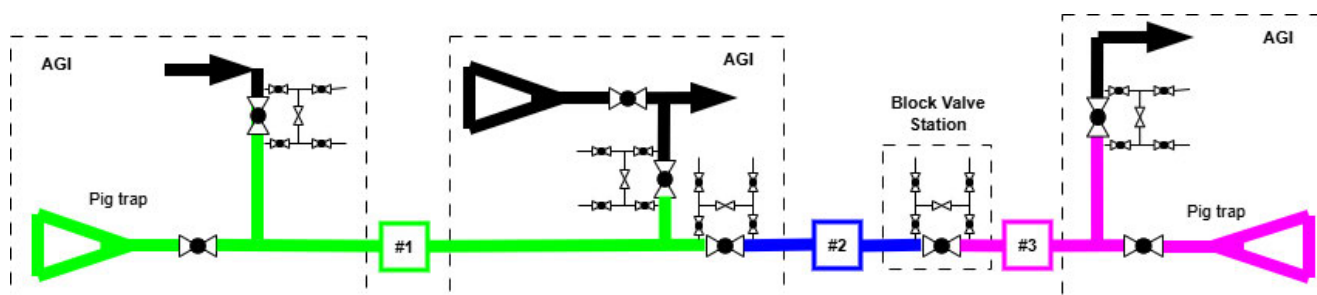


Figure 4: Systemisation Schematic

Following shutdown, the following may be considered in developing a schedule:

- End-to-end pigging operations (e.g. cleaning) should be undertaken while the system remains mechanically complete.
- Consider the need to preserve sections in advance of later intrusive works, by either purging to nitrogen or using dry air for decommissioning purge and then leaving positive pressure blanket in place.
- Repair works / valve replacements generally expected to proceed section by section.
- The commissioning strategy could take different approaches:
 1. Wait until all sections mechanically complete. Can run cleaning, gauging, and ILI (if necessary) pigs, then dry full pipeline (#1, 2, 3) simultaneously. This approach will be simplest and usually preferred.
 2. Complete each section and implement intermediate preservation measures (e.g. nitrogen purge) individually. When all sections complete, run cleaning/gauging/baseline ILI pigs and dry full pipeline simultaneously (as per 1.). This approach may be necessary based on timescales and preservation plan.
 3. Complete, dry, and commission each section individually. Provides most flexibility to changes in construction schedule, etc. and means leakage surveys can be done one site at a time during commissioning. However, higher cost as need to move drying / purging equipment to multiple

locations. Cannot run any cleaning / gauging / ILI pigs until pipeline fully commissioned and in service.

4. Testing and Commissioning

Within this chapter, a high-level overview of the key stages of the testing and commissioning phases for re-purposed and new-build pipelines will be provided. Certain aspects of the commissioning process have been well covered by other studies and reference is made to these throughout.

4.1. Strength Testing (New-Build)

The hydrostatic strength testing scope for new-build pipelines and AGIs is set out in the IGEM/TD/1 and 13 standards, as illustrated in the table below:

Table 5: Testing standards

Pipelines (IGEM/TD/1)	AGIs (IGEM/TD/13)
8.1 Planning / preliminary requirements	12.1 General
8.2 Hydrostatic strength testing	12.2 Safety – General
8.3 Pre-testing	12.3 Safety
8.4 Test equipment	12.4 Test method, test pressure and duration
8.5 Acceptance criteria	12.5 Planning / Preliminary requirements
8.6 Safety – general	12.6 Hydrostatic strength testing
8.7 Safety – pipelines	12.7 Pneumatic testing
8.8 Safety – small bore pipework on pipelines (pneumatic testing)	12.8 Test equipment
8.9 Test sections	12.9 Acceptance criteria
8.10 Fitting of Test ends	12.10 Test sections
8.11 Water supply	12.11 Fitting of test ends
8.12 Repair of test failures and leaks	12.12 Water supply
8.13 Recording and documentation	12.13 Repair of test failures and leaks
Appendix 5: Pressure testing procedures	12.14 Recording and documentation
Appendix 6: Testing – water filling and emptying procedures	Appendix 8: Pressure testing procedures

The testing scope for new-build hydrogen or carbon dioxide pipelines will generally be in accordance with the above table, as set out in their respective fluid-specific standards:

Hydrogen:

- **IGEM/TD/1 Supplement 2:** The testing requirements from IGEM/TD/1 apply, with a footnote stating that test requirements cannot be relaxed for H₂ service.

Carbon dioxide:

- **ISO-27913:** Section 8.2 states “pipeline pre-commissioning shall be carried out in accordance with the procedure described in standards for natural gas or oil pipelines”.
- **DNV-RP-F104:** Section 6.2.2 references ISO-13623 for pressure testing of onshore pipelines, where Section 11 of ISO-13623 outlines a broadly similar process set of considerations to those from Table 5, although the specific test pressure and acceptance criteria (Section 6.7) differ.

The specific test pressures and acceptance criteria may therefore differ depending on the design code and pipeline design considerations, but the process, methodology and equipment required to undertake the hydrostatic strength test will be otherwise in accordance with current practices for natural gas pipelines, and per NGTs standard T/PM/PT/1 (which largely incorporates IGEM/TD/1). The T/PM/PT/1 specification also covers the requirements for welded test ends in Appendix F.

For hydrogen pipelines, a high level hydrotest will be carried out, corresponding to $f = 1.0$ to 1.05 as per Table 11 in IGEM/TD/1. Potential relaxation of this requirement to $1.5 \times \text{MOP}$, as per Section 8.2.2.1 Note 2, is not applicable for hydrogen pipelines. A high level hydrotest has a beneficial effect in terms of reducing the welding residual stress at the seam weld, although a mill pressure test will already have been carried out during pipe fabrication. It also helps to confirm the absence of large welding defects. However, it should be noted that a hydrotest does not confirm the absence of all critical defects that may fail during hydrogen service, as the fracture toughness of material during the hydrotest is significantly higher than it will be in hydrogen service. The primary means of demonstrating adequate weld integrity status is therefore by non-destructive testing (NDT) using techniques such as Advanced Ultrasonic Testing (AUT) and implementing a strict weld flaw acceptance criteria.

There are a number of “smart” or AI-driven digital tools available on the market to help improve the efficiencies of hydrostatic testing and aid compliance. These include a range of digital recorders which can present online instrumentation data via wireless/satellite communication links and apply PV / temperature corrections automatically to present stabilised pressure trends. There are also technology offerings to help identify with leak detection using high resolution pressure / acoustic instruments, and track pig positions.

4.1.1. Dewatering

Dewatering should be undertaken immediately following the completion of the hydrotest. The test ends specified in T/PM/PT/1 installed prior to hydrotesting allow pigs to be pre-loaded (this is mandated to avoid air gaps / liquid pooling during filling and dewatering) which are pushed ahead of the test water to ensure the line is free from air pockets. For dewatering, these pigs are then pushed in the reverse direction using air or nitrogen to remove water from the line. Where necessary, further swabbing runs can be conducted (pushing the pre-loaded pigs back and forth) to achieve a high degree of liquid removal.

4.2. Strength Testing (Repurposed lines)

For repurposed pipeline sections, there will generally be no requirement to undertake any further hydrostatic strength testing, and the re-qualification process will be based on consideration of the original hydrotest results and current integrity assessment. However, in some circumstances, particularly for lines being repurposed to hydrogen, there could be a benefit in performing a new hydrotest, as a means of demonstrating the absence of deleterious defects. The need for this will depend on the level of the previous hydrotest and availability of other historical information available to confirm current condition. The need for repeated hydrotest should be a critical outcome of the re-qualification assessment carried out for each pipeline section.

If a repeat hydrotest is required on a pipeline to be repurposed, the following issues need to be considered:

- Testing against closed valves is not accepted, therefore suitable welded ends / settable plugs need to be installed.
- The hydrotest envelopes may not necessarily be the same as those used during the original construction, due to the addition of branch lines, crossings, and changes in infrastructure.
- Hydrotest of above-ground pipe sections at road/rail/ bridge crossings will require special assessment. Structural response under hydrotest conditions would need to be evaluated and potential safety/environment impacts assessed. Venting of high points to avoid trapped air is also a concern. In some instances it may not be practical to mitigate all of these factors, so a new underground diversion may be needed.
- Maximum elevation difference, supply/disposal of test water, and other factors need to be considered per existing standards.

Where intrusive repairs (i.e. replacement pipe pups) are installed to repair defects, per current practice these will always be pre-tested pipe of a grade and thickness appropriate to the duty, as per GN Specification F6 (Technical specification for carbon and carbon manganese steel pipe pups for operating pressure greater than 7 bar). It will typically not be practicable to undertake hydrostatic strength testing on the tie-in welds for such

repairs, and therefore all tie-in welds should be conducted in accordance with “golden weld” procedures, which per IGEM/TD/1 typically require:

- Visual and dye penetrant (DP) or magnetic particle inspection (MPI) of the weld end preparation.
- 100% radiography and/or 100% ultrasonic (manual or phased array) testing.
- DP or MPI of the completed weld.

This approach would also apply to any tie-in welds for mainline valves, and also to tie-in welds for any small bore connections (normally small bore pipework would be strength tested, possibly using a pneumatic test, separately prior to tie-in welds).

In the event that a longer length of pipeline needs to be cut out and replaced, comprising multiple line pipe sections, it may be appropriate to undertake a hydrostatic strength test on the completed section prior to using golden weld procedures on the tie-in welds at either end. This would depend on the length of pipe and be subject to practicability considerations, such as the ability to supply sufficient test water via tanker to the location.

4.3. Leak (Tightness) Testing

Leak (tightness) testing is used to demonstrate the integrity of flanged, screwed, and clamped joints prone to leakage before the system is pressurised with hazardous fluid. Several different types of leak testing methods exist:

- **Gross leak test:** conducted at low pressure using an inert fluid (e.g. nitrogen, water, air) as a quick and cost effective step prior to either a full leak test or service test to confirm there are no excessive leaks.
- **Hydraulic leak test:** where the system is filled with a low hazard liquid (e.g. water) to perform a gross or full pressure leak test. This can sometimes be combined as part of the strength test. Hydraulic leak testing may not be accepted as sufficient to prove tightness for gas systems, due to a lack of sensitivity.
- **Pneumatic leak test:** where air or an inert gas (usually nitrogen, with or without tracer) is used to pressurise the plant to high pressure, usually to the system design pressure or MOP. Alternatively, tests at lower pressure can sometimes be accepted for large pipeline inventories.

A variety of different methods allow leaks to be detected. A pressure decay test, visual survey, dye test, or bubble/foam test (sensitivity of circa 10^{-3} mbar.l/s) can be used which do not require specialist detection equipment, but can lack sensitivity and the ability to identify and quantify leakage from individual joints. The use of specialist leak detection equipment such as halogen/helium/hydrogen tracer gas detectors to “sniff” for leaks can provide significantly higher sensitivity (to 10^{-4} mbar.l/s or better) and allow leakage from individual joints to be quantified and such methods are usually preferred on systems with the lowest tolerance to leaks (e.g. confined modules) or for systems with many untested joints. Leak testing should not be misconstrued as a service test (system is started up with normal process fluid, equipment, and operating conditions for low-hazard systems where residual risk is low or not practicable to perform leak testing, or when testing a witness joint), or a leakage survey (carried out on in-service systems as part of a regular or risk-based inspection regime (as set out in IGEM/TD/1 section 12.7.5).

The requirements for leak testing new-build or repurposed pipelines in hydrogen or carbon dioxide service will be similar, though there is generally a clear distinction between pipeline sections and AGI / pipework sections, as follows:

- **Pipelines:** IGEM/TD/1 Section 8 states pneumatic testing is not required prior to, or after, hydrostatic testing though can be used if items are omitted from the hydrostatic test. Section 9.5 on pressurising during commissioning states only that a leakage survey shall be conducted on flanges and fittings at 7 bar intervals. Generally, all joints between the pipeline and the first valve off the pipeline will be welded (required per Section 11.2) to restrict the potential for leakage which cannot be isolated by closure of the valve, so most pipeline sections will have very few made-up joins or potential leak points which require a tightness test.

- **Pipework / AGIs:** Per IGEM/TD/13 Section 12, a gas tightness test shall be conducted prior to purging and commissioning in all cases where repairs or modifications have been carried out that could affect the gas tightness of the system.

Leak (tightness) testing acceptance criteria for hydrogen and carbon dioxide fluids will be the same as standard industry practice. There may be advantages to leak testing with halogen/helium/hydrogen tracer gases in some locations where there are a high number of joints to be tested, due to their higher sensitivity, ability to quantify leaks, and ease of detection (particularly in confined areas) and an update to T/PM/PT/1 to permit the use of such techniques may be considered. However, given many AGIs have minimal joints located in outdoor, well-ventilated areas the traditional air/nitrogen pneumatic leak test with bubble/foam method will remain sufficient.

Separate small-scale pneumatic or hydrostatic leak testing may be undertaken on joints and assemblies not included in the main pipeline hydrotest scope. Where a “one tested joint vs. one broken joint” applies, testing will typically not be required. A leakage survey is also mandated during commissioning (pressurisation phase) of the pipeline, at 7 bar intervals, in line with NGT and IGEM standards.

4.4. Drying

4.4.1. Specification

Drying the pipeline and demonstrating that the water content meets the necessary specification is a critical activity for both repurposed and new-build pipelines. For carbon dioxide, the threat of sweet corrosion where carbon dioxide dissolves in water to form carbonic acid which can lower the pH and accelerate corrosion of the pipe metal presents a higher risk to pipeline integrity compared to that of water accumulation in natural gas or hydrogen pipelines.

An NIA project undertaken in 2024 [5] looked specifically at the commissioning process for re-purposed pipelines for carbon dioxide pipeline systems and undertook a comparison against the stages outlined in IGEM/TD/1. This study proposed that carbon dioxide pipelines will require a water dewpoint of -40°C or lower (compared to -20°C for natural gas). This was based on pipeline pressure of circa 30 bar at ambient temperature having a saturation point of around 400 ppm with safety factor of 2 applied to give a required drying standard of 200 ppm of water (equivalent to a dewpoint of -40°C).

Figure 5 shows the approximate saturation water content (by volume) in carbon dioxide at different pressures and temperatures. The curves were generated for pure carbon dioxide and water using the cubic plus association (CPA) equation of state, so may vary slightly for different levels of impurities. For a given water content curve, adjusting pressure and temperature to the left of the curve would lead to liquid water drop-out. The black line is the carbon dioxide phase curve, which is approached from right to left would lead to carbon dioxide drop-out, though note that liquid carbon dioxide can hold a significantly higher quantity of water before a separate aqueous phase partitions out.

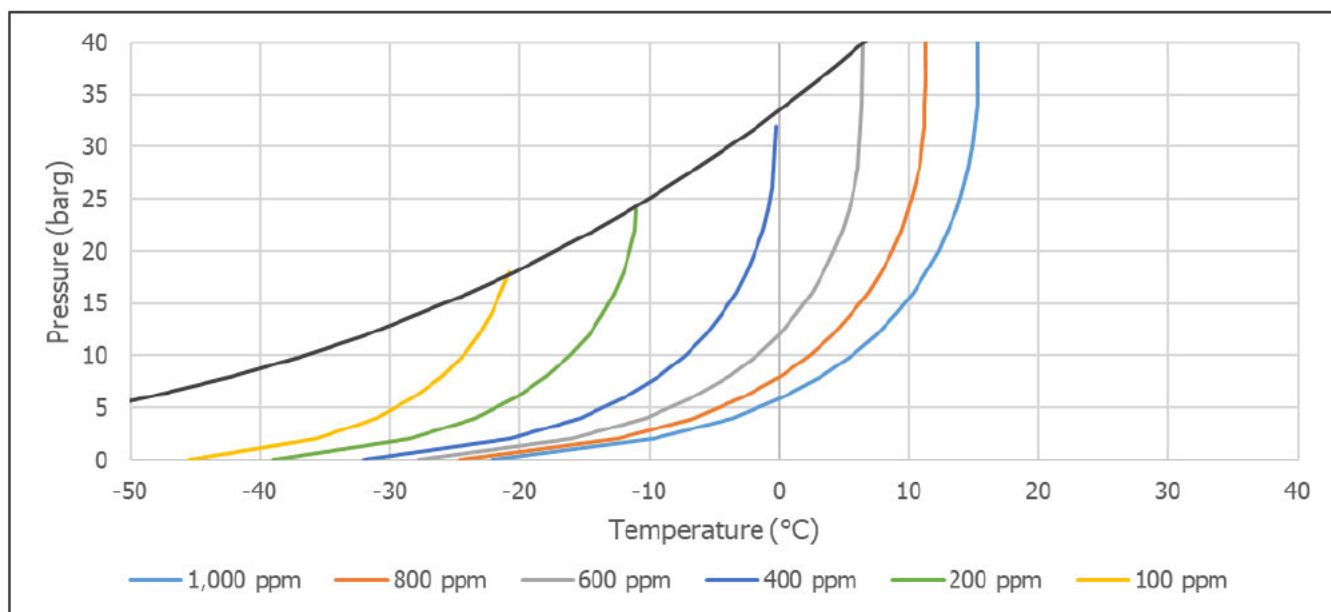


Figure 5: Water Content in Carbon Dioxide Gas

In agreement with the previous study, [5], it can be seen that the water content of above 400 ppm (equivalent to a dewpoint of circa -32°C at atmospheric pressure) would result in water drop-out at pipeline pressures and temperatures above circa 0°C . Applying a safety factor of 2, or 200 ppm, would correspond to a dewpoint of circa -40°C at atmospheric pressure (note, the water dewpoint in carbon dioxide gas and air/nitrogen are similar at low pressures).

In Kent's view, applying the above logic in requiring a -40°C dewpoint specification for commissioning a carbon dioxide pipeline appears reasonable but potentially overly conservative. This is because the fluid within the pipeline would be purged at low pressure before the system is pressurised, so the system contents will be filled with gas at the prevailing supply water content (expected to be in the region of 50 ppm) prior to pressurisation.

One of the main goals of setting a stringent dryness specification is to demonstrate the lack of liquid accumulations within the pipeline, which becomes more difficult as the pipeline has more complex branches, elevation changes, etc. In theory, if the gas is uniformly mixed then any dewpoint below ambient temperature demonstrates there is no free-water present, but in practice long pipeline lengths do not allow the gas to mix therefore setting a lower dewpoint specification (of typically -20°C) is used to provide a margin for uncertainty that the tested sample is representative of the full pipeline. On this basis, setting a dewpoint specification lower than -20°C again may be appropriate given the higher integrity risk posed by free water to a carbon dioxide pipeline.

In summary, setting a target dewpoint specification of -40°C (or 200 ppm) for commissioning of carbon dioxide pipelines appears a reasonable target, particularly for more complex systems where the possibility of liquid water accumulations going undetected is more likely. It may be overly conservative for more simple / smaller inventories, where a dewpoint in the region -20°C to -30°C would still provide high confidence that all free water accumulations have been removed.

4.4.2. Equipment / Technologies

Section 13 of T/PM/PT/1 and Section 9.4 of IGEM/TD/1 outline the existing practices for pipeline drying, with available techniques summarised below:

- **Foam pigging / swabbing:** Foam pigging may be used bulk water removal from pipelines, including accumulations at low points and condensed water on walls. Weighing the foam pig upon receipt gives

an indication as to whether any water has been absorbed. The use of incorporated cameras may also be useful to confirm there are no water deposits at complex piping arrangements.

- **Chemical swabbing:** A plug of methanol, MEG, or alternative is run between two pigs. These chemicals are hygroscopic so will absorb water and can be used to minimise the risk of hydrate formation during initial line fill. Corrosion inhibitor may also be dosed into the plug. It is becoming less commonly used, and normally as a last resort if other techniques are not practicable. This technique may not give high confidence that water accumulations in hard-to-access locations have been inhibited, therefore may not be suitable for more complex pipeline arrangements.
- **Dry air / nitrogen gas:** Desiccant dried air, or alternatively nitrogen (likely supplied in liquid bulk rather than via compressor-membrane units) can be flowed through a pipeline to evaporate and remove water. Passing dried air down the pipeline is generally the quickest, cheapest, and most readily available method and this is the preferred method in T/PM/PT/1. Nitrogen may be advantageous for hydrogen pipelines where air must be removed with nitrogen prior to commissioning. Heat can also be added to reduce the drying time. For dry air, pressure swing adsorber units which can achieve dewpoints well below the required -40°C are readily achievable with equipment on the market. The effectiveness of air/nitrogen drying can be limited on branched pipelines or pipelines with deadlegs, since evaporation will be limited without a stream of gas flowing over the liquid accumulation. It is possible to mitigate this if vents can be opened at the end of each branch.
- **Vacuum drying:** Achieving a -40°C dewpoint requires a pressure of circa 0.1 mbara, compared to 1 mbara for a dewpoint of -20°C . Equipment is readily available commercially (some equipment vendors state achievable pressures down to 0.05 mbar) which can achieve such conditions, though the choice may be more limited since the specification is more stringent than most oil and gas applications. The lower pressure will likely require multistage pumps (typically a rotary vane pump or sometimes a claw pump is used as first stage, with a roots blower as second stage). Air-cooled units are available which have compact footprints. Vacuum drying will typically give a higher degree of surety that water has been removed from valve cavities, side branches, and other hard to reach areas compared to other methods since evaporation will be induced everywhere the pressure is lowered. However, the evaporation rate is limited by ambient heat input from the environment (unlike air drying there is no gas to provide heat) so vacuum drying can often take longer than other techniques. One example on a vendor website is for a 48", 90 km pipeline being dried to 0.3 mbara (-32°C) in 6 days six double stage vacuum pumps of between 2,500-3,000 m^3/h capacity each.

The most appropriate drying technology should be selected based on the timing of operations, the nature and characteristics of the gas to be transmitted and the design, operation and maintenance criteria for the system. Running swabbing pigs will be useful for bulk liquid removal but may not fit with a section-wise approach to drying in order to manage the pipeline preservation if end-to-end pigging is not possible.

There may be a benefit of adopting multiple drying techniques, e.g. foam pigging for bulk removal, pull a vacuum (e.g. 1 mbara) to provide high confidence removal of water from branch lines and valve cavities etc., followed by a nitrogen purge to reach the -40°C dewpoint. However, this would obviously be more complex and potentially higher cost. While the vacuum pumps and air compressors/dryers to achieve the -40°C dewpoint are available, it is recommended that early engagement with vendors (or hire equipment contractors) be started in advance of the necessary lead times.

Following drying, in all cases a "soak" period of 12 to 24 hours is required. For dry air or nitrogen, the pipeline will be left with a positive pressure and then vented to check the dewpoint and ensure this has not increased above specification. For the vacuum method, the vacuum pump is typically switched off and system left under vacuum to confirm no pressure increase, though adding air/nitrogen and undertaking a positive pressure soak test may also be considered.

4.4.3. Drying Procedures

Drying can either be undertaken on mechanically complete pipeline sections (i.e. between block valves with suitable purge rider/vent connections) as soon as all final tie-in welds have been completed, or on larger network sections simultaneously, depending upon the commissioning approach (also refer Section 3.10). Drying long pipeline sections in one go can be challenging, however the practicability of siting the necessary equipment at available block valve / purge points may dictate the drying approach.

The issue of sweet corrosion due to free water in carbon dioxide pipelines has been considered within a separate NIA project [6]. This study outlined some updates needed to existing management procedures and work instructions covering pipeline maintenance, inspection, and repair. A later work package within the same NIA project [5] outlined some further considerations, namely the need to ensure dryness in valve cavities.

Figure 6 shows a schematic of the cavity arrangement in a typical trunnion ball valve (taken from NGT's isolation standard). By partially closing the valve, the cavity becomes open to the main line, and if using a vacuum drying technique this should allow the cavity to be fully dried. Opening the cavity bleed valves would help dry the cavity using the desiccant air drying method (and this would also apply to other branch / deadleg connections which have vent valves). Such rigorous procedures may not always be necessary however it is recommended that NGT update the T/PM/TR/17 to include guidance on this issue.

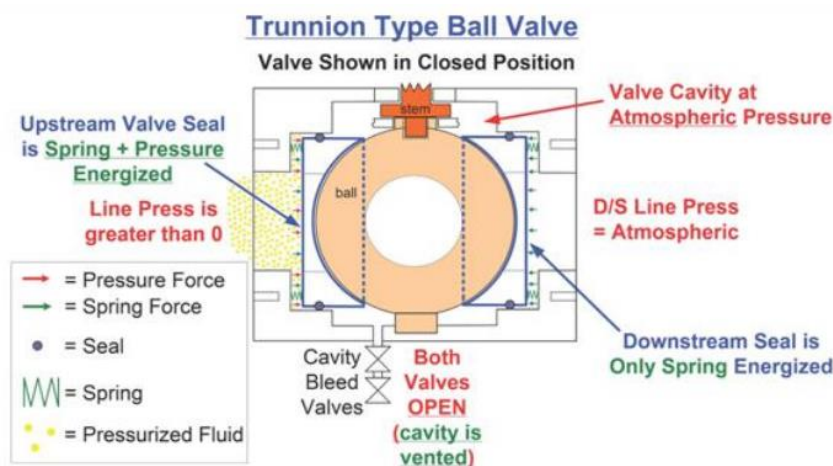


Figure 6: Trunnion Type Ball Valve (from T/PM/TR/17)

For hydrogen, the presence of water is less critical than for carbon dioxide, however the required dryness and drying procedures should be in line with existing natural gas service.

4.5. Baseline ILI

It is generally recommended to undertake a baseline ILI run either before, or shortly after commissioning, to determine the condition of the pipeline and to give a reference for later in line inspections. This would be done after the system is mechanically complete with all tie-in welds completed. There may be an opportunity to do this in conjunction with the drying operation (i.e. using the same compressed air / nitrogen supply), however if the pipeline commissioning strategy is planned to be done by sequential pipeline sections then the baseline inspection may need to be done after introduction of fluids since end-to-end pigging will be necessary. Upon discussions with NGT, undertaking ILI within the first year after startup is deemed acceptable, with no critical requirement to ILI the line prior to startup.

4.6. Purging

Controlled purging procedures are required during the commissioning and decommissioning of pipelines containing flammable gases to prevent the formation of large flammable mixtures which, if ignited, can pose a

hazard to people, plant and the environment. The purging procedures will be the same for repurposed and new-build pipelines, but will differ for hydrogen and carbon dioxide service.

4.6.1. Hydrogen

For hydrogen, all of the current standards and guidance specify that indirect purging (with nitrogen) is required, to prevent air and hydrogen mixing. This requires a separate purging stage to be completed before hydrogen can be introduced. The necessary updates to existing NGT standards (e.g. T/PM/TR/30) require to be enacted, however the theoretical basis, underpinned by CFD work and testing of purge rates has been largely completed. Many of the issues are set out in the HyDelta study [8] and the NGT NIA purging project [9], which give details on the minimum required hydrogen purge velocities, rider and vent diameters, and end points (i.e. the gas composition threshold which indicates purging is complete). For commissioning purposes, a reliable supply of hydrogen should be available at sufficient flowrate / pressure to allow purge velocities to be maintained, and the pipeline to be pressurised in a reasonable time frame.

4.6.2. Carbon Dioxide

4.6.2.1. Purging

Purging procedures for carbon dioxide have received less attention than hydrogen, since it is not flammable there is no critical need to prevent air and carbon dioxide mixing. As such, there is no requirement to purge the system with an inert gas (e.g. nitrogen) prior to startup and pressurisation with carbon dioxide.

Nevertheless, it is expected that the commissioning process for carbon dioxide should ensure that the system is suitably purged of air/nitrogen to avoid any issues this may cause downstream. Pressurising up a pipeline from nitrogen/air at atmospheric pressure to 30 bar with carbon dioxide would lead to circa 3% nitrogen/air content, and therefore there will generally still be a requirement to evacuate the air/nitrogen prior to pressurisation to avoid problems downstream (though for commissioning of smaller inventories, the option to avoid purging at all may be a viable option).

With regards to the purge velocity for carbon dioxide, for in terms of inert gas (i.e. indirect purging) T/PM/TR/30 only covers nitrogen with a velocity of 0.6 m/s for all pipe sizes. The guidance from IGEM/SR/22, upon which T/PM/TR/30 is derived, is that for indirect purging most combinations of fuel gas, inert gas and air, a minimum velocity of 0.6 m/s is adequate but that when using purge gases which are heavier than air, the minimum velocity should be increased in proportion to the relative densities. Since carbon dioxide is denser than air the minimum purge velocity would therefore be 1 m/s. However, a similar approach can be taken as that of recent studies [8] into hydrogen purge velocities which derived the necessary purge velocity based on critical Reynolds number (to ensure turbulent flow) and Froude number (to limit stratification) criteria. Figure 7 presents the calculated minimum purge velocities for carbon dioxide, hydrogen, and natural gas displacing nitrogen (or air).

The table shows that the minimum purge velocity for carbon dioxide displacing nitrogen is very similar to that of natural gas displacing nitrogen. This is due to the fact that the Froude number criterion is symmetrical (it doesn't matter which gas is displacing which) and the density ratio between carbon dioxide and nitrogen is about the same as that between nitrogen and natural gas. A purge velocity of 0.5 m/s is required for a 4" diameter pipe, rising to 1.7 m/s for a 48" diameter pipe.

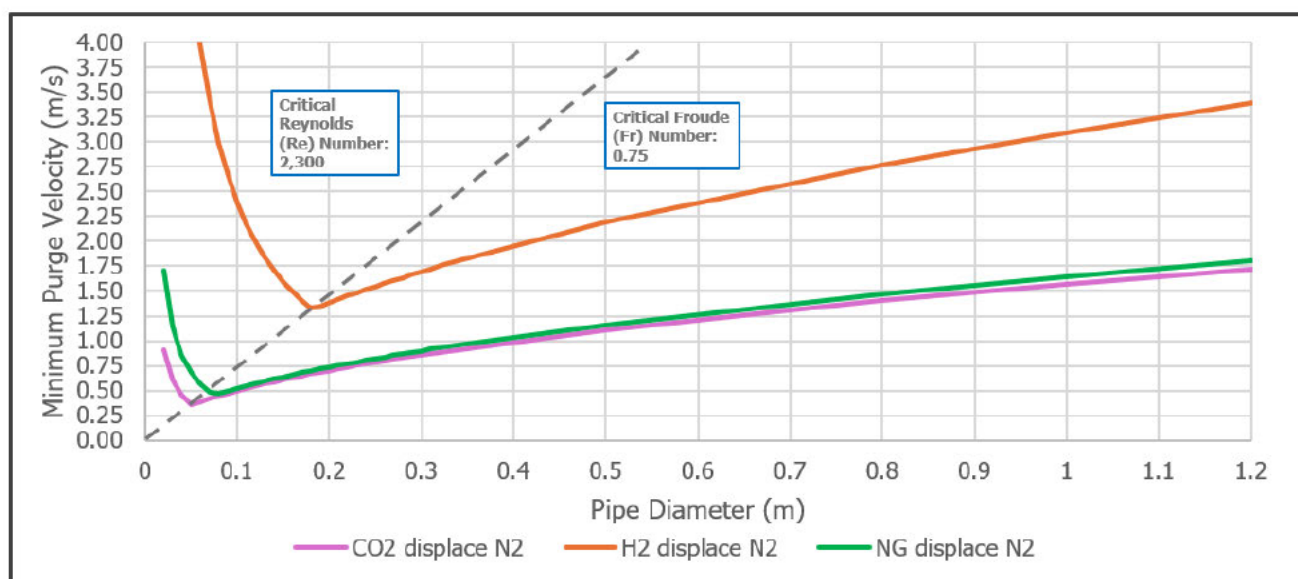


Figure 7: Minimum Purge Velocities (Displacement Purging)

It is therefore recommended that when displacing air or nitrogen with carbon dioxide, the minimum purge velocity be maintained per Figure 7 where practicable. While carbon dioxide is not flammable, ensuring an efficient purging will minimise the total quantity of carbon dioxide which needs to be vented and means the compositional switch and end point specification will be achieved in the shortest time frame.

4.6.2.2. Pressure letdown

While many carbon dioxide pipelines are designed to operate in the supercritical / dense-phase region (i.e. at pressures above 73.8 bara), the upcoming NGT projects (e.g. SCO2T Connect) will operate at up to 30-35 bar. Figure 8 shows the carbon dioxide phase envelope, for 100% and typical 95% carbon dioxide composition (adapted from ISO-27913). The effect of impurities in the composition creates a multiphase envelope where both gas and liquid phases can exist, as opposed to a single saturation line for pure carbon dioxide. At 35 bar operating pressure, CO₂ will be a gas unless the temperature drops below 1-2°C.

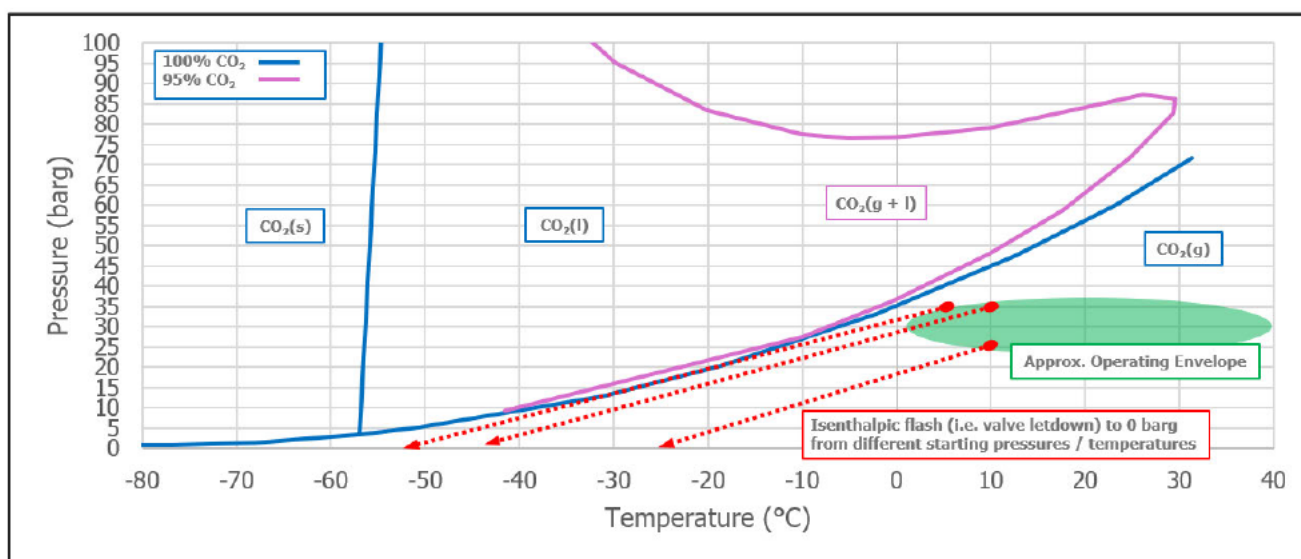


Figure 8: CO₂ Phase Envelope

Also shown on Figure 8 in red arrows are the paths for isenthalpic depressurisation (i.e. valve letdown) to atmospheric pressure for different starting pressures and temperatures. At 35 barg and 5°C, the mixture will be 100% vapour at a temperature of -53°C downstream of the letdown valve at 0 barg, though liquid drop-out of 1-2% is possible (indicated by the red arrow touching the phase envelope curve at 10-20 barg). At 35 barg and 10°C, a minimum temperature of -43°C is expected but no liquid drop-out will occur. In most cases, buried pipelines in the UK would be at an ambient temperature of 8 – 12°C, therefore the risk of liquid dropout is low. Nevertheless, it is recommended that procedures highlight the risk of liquid dropout, for example if depressurising sections of exposed pipework in cold conditions.

The issue of low temperatures causing the metal design temperature to be breached should also be considered, since the repurposed line may not be designed for such low temperatures. During commissioning, this risk could be managed by using lower pressures (e.g. 20-25 bar) when initially introducing fluids, however this may not always be possible and this issue should be considered during the re-qualification and design process for CO₂ service.

4.6.3. Pressurisation Phase

During pressurisation with hydrogen or carbon dioxide, pressure should be raised in 7 bar increments per IGEM/TD/1 and a leakage survey undertaken. This would include a survey of all joints prone to leakage, which should have been left exposed for this purpose.

4.7. Commissioning Venting / Contingency Venting

During commissioning, there must be a means of disposing the displaced gas (air or nitrogen) during purging. Current practice with natural gas is to vent such commissioning flows via temporary standpipes fitted to purge riders, as set out in IGEM/SR/23. Such commissioning venting of pipelines undergoing displacement purges will primarily involve venting of air or nitrogen, until the composition switches over to the process gas (i.e. natural gas, or hydrogen or carbon dioxide) over a relatively short period until the end point is achieved and venting is complete. In addition to commissioning venting, there must be adequate provision for contingency depressurisation in the event that the system must be depressurised to rectify any problems.

4.7.1. Hydrogen

There have been a number of studies on the subject of hydrogen venting / flaring for both commissioning venting and contingency depressurisation:

- **Hydrogen Venting and Flaring Trials, 2023 [10]**
Part of the LTS Futures study, included testing of delayed ignition overpressures with 2" and 10" vents.
- **Safe Venting and Recompression of Hydrogen, 2024 [11]**
Outlines the considerations of venting vs. flaring and proposes a flowchart to inform decision making. The study recommends mobile flare packages be used in most scenarios, with enclosed flares for smaller flowrates (1,000 Nm³/h) or open flares for larger flowrates.
- **Proposed Hydrogen Purging Plan to Achieve Transition / Post-Transition, 2025 [9]**
This study investigated purging technologies for hydrogen / hydrogen blends, standards and procedures for purging, proposed a purging plan and identified skills gaps / training requirements.
- **Hazardous area studies:** Aspects related to hazardous areas have been considered in [12][13] and have also been addressed by updates to recent standards (IGEM/SR/25).

Many of the aspects of hydrogen venting have therefore been covered elsewhere and will not be repeated in this document. It is expected that procedures will be updated to capture the recommendations and findings of these studies.

4.7.2. Carbon dioxide

The NIA project for NGT on carbon dioxide venting [7] covered existing CO₂ venting guidance and also more specifically CO₂ venting via existing NTS rider arrangements which are generally in accordance with the IGEM/SR/23 standard. The findings indicate that, given the proposed NTS operating pressures of circa 35 barg, CO₂ venting via existing vent types will be possible. The dispersion modelling showed that in most cases the flowrates will be sufficient to adequately disperse the CO₂ above the release position, with minimal risk to people on the ground, though at low wind speeds the CO₂ concentration did reach 0.5 – 1.5% (short term exposure limit 1.5-2% for 15 minutes). Some mitigations may therefore be needed based on a risk assessment of the specific site conditions and proximity to building, obstacles, etc.

4.8. Facility Types

As part of this study, some of the implications with respect to commissioning aspects for different types of suppliers/offtakers will be considered. It is proposed to address this further within the WP3 scope, which will investigate different connection designs and connection processes for hydrogen and carbon dioxide, for the expected range of tie-ins (e.g. small scale offtakers, large industrial emitters, dispatchable power generators, blue/green hydrogen suppliers).

5. Conclusions and Recommendations

A high-level procedure has been developed for the repurposing of existing natural gas pipelines to hydrogen or carbon dioxide service. The key conclusions and recommendations are summarised below:

1. Efforts should be made to run all required pigging operations (i.e. cleaning, swabbing and ILI tools) while the pipeline remains in natural gas service. [REDACTED]
[REDACTED]
[REDACTED]
2. A pre-cleaning assessment should be undertaken, to determine the current condition of the pipeline and highlight any testing or inspections necessary to inform the development of a cleaning plan for the decommissioning works. The subsequent development of a cleaning plan should take into account the product specifications, contaminant behaviour and interactions, and practicability/safety aspects (i.e. can all pig runs be done in while in natural gas service, or will these need to be done after shutdown).
3. A base line cleanliness level equivalent to that needed to run an ILI tool (i.e. removal of all bulk debris from the pipeline, deposits removed to as close to metal surface as possible, removal of all ferrous debris) is proposed as a readily achievable objective for repurposing. This may need to be combined with more aggressive mechanical cleaning tools or a chemical cleaning programme if necessary, which may need to be done after shutdown (done immediately after shutdown, while system remains mechanically complete). It is understood that there is an ongoing study to investigate NTS contaminant types, behaviour, interactions, and removal techniques which should help to inform the cleaning requirements.
4. Isolation, depressurisation, and purging for decommissioning are expected to be in line with current practices.
5. A preservation plan should be developed to manage external / internal corrosion and set out the necessary preservation measures and monitoring regime during the mothball period. This should take into consideration the phasing and duration of works as well as the commissioning date. Establishing a positive pressure nitrogen blanket (and dewpoint specification) may be considered on a section-by-section basis, before or after intrusive repair/modification works are undertaken. The use of SCIs/VCI's could also be considered if the risk of product contamination is acceptable.
6. The excavation, uplift, removal, re-processing and re-use of line pipe sections from obsolete parts of the network is deemed unlikely to be practicable on a project level basis and would require a significant investment / strategic initiative within NGT to develop the procedures and processes to do so. There are significant risks and challenges with the re-use of line pipe sections it is deemed unlikely that this would be cost effective, though a detailed assessment has not been carried out. The potential for re-use of line pipe should be considered as part of the decommissioning study for redundant pipeline sections.
7. Early consideration of systemisation and LOSH boundaries, and the sequencing of works and testing / commissioning stages, will be important to avoiding unnecessary additional stages and optimising the location / usage of temporary equipment packages resources such as pigging facilities, drying / purging equipment, and so on.
8. Hydrostatic strength testing is will typically not be necessary for repurposed pipelines (though there may be a benefit in some cases for hydrogen pipelines), however all replacement pipe sections should be pre-tested and golden weld tie-in procedures implemented. New pipe runs and assemblies should be similarly be strength tested separately prior to tie-in. Hydrotesting for new-build pipeline sections should be in line with current practices for natural gas pipelines.
9. The dryness specification for carbon dioxide is expected to be more stringent compared to natural gas and hydrogen (up to -40°C vs. -20°C for natural gas/hydrogen), and is also likely to require additional procedures to prove that low points, branch lines, small bore piping and valve cavities have been adequately dried. Both dried air and vacuum drying techniques are capable of achieving this specification, and both may be

appropriate but come with their own strengths and weaknesses. While the necessary equipment is readily available on the market place, and specialist contractors have demonstrated case studies of meeting this specification, it is recommended that NGT engage with the supply chain to ensure local contractor/ hire equipment vendors have appropriate packaged units available. Drying procedures for carbon dioxide systems should consider the requirement to prove dryness at all vent/drain points and valve cavities.

10. The purging and venting / flaring requirements for hydrogen have been have been studied by numerous other works. The theory, modelling, and testing of hydrogen purging (which requires indirect purging with nitrogen) is largely settled, pending larger scale testing, while testing work suggests that mobile flares will be required for commissioning and contingency depressurisation scenarios due to the risks posed by delayed ignition.

11. [REDACTED]

12. [REDACTED]

13. With respect to current NGT standards, the T/PM/TR/30 and T/PM/PT/17 standards do not currently cover hydrogen or carbon dioxide service and therefore would need to be updated (or supplements issued) to account for the differences associated with these gases. Specific points for consideration have been outlined within the report. It is also recommended that standards or guidance documents be created to cover pre-cleaning assessment, preservation assessment, and drying procedures.

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Redaction Statement – WP2 Pipeline Installation Techniques for Net Zero

The WP2 Pipeline Installation Techniques for Net Zero work package has generated outputs that include detailed information relating to pipeline installation methodologies, construction techniques, engineering assessments, delivery strategies, cost assumptions, procurement considerations, and the evaluation of emerging technologies. This information has been developed in collaboration with project partners and suppliers and contains commercially sensitive material that is subject to confidentiality obligations.

The report includes proprietary approaches, technical know-how, market assessments, and commercial evaluations that provide competitive advantage to the organisations involved. Public disclosure of this information could prejudice the commercial interests of project participants, undermine future procurement and contracting activities, and compromise the confidentiality of intellectual property and commercially sensitive business information.

In accordance with NIA governance requirements and contractual confidentiality obligations, publication of the full report would require extensive redaction of key technical and commercial content. As the report's findings, recommendations, and conclusions are closely linked to this confidential information, substantial redaction would significantly reduce the document's value, context, and usefulness to external stakeholders.

For these reasons, the full WP2 report will not be made publicly available. However, in line with the aims of the Network Innovation Allowance to promote innovation and industry learning, non-confidential findings, high-level insights, and lessons learned will be disseminated through appropriate summary materials where this can be achieved without compromising commercially sensitive information or the legitimate commercial interests of project participants.

NIA NGT0267: Pipeline Installation Techniques for Net Zero

WP3: Connections Process for Net Zero NTS Customers

National Gas

26/02/2026

5300-RP-03

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A.1.	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]

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Abbreviations

Abbreviation	Description
AGI	Above ground installation
A2O	Application to offer
CCGT	Combined cycle gas turbine
CCUS	Carbon capture, utilisation, and storage
CIL	Commercial integrity level
D/S	Downstream
DIB	Double isolation and bleed
DN	Diameter nominal
DPE	Double piston effect
DVBB	Double valve block and bleed
ECV	Emergency control valve
EH	Electro-hydraulic
EV	Electric vehicle
FCO	Full connection offer
GI	Valve position feedback indication
KP	Kilometre point
HAZOP	Hazard and operability study
HS	Manual valve position switch
I/J	Isolation joint
IGEM	The Institution of Gas Engineers and Managers
LE	Local electric (valve actuation)
LNG	Liquid natural gas
LOPA	Layer of protection analysis
LOR	Lock-o-ring
MI	Moisture indication
MOP	Maximum operating pressure
NIA	Network innovation allowance
NGT	National Gas Transmission PLC
NRV	Non-return valve
NTS	National Transmission System
O/C	Open/closed
PI	Pressure indication
P&ID	Piping and instrumentation diagram

Abbreviation	Description
PRS	Pressure regulating station
QI	Gas composition indication
QRA	Quantitative risk assessment
RGH	Remote gas + hydraulic (valve actuation)
RLEH	Remote + local, electric + hydraulic (valve actuation)
ROV	Remotely operated valve
SDV	Shutdown valve
SIL	Safety integrity level
SPE	Single piston effect
TI	Temperature indication
TPD	Transportation principal document
U/S	Upstream
UNC	Uniform network code
WP	Work package

Executive Summary

This report presents the output of Work Package 3 and proposed connection designs for hydrogen producers / offtakers and carbon dioxide emitters, to facilitate their connection to the NTS (or equivalent) in a way that is safe and minimises time, cost and complexity while ensuring network resilience. The starting points or reference cases are the existing connections process and connection designs for the NTS. These have been reviewed and consideration is given to the modifications necessary to support hydrogen or carbon dioxide service, and also where additional optimisation / streamlining may be achieved.

There are three overarching types of connection: entry, exit, and combined entry / exit, for which a generic base case connection design is proposed for both hydrogen and carbon dioxide. A typical hydrogen offtake connection and carbon dioxide emitter connection will be most numerous on each network and these would be the best candidates for efficiency savings from standardisation.

The base case design is further developed with (non-exhaustive) examples for different types of foreseeable sites / tie-in locations across the pipeline network. The objective is to propose a standardised connection arrangement which can be applied to the majority of foreseeable scenarios, though it is also recognised that site-specific factors will always need to be taken into consideration which are likely to require some modifications. In addition, a risk-based approach to assessing impacts from e.g. off-specification fluid is recommended, which may lead to differences in the mitigation measures needed for different entrants / locations.

With respect to the interface and division of responsibility for equipment build/operation between NGT (the transporter) and 3rd parties, the concept of "maximum" and "minimum" connection models is discussed. The proposed connections designs are mostly in accordance with the "minimum" model, based on discussions with NGT as there are a number of inherent efficiencies to the connections process with this approach.

Hydrogen

The proposed hydrogen connection [REDACTED] gives a higher level of integrity [REDACTED]

[REDACTED] A [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

[REDACTED] Justification to support the proposed arrangement and requirement for equipment [REDACTED] provided to inform future design works.

Carbon Dioxide

Carbon dioxide is an asphyxiant, but is not flammable therefore does not pose the same deflagration/detonation hazards as hydrogen. The proposed carbon dioxide networks will also operate at lower pressure [REDACTED] [REDACTED], and therefore [REDACTED] may be deemed appropriate. The threat of sweet corrosion to integrity and commercial agreements with disposal sites if water content breaches specification limits is likely to require additional mitigations [REDACTED] be in place for carbon dioxide connections versus natural gas operation. [REDACTED]

[REDACTED] as far as practicable.

Efficient Connections

It is hoped that this report will be useful for projects in their development of connection designs for hydrogen and carbon dioxide, and help NGT in assessing where a more strategic approach to a modular connections design, procurement and build process may facilitate customers to join the new networks efficiently.

1. Introduction

1.1. Project Background

National Gas Transmission (NGT) is committed to supporting the government and the broader industry in achieving the Net Zero target by 2050. Carbon Capture, Utilisation and Storage (CCUS), alongside hydrogen, will play a critical role in reaching this goal. Since existing infrastructure was originally designed for natural gas, adapting it to transport these new gases presents significant engineering challenges. To address this, an extensive research program has been launched to assess the technical feasibility of repurposing sections of the National Transmission System (NTS) for hydrogen and carbon dioxide transportation.

While repurposing existing pipelines will be an essential part of the transition, it will not be sufficient: new infrastructure will be required to support a scalable hydrogen and carbon network. Given the ambitious deployment timelines, meeting these targets will require not only innovative technical solutions but also a holistic strategy that integrates the supply chain and fosters collaboration across the industry. Nonetheless, the capacity to repurpose existing pipelines for hydrogen and carbon transportation is constrained by routing complexities, the geographical distribution of users, and the necessity to maintain the resilience of the natural gas network. Consequently, it will be imperative to construct new pipelines and customer connections efficiently and safely.

The construction of new hydrogen and carbon dioxide pipelines presents several challenges, including selecting the most effective construction methods and managing commissioning risks. Establishing a standardised process to connect future producers, emitters, and users is also a challenge. The lack of a formalised approach can lead to inefficiencies and potential delays. Through this project, NGT aims to investigate new construction practices, identify technical requirements and compliance, and address commissioning challenges. The project also aims to identify a conceptual connection design that will enhance efficiency, reduce costs, and support future network expansion.

The project is divided into four work packages:

- Work Package 1: Pipeline Construction and Commissioning Techniques for Net Zero
- Work Package 2: Procurement and Supply Chain Management
- Work Package 3: Connections Process for Net Zero NTS Customers
- Work Package 4: Reporting

This document is the Technical Report for Work Package 3.

1.2. Document Purpose

The objective of Work Package 3 is to develop conceptual connection designs for hydrogen producers / offtakers and carbon dioxide emitters to facilitate their connection to the NTS in a way that is safe and minimises time, cost, and complexity while ensuring network resilience. By taking the current natural gas connections process and existing connection designs as points of reference, Work Package 3 will review key aspects and consider what modifications are necessary for hydrogen or carbon dioxide service and where further optimisations / streamlining can be achieved.

Starting with a proposed base case configuration for the main connection types [REDACTED], any necessary modifications required to accommodate different site arrangements [REDACTED]

[REDACTED] Where practicable, it will be desirable to use a standardised arrangement as far as practicable to simplify the connections process.

The scope will include connections made as part of initial project build (e.g. Project Union, SCO2T Connect) as well as connections made during later expansion of pipeline networks ([REDACTED])

With any connection, there will be an interface and division of responsibilities between the pipeline operator (NGT) and the producer/offtaker customer, where an agreement must be reached regarding the equipment each party must design, construct, and operate. Historically and across the existing network, there are differences in how connection agreements have been made which has led to NGT being responsible for operating certain types of equipment [REDACTED] on behalf of customers at some sites but not at others. To optimise the connections process, it is desirable to take a consistent approach and minimise any duplication of functionality on either side of the fenceline (connection boundary), as far as practicable. Within this document, the focus is on the proposed equipment within the pipeline network operator (i.e. NGT) side of the interface, though expectations are set out in broad terms for the necessary equipment (and assurances / telemetry mirroring) which would need to be provided by 3rd parties seeking a connection agreement.

A multidisciplinary framing workshop was held 24th November 2025, to discuss the work scope and relevant aspects of connection designs, the outcomes of which have been incorporated into this document.

2. Codes and Standards

NGT company and industry-wide codes and standards referred to during the development of and within this report are listed in Table 1 and Table 2 respectively. In all cases the latest revision is referred to unless otherwise stated.

Table 1: NGT Company Standards

[Redacted content]	
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Table 2: Industry Standards

Reference	Description
DNV-RP-F104	Design and operation of carbon dioxide pipelines
HSL82	A guide to the Pipelines Safety Regulations 1996
IGEM/SR/22	Purging operations for fuel gases in transmission, distribution and storage
IGEM/SR/23	Venting of natural gas
IGEM/G/1	Defining the end of the network, a meter installation and installation pipework
IGEM/TD/1	Steel pipelines for high pressure gas transmission
IGEM/TD/1 Supp. 2	High pressure hydrogen pipelines
IGEM/TD/13	Pressure regulating pipeline installations exceeding 7 bar
IGEM/TD/13 Supp. 1	Pressure regulating installations for hydrogen at pressures exceeding 7 bar
IGEM/TD/13 Supp. 2	Pressure regulating installations for new and repurposing of existing PRIs for transmission of natural gas / hydrogen blends for pressures not exceeding 7 bar
ISO 13623	Petroleum and natural gas industries - pipeline transportation systems
ISO 27913	Carbon dioxide capture, transportation and geological storage: Pipeline transportation systems
PD 8010-1	Pipeline systems: steel pipelines on land

3. Background

3.1. Overview

There are three overarching types of NTS connection which require different valve and equipment layouts in order to integrate with the NTS network:

- Entry point
- Exit point
- Combined (entry and exit) point

For each overarching connection type, the technical requirements of the connection design may also need to cater for differences in the type/nature of the site. For example, the connection design may differ if a customer connection is at a multi-junction AGI, pipeline termination AGI, block valve station, or a new hot-tap location, and for example depending on the length, operating conditions and requirements [REDACTED] for the customer-operated connecting pipe.

Table 3 lists some examples of the types of sites expected for the different fluids. The approximate numbers of each type of connection in the current NTS with natural gas are also given in brackets, for reference. The current NTS operates with relatively few, large producer sites and more numerous offtakers. For hydrogen, offtaker connections will similarly be the most numerous connections while for carbon dioxide nearly all customer connections will be entry points, and these connection designs (highlighted in grey) will therefore be the best candidates and focus for standardisation.

Table 3: Types of Customer Sites (Natural Gas, Hydrogen, Carbon Dioxide)

Type	Natural Gas	Hydrogen	Carbon Dioxide
Entry	[REDACTED]	Blue hydrogen producers Green hydrogen producers	Industrial emitters Biogenic sources (e.g. biomethane sites) Direct Air Capture
Exit	[REDACTED]	Power generators and industrial users Local grid distribution and blending Transportation	Disposal well sites Export terminals Potential industrial users
Combined	[REDACTED]	Storage sites Combined sites (e.g. with power generation / industrial hydrogen consumption and hydrogen production)	N/A (possibility for some import/export/storage sites to require combined connections in future)

3.2. Application to Offer (A2O)

The current connections process to the NTS for natural gas customers is set out in the Uniform Network Code (UNC) Transportation Principal Document (TPD) under Section V, with relevant section headings illustrated in Figure 1. The code defines:

- The process for submitting a connection application.
- How the application will be managed throughout the process.
- The types, and content, of connection offers.
- Information publication requirements.

The connection (and disconnection) charging methodology is also set out in Section Y, which sets out certain connection requirements (e.g. the need for an ROV) and division of responsibilities (e.g. transfer of a new-build pipeline to NGT ownership).

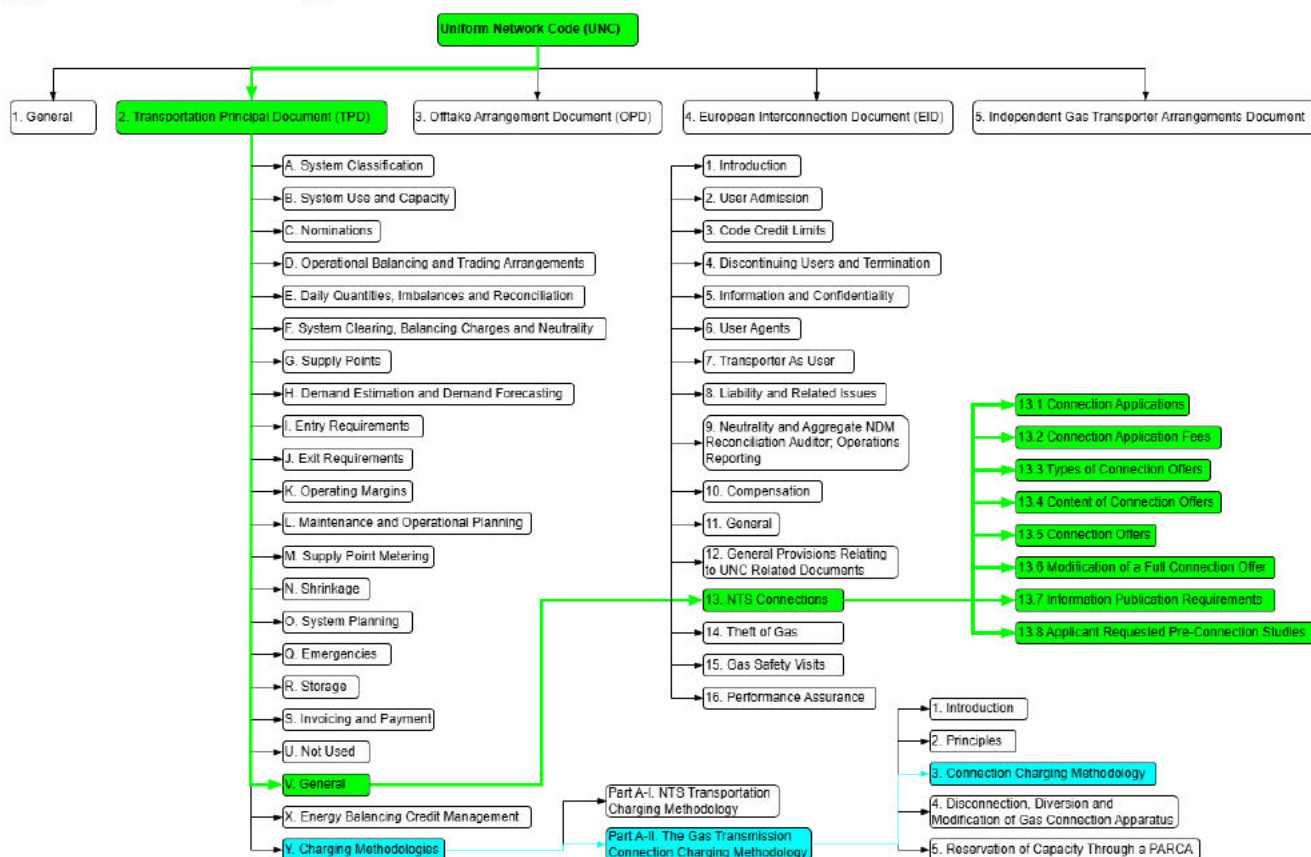


Figure 1: NTS A20 Connections Process (UNC Sections)

From the current A2O guidance material it is understood that NGT holds capacity assessments for all existing sites to determine if they are viable connection points, require further investigation, or are non-viable, with the key attributes that affect connection viability are available space within the AGI, the bridle pipework size [REDACTED], and whether the site has any special characteristics.

Within the scope of this document, it is generally expected that all new hydrogen and carbon dioxide AGIs and block valve stations will be suitably provisioned for future connections, except where this would be clearly redundant (e.g. block valve locations in remote areas, or particularly constrained / congested sites).

It was noted during the framing workshop that for any customer connection enquiry, both the closest AGI and the closest pipeline (as the crow flies) will be identified, and in most cases a clear preference will usually be established for either a standard connection to an AGI or a new [REDACTED] connection into the pipeline.

3.2.1. Capacity Assessment

The Planning and Advanced Reservation of Capacity Agreement (PARCA) is a separate (though usually dependent) process from the A2O application on the existing NTS, which allows capacity to be reserved for a customer whilst they develop the initial phases of their project. There are four stages of the PARCA process, including the initial application, then phase 1 including a desktop study to determine ways of delivering the capacity and establishment of future long term capacity through quarterly auctions. Phase 2 initiates the relevant investment and statutory planning activities and reservation of the capacity, while Phase 3 is the time between capacity allocation and registration date, which may include network reinforcement. Future hydrogen and carbon dioxide connections will require an equivalent means of reserving network capacity, though this is outside of the scope of this document.

3.3. Standard / Non-Standard Connections and Timescales

Over the past decade, NGT has brought in several standardised connection designs to optimise the connections process to the NTS. As shown in Figure 2, such standardised designs cover entry or exit customers seeking a connection at an existing NGT site, for which a full connection offer (FCO) can be made in 3 to 6 months (depending on whether a feasibility study is required, taking 3 months) with detailed design and build stage ensuing between 12 to 24 months. The ability to provide such a connection will be underpinned by the factors outlined above (i.e. space, capacity, and site characteristics).

Where a new connection site is required, a simple greenfield design (e.g. a hot-tap connection with site close to pipeline tie-in) can typically be delivered with FCO made in 6 to 9 months and design and build within 24 to 36 months. The timescales for more complex connections would by their nature depend on the project specifics.

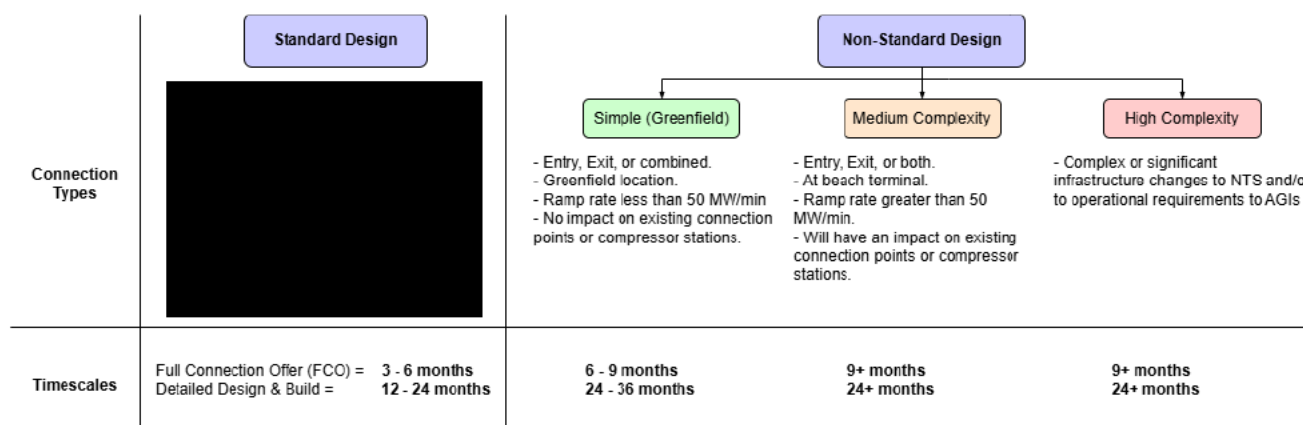


Figure 2: Standardised Connection Types and Timescales

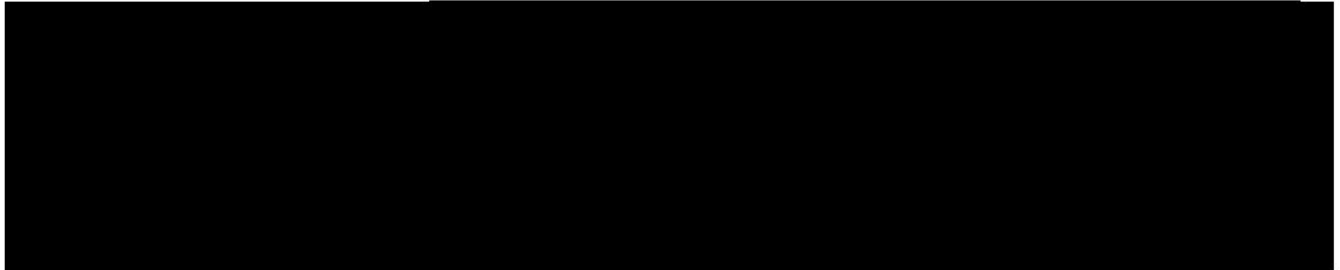
Within the scope of this document, the proposed conceptual connection designs should provide a starting point or base case, which can be adapted (where necessary) to account for site-specific or customer requirements. This approach reflects the current natural gas connections where the bespoke greenfield connection sites will typically be based on the standardised design, though with additions in the planning, design and construction process. Sizing calculations to determine rated capacities of the different connection sizes are not considered at this stage.

3.4. NTS Connection Examples

Five examples of natural gas connection designs have been provided by NGT for reference, as summarised in Table 4. Associated piping and instrumentation (P&ID) and layout drawings for these are also given in Appendix A and reference is made to these throughout this document. It was noted during the framing workshop that these examples do not necessarily represent a "gold standard" or best practice, and may include site-specific features, but are thought to be generally representative of typical entry, exit, and combined connection points.

None of these examples would actually fall under the recently developed standardised design criteria outlined in Section 3.3 above, being either larger than that of the standard connections (i.e. DN300+) or being a greenfield hot-tap connection.

A high-level summary of each site is provided below:



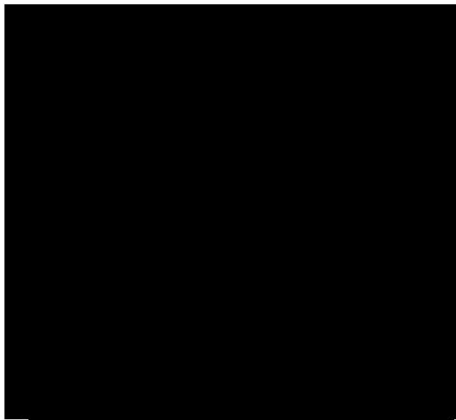
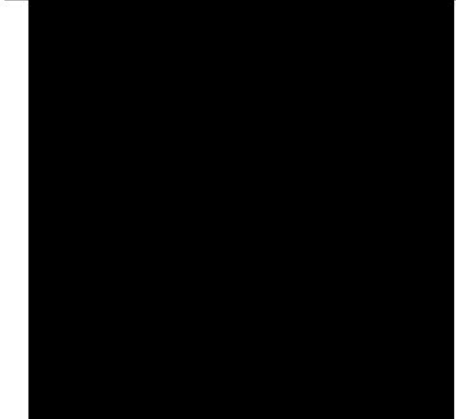
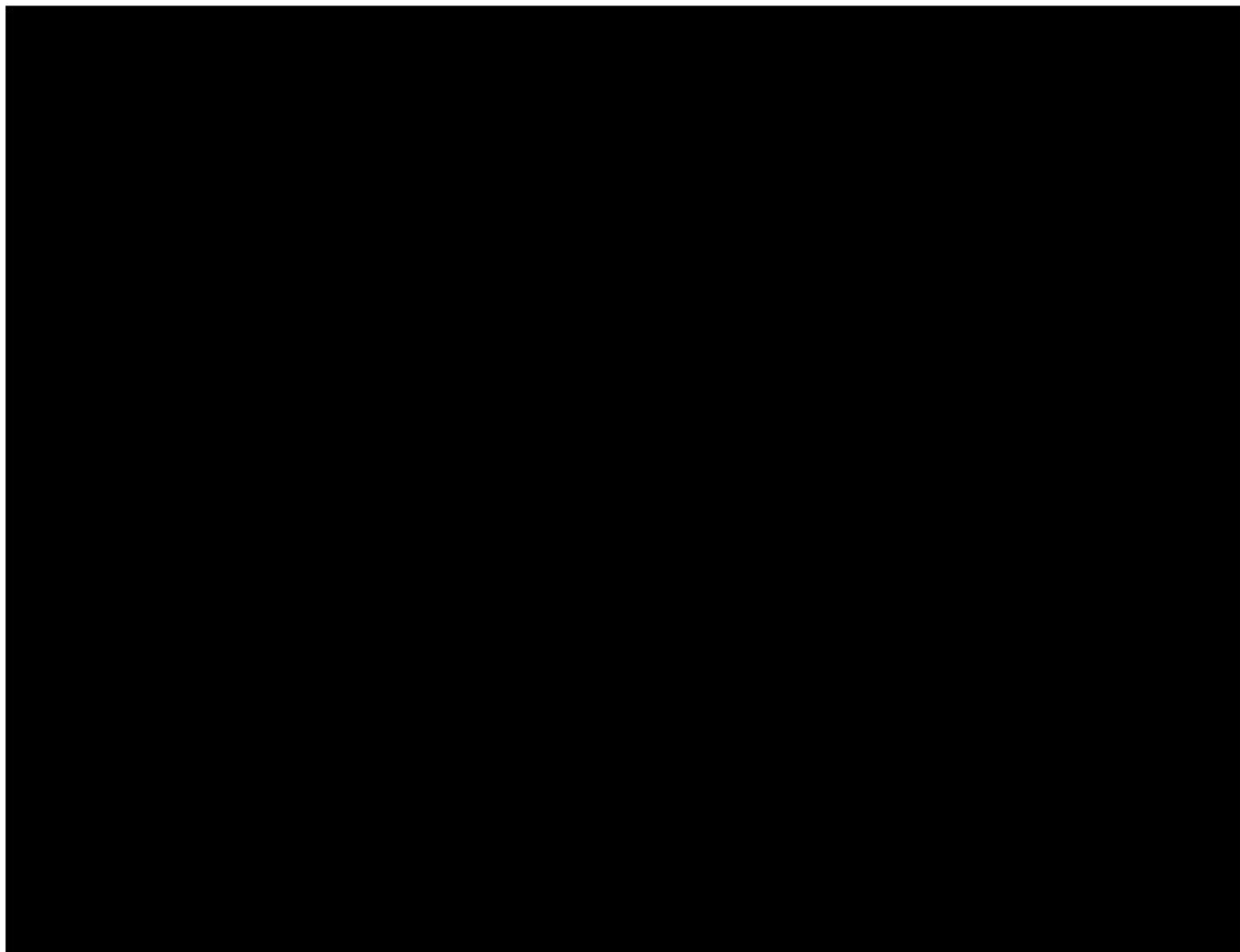
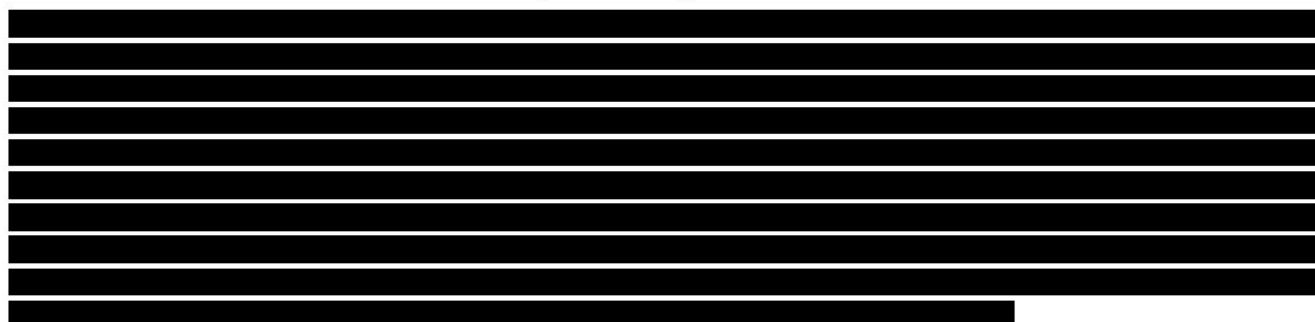
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				

Table 4 below also provides a further high-level summary, at a glance, for some of the key characteristics of each site.



3.5. Connection Variations / Battery Limits



■ ROV and isolation valve are bolted to the respective hot tap tee. It is assumed these valves were the original construction valves used during tapping, or alternatively replaced the original construction valves (e.g. using lock-o-ring system or plug after construction).

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[Redacted content]

[Redacted content]

[Redacted content]

- [REDACTED]

[REDACTED]

4. Hydrogen Connection Design Development

In this chapter, the technical considerations underpinning the development of the proposed hydrogen connection designs are discussed, which are then put into practice with the conceptual connection designs presented in Chapter 5.

4.1. Types of Sites

Consideration must be given as to whether the type of customer site will dictate any specific requirements on the connection design, and connections process. As an example of this, the recent development of biomethane entrants to the NTS has led to the development of a standardised, minimal connection design which reflects the relatively small scale (but potentially high number) of biomethane sites in development and a risk-assessment process to remove the requirement [REDACTED]. Other changes, for example relaxation of limits on the maximum oxygen content, have also been made to facilitate these sites entry to the network.

4.1.1. Hydrogen Suppliers (Entry Points)

A brief, high-level overview of the types of supplier sites expected for hydrogen is provided below:

- **Green Hydrogen:** Produced from electrolysis of water, with several different technologies under development (e.g. proton exchange membranes, alkaline water electrolysis, solid oxide electrolysis cells, and anion exchange membranes). Upon leaving the electrolysis cell, the hydrogen gas contains some impurities, primarily oxygen and water. A catalytic oxidation step is typically used to convert oxygen to water, and then a dehydration step is used to dry the gas. A high-purity product (e.g. 99.9+% molar) is produced after drying. Production of green hydrogen will likely capitalise on curtailed wind power meaning production may be much more variable than current NTS entrants. [REDACTED]. The production capacity of green hydrogen sites is likely to be small to begin with, though with modular electrolyser designs there is the potential for significant expansion at sites in future.
- **Blue Hydrogen:** Blue hydrogen will be produced using auto-thermal or steam reforming of natural gas, likely located at existing upstream gas terminals and/or gas import terminals, where there is a ready source of natural gas and disposal route for carbon dioxide produced in the process. The syngas mixture produced from the reformer and water-gas shift reactors contains a mixture of hydrogen, natural gas, carbon monoxide, carbon dioxide, oxygen, and water. After purification steps, a high purity product (99.9+% molar) can be achieved. [REDACTED]
- **Storage Sites:** The majority of hydrogen storage is likely to be [REDACTED]. The halite layers usually contain mineral impurities which, when leached, can react with hydrogen to release hydrogen sulphide (H_2S), carbon dioxide, and other gaseous impurities. Microorganisms can also consume hydrogen and produce hydrogen sulphide, methane, and other byproducts. Further, salt caverns usually contain brine which will increase the water content of the hydrogen. The hydrogen produced from salt caverns may therefore require both treatment for impurities and/or a dehydration step prior to re-entry to the network. Depending on the cavern operating pressure, hydrogen may require compression during injection to the cavern, or upon production from the cavern and re-entry to the pipeline network.
- **Hydrogen De-Blending:** The possibility of de-blending hydrogen from natural gas for entry to a hydrogen-only network was noted during the framing workshop. The requirement for such sites is more speculative at this stage and feasibility work is ongoing.

In terms of potential differences in connection designs for each site, the following points are noted:

- For green hydrogen producer sites, there is likely to be a requirement for a “minimal” connection initially, suitably for small-scale entrants, though consideration should be given to accommodating significant future expansion potential in the future. This could involve the provision of oversized tees / branch connections with an initial, smaller modular connection skid initially with provision to add future valves to increase capacity.
- With regards to impurities and the risk of off-specification fluid, all entrants present a risk of deviations in oxygen and moisture content, with blue hydrogen and storage sites more likely to produce gas which contains additional contaminants such as natural gas, carbon monoxide/dioxide, hydrogen sulphide, and others. The telemetry, gas analyser, and NGT assurance requirements may need to be tailored accordingly (based on a risk-assessment process, [REDACTED]).
- A more frequent telemetry updating frequency for metering flows may be necessary to balance supply and demand for the network, compared to the existing NTS metering classes.

4.1.2. Offtakers (exit points)

The expected types of hydrogen offtakers are likely to include:

- **Power generators:** May include open or combined cycle gas turbines, reciprocating engines, and fuel cell generators. In future the power demand will be much more sensitive to weather-derived swings in renewable output, and intra-day variations, longer term / seasonal weather patterns, electricity network constraints, and therefore it is likely that the demand profiles will be more variable than current dispatchable power usage on the NTS.
- **Distribution grids:** For industrial sites or domestic uses if hydrogen blending is permitted in future. Demand patterns are likely to be similar to current daily / seasonal usage patterns.
- **Industrial users:** Likely to be used to decarbonise thermal demand, and other uses for hydrogen.
- **Transportation:** Fuel distribution sites and other related uses.
- **Storage sites:** As per Section 4.1.1 above.

Some potential considerations for differences between sites may be:

- It is deemed likely that a minimal offtaker connection design (i.e. no ROVs) will be desirable for multiple small-scale sites where safety and site configurations permit, similar to recent developments for the NTS.
- While it is clear that connection sizing will differ between sites, it was noted during discussions with NTS that this, in general, does not affect connection design significantly and any sizing or standardisation of connection sizes is outside the scope of this study.

4.2. Isolation Valve Configuration

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

A full discussion on the isolation philosophy for hydrogen pipelines is outside the scope of this document. However due to the wider flammability range and lower ignition energy for hydrogen, and also the desire to improve resilience (leaking valves can lead to inability to enact an isolation, requiring expensive work arounds) there is a developing consensus that providing for DVBB isolation will in most cases be best practice and the ALARP solution. Note, while positive isolation will always be the most secure isolation, it requires a means of proven isolation to enact and is often not practicable to provide at all locations (it also comes at the trade-off of adding leak points at made-up joints).

When using two independent isolation valves, there are no strict limitations on the size of the DVBB cavity, therefore in some cases DVBB isolation may be achieved by taking credit for other valves across AGI header or pipeline sections to provide the cavity. In principle it may also be possible to take credit for valves on different sides of the NGT-customer interface to achieve a DVBB isolation, though this would require coordination between parties to close the other valve and hold the isolation permit. Within the scope of this document, it is assumed that DVBB isolation will represent best practice in the majority of isolation scenarios with hydrogen, to permit intrusive works to either install positive isolation, or otherwise to conduct necessary maintenance, repair, or modification works.

4.3. Remotely Operated Valves (ROVs)

[REDACTED]

[REDACTED]

4.3.1. Actuator Type

[REDACTED]

[REDACTED]

[REDACTED]

4.4. Instrumentation / Telemetry

Table 5 summarises the expected instrumentation / telemetry requirements for different hydrogen connection arrangements, and the division of responsibilities between NGT and each customer. In general, these are expected to be broadly similar to that set out in the current (not historical) connection process for natural gas customers and also in accordance with Section 10.2.3 of IGEM/TD/13.

[REDACTED]

[REDACTED]

[REDACTED]

Table 5: Hydrogen Connection Instrumentation Requirements

Connection Type	NGT Scope	Customer Scope
Exit	Pressure ROV Position (and status)* Cathodic protection system status* Leak / flame detection* Site security / utilities status*	Metering (Class 1 – 4) Nominations
Entry	Pressure Temperature ROV Position (and status)* Cathodic protection system status* Leak / flame detection* Site security / utilities status*	Metering (Class 1 – 4) Gas Quality (diverter?) Nominations
Combined	Pressure Temperature ROV Position (and status)* Cathodic protection system status* Leak / flame detection* Site security / utilities status*	Metering Gas Quality (diverter?) Nominations

**Where applicable*

In accordance with the “minimum” connection model, it will be the customer’s responsibility to install metering equipment and provide suitable telemetry back to NGT.

A detailed discussion of metering classes is outside the scope of this document (it will not influence NGT’s scope for connection design), though it is noted that hydrogen networks are likely to operate more dynamically to price and demand fluctuations than the current NTS, therefore additional resolution for metering data is likely to be required. This must be balanced against ensuring the metering equipment is cost effective for the customer. It is assumed that a daily gas volume nominations system would also work similar to the current system though this is outside the scope of this document.

For all suppliers to the pipeline network, gas quality sampling data must be provided to NGT. Combined with the gas metering system, this will allow the total volume and energy flowrate to be determined. The telemetry parameters should include all of the key compositional readings set out in the relevant gas quality specification for entrants, except those where it can be demonstrated there is no possibility for the limit being exceeded (e.g. due to the fundamental process used to produce hydrogen which mitigates the risk of certain contaminants being present). This is important both to ensure integrity of the network, and also to ensure safety / functionality to all off-takers. There may also be a requirement for position feedback of a recycle / diverter / pipeline export valve or similar, in situations where off-specification gas is being produced but is being appropriately managed by the customer, although this may be inferred through the metering package output (i.e. off-specification fluid but no metering flow indicated to pipeline).

For off-takers from the hydrogen network, no provision for permanent sampling points is proposed, on the basis that controlling the inlet specification should generally be sufficient to ensure the outlet specification is maintained. Any requirement for temporary sampling points should be confirmed.

4.5. Non-Return Valve (NRVs)

Non-return valves (NRVs) may be used to prevent reverse flow to/from the pipeline network. For exit-only connections, there is a theoretical risk of both overpressure and loss of integrity / off-specification fluid in the event of reverse flow from offtaker sites. For entry-points, there is an inherent functional requirement to prevent reverse flow from the network back to the producer site in certain circumstances (e.g. compressor stop/trip), though the upstream producer will always need to provide this functionality internally.

The provision of NRVs has historically been a best practice measure. However, NRVs in any connection design will potentially have a significant adverse impact on the CAPEX and OPEX of the connection, due to:

- [REDACTED]
- [REDACTED]
- [REDACTED]

For hydrogen **exit-only** connections, it is proposed that NRVs are not required within the NGT scope connection design, however it would be reasonable to audit a offtaker customer's arrangements to prevent reverse flow as part of any connection agreement (in most cases, this will naturally result from a pressure reduction station arrangement, internal NRVs, pressure relief valves, and similar). [REDACTED]

An interface HAZOP conducted as part of the connection process should be used to confirm there are no relevant issues.

For hydrogen **entry** connections, taking the bullet points above into consideration, there will be a significant CAPEX and OPEX cost impact of including NRVs into the connection design. As part of this innovation project it is therefore proposed / challenged whether [REDACTED] the following further points / justifications are made:

- Compressor trains within supplier sites will typically have NRVs and actuated valves to prevent reverse flow upon stop/trip. NGT should not be involved or take responsibility for (part of) supplier's layers of protection. Provision of NRVs within NGT's connection scope in this regard is therefore an unnecessary duplication.
- Any gas shrinkage concerns are not warranted, since metering is in any case provided by the supplier (though NGT may undertake assurance to confirm any blowdown / depressurisation functions on the supplier site would not affect metering and lead to shrinkage losses).
- If necessary, a reverse flow shut-off functionality could be implemented using the existing ROVs, coupled with flow measurement (this need not be class 1-4 metering but a coarse, reliable type e.g. venturi meter) and pressure measurement either side of the ROV with a new logic function implemented. However, there is not thought to be any requirement for this functionality as a standardised connection feature.

For all combined entry/exit connections, the expectation is the NGT-customer interface will always be at a single point (unless there are site-specific exceptions), with no requirement for NGT to change valve positions to facilitate an "offtake" mode and a "supply" mode, with bidirectional flow always possible.

4.6. Overpressure Protection

Overpressure of pipelines and AGIs is discussed in Section 12.5 of IGEM/TD/1 and Section 8.5 of IGEM/TD/13. Typically, upstream compressors will have controllers to prevent overpressure (modulating compressor speed and/or recycle valves) as well as other safety layers such as relief valves, high-pressure trips (which close actuated valves and/or shutoff compressor/pump motors), and slam-shut valves. In some cases, it may be possible to avoid such devices if the compressor (or pump) can be demonstrated such as to not pose an overpressure risk (e.g. maximum discharge pressure is less than the pipeline design pressure).

For hydrogen entrants, it would be expected that NGT will audit customer sites for suitable overpressure protection measures set at the correct setpoints to protect the pipeline network. This may require a combined HAZOP/LOPA/QRA assessment to ensure the appropriate SIL rating is assigned, taking into account the potential consequences for overpressure of the pipeline network. In addition, following on from discussion on NRV configuration above, it is not expected that NGT would provide NRVs to protect entrants from overpressure due to reverse flow, which per API-521 would typically require dual and diverse NRVs which are tested and inspected.

4.7. Filtration / Strainers

Filters or strainers can be used to prevent foreign object debris (welding slag, construction debris, corrosion products, pig tool wear parts, etc.) from entering the network, and also to protect sensitive equipment from debris material which is naturally generated from within the pipeline network. Repurposed pipelines may also present some additional risks to particulates generation compared to new pipelines.

The provision of a commissioning strainer has historically been a best practice measure to prevent a range of potential issues during operational life of the pipeline system caused by initial construction debris. For example, debris could affect the operation and sealing effectiveness of valves, could damage internal coatings and other equipment, could hinder pigging, and potentially cause liabilities if debris is transported onwards to offtakers.

Alternatives to the provision of commissioning strainers could be to put a duty on the supplier to demonstrate appropriate inspection and commissioning methodology / equipment to mitigate the risk of any construction debris entering the NTS. For short connecting lines, this could for example include boroscope inspection or running cleaning pigs with temporary equipment. Where the upstream supply is via pipeline connection, cleaning pigs may be run to the permanent pig traps.

On balance, the following approach is proposed for hydrogen service:

Commissioning Strainers

- A commissioning strainer may be waived in cases where the upstream connecting pipe is short, and can be demonstrated to be free from debris by other means and/or the risk of debris from the customer site during startup is deemed to be low.
- Elsewhere a strainer should be provided, however the cost impact of providing a strainer would be significantly reduced by:
 - Installing the strainer as the first piece of equipment downstream of the supplier-NGT interface.
 - Coordination would be required with the supplier to depressurise the connecting pipe section and remove the strainer. This would need to be scheduled with a planned outage within the first

few years after startup (assuming there is no major differential pressure across the strainer which would necessitate earlier changeout).

Filters

- Filters are not expected to be necessary to protect from solid materials from the supplied gas as a matter of course throughout operational life. Per Section 7.5 of IGEM/TD/13, consideration shall be given to incorporating a filtration system if there is a credible risk of dust or liquid from upstream, and if adopted should not be more stringent than necessary to protect downstream equipment. It is proposed that this may be managed by the gas quality measurement process and audit/assurance of the supplier process (given the production processes for blue/green hydrogen it is deemed very unlikely that any significant solids would be likely to be produced in any case).
- [REDACTED]
Where any offtakers require a particulates level better than that agreed in the transportation agreement, they would need to make provision for suitable filters within their site.

4.8. Pressure-Reduction Stations

Currently, the NTS operated by NGT is a high pressure (above 7 bar, to IGEM/TD/1) network, and NGT does not

[REDACTED], [REDACTED]
[REDACTED] Based on discussions during the framing workshop, it is understood that a similar operational philosophy is expected to apply to upcoming hydrogen projects (e.g. Project Union, SCO2T Connect), whereby the expectation is that pressure reduction stations would normally be a customer responsibility, in line with the “minimum” connection model.

4.9. Odourant Injection

In accordance with the Gas Safety Management Regulations 1996, odourisation of gas is currently only required where the gas is at a pressure of 7 barg or below (i.e. LP, MP or IP distribution pressures). As such, the NTS currently operates without odourised gas. Similar to the discussion on pressure reduction stations above, since

[REDACTED]
[REDACTED]
[REDACTED]

4.10. Chemical Dosing / Analysers

As discussed in Section 4.4, since online gas quality measurement will be a responsibility of all suppliers and telemetry must be provided to NGT. It is expected that NGT may undertake periodic auditing to ensure appropriate calibration / independent verification testing of supplier equipment. It is not expected that NGT undertake independent gas quality measurement with online samplers by default at all connection points, though NGT may elect to undertake gas sampling at some key locations across the network to get representative samples and help identify any deviations and allow these to be traced back to specific sources.

For hydrogen pipelines, it is noted that there are ongoing discussions around the potential requirement to inject a low dosage of oxygen into the fluid, to act as an inhibitor for pipeline embrittlement. If this approach is pursued, there may be a requirement for oxygen supply equipment at entry points to the network and an oxygen source (e.g. multi-cylinder packs or bulk liquid supply). This would likely require additional sampling / gas analysers to confirm the composition downstream of the injection point. Gas cylinders for carrier and/or test/calibration gases may also be required in this case. This would also require safety assessment of the hazard posed by too much oxygen injection and risk of forming a flammable atmosphere within the system. At this stage, as it is unclear whether oxygen dosing is likely to be pursued the proposed arrangements do not include this functionality, however this should be kept under review as the projects progress.

4.11. Pig Traps

Pig traps will be present for all pipeline sections, and NGT as the network operator will own and operate all pig traps upstream of the customer connection (and ECV). This will include the barred tee arrangement, isolation valves on the tee branch and pig trap inlet, kicker line (also known as the forcing/receiving line), and all vents, drains, and equalisation (or balancing) line on the pig trap. Figure 7 shows an indicative arrangement for a typical pig trap, as taken from IGEN/TD/1 (note: this is shown with DIB isolation, but for hydrogen this is expected to require DVBB isolation per discussions in Section 4.2).

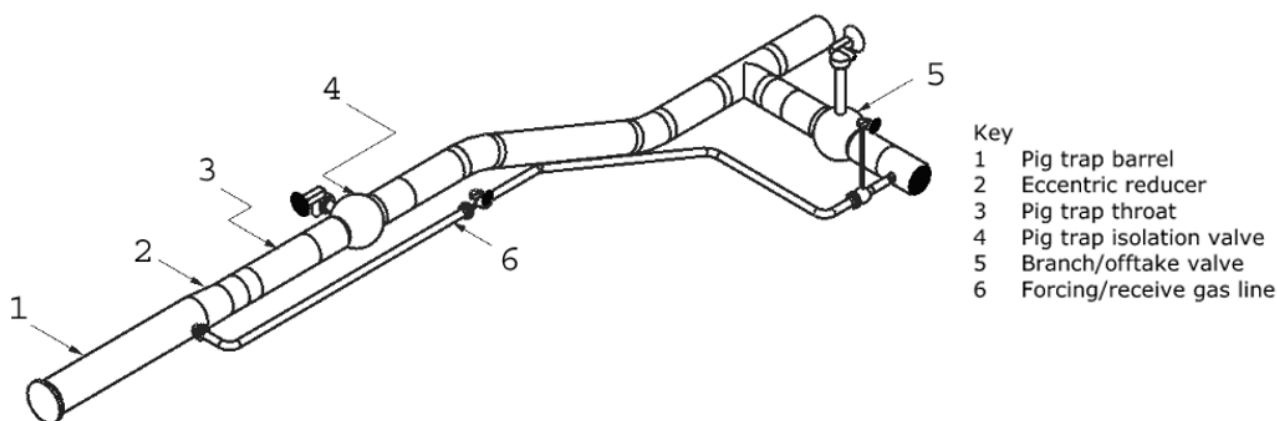


Figure 7: Pig Trap Arrangement (from IGEN/TD/1)

[REDACTED]

[REDACTED]

[REDACTED] Parties may optimise the standard design to suit site-specific circumstances in any case.

4.12. Drain/Purge/Vent Points

4.12.1. Drain Points

Pipeline drain points are not expected to be required as part of the hydrogen connection design, since the pipeline network will operate with a sufficient safety margin above the gas dewpoint that no free liquids will be present within the pipeline network which require draining.

AGI drain points may be provided for:

- **Pig Traps:** Not specifically part of the connection design, though it is noted that all pig traps will generally have a drain valves, which should be fitted with suitable flange blind / plug when not in use.
- **Hydrotesting:** Drain points may be required in some locations to facilitate hydrotesting, particularly non-piggable sections which cannot be swabbed directly using pigs within the hydrotest ends. Where (and if) required, it is expected that these would be suitably capped off after use for the operational life. The valves may be removed and replaced with lock-o-ring connections. See later discussion on the proposed modular connection design solutions which may be FAT tested prior to golden tie-in welds on site.

4.12.2. Vent Points

Vent points of nominal size [REDACTED] are generally required upstream/downstream of all major valves and equipment to allow for commissioning, purging, depressurisation (and pressurisation in some cases), as part of normal maintenance, repair and modification activities. These should be fitted with a suitable blind / plug in normal operation. In some cases, vent points may be combined with instrument valves to avoid unnecessary additional small bore connections to the main piping.

4.12.3. Purge Points

For most AGI pipework, there is no requirement for purge points to be specifically sized to accommodate purging practices. As such, dedicated purge points are not generally necessary and vent points discussed above will suffice.

For all pipeline sections, there will be a mandatory requirement to accommodate indirect displacement purging to IGEM/SR/22, which requires that purge points be suitably sized to avoid excessive backpressure (and thus, gas usage) when purging the pipeline. However, these purge points will not be included in the standardised connection design:

- NGT-operated pipelines will require a suitable purge rider at the pipeline interface (i.e. at the first valve located off the barred pipeline tee).
- For any customer-operated pipeline it will be the customer's responsibility to provide any suitable purging points.

4.12.4. Recompression Connections

Recent changes to regulations in the USA/Europe have introduced bans to routine venting and flaring activities for natural gas pipeline networks, and while the future regulations which will apply to hydrogen networks are still being developed, it is likely that routine hydrogen venting will not be permitted (hydrogen has a GWP100 of 11.6). To comply with a net-zero approach to emissions, hydrogen connection designs should have suitable provisions for relevant parts of pipelines and AGIs to be recompressed and/or flared. In most cases, this can be achieved via existing vent/bleed valve provision within AGIs, and purge riders for pipeline sections. It is assumed that it will generally be acceptable to cold vent smaller sections (ball valve cavities, bleed cavities, instrument lines, etc.).

4.13. Pressurisation / Start-Up / Bypass Valves

Pressurisation or start-up valves are typically required to:

- Facilitate controlled purging and pressurisation stages during initial commissioning, and commissioning following maintenance/repairs/modifications.
 - For pipeline sections, displacement purging velocities should be in accordance with IGEM/SR/22.
 - For AGI and smaller connecting pipework sections, pressure or dilution purging may be acceptable, given the relatively smaller inventory, which will generally not require specific purging rates.
- To avoid excessive piping forces, noise, and seal damage associated with opening large valves with significant pressures differences present.
- In some cases, bypasses may be operated to facilitate maintenance activities on the main line valves (though this is rare, the use of combined gas-hydraulic actuators has historically allowed the gas-side to be fully disassembled while the manual cylinder can be used).
- Bypasses may also be opened to minimise interruptions to supply caused by partial/full stroke testing of ROVs.

Within any connection design, there is a decision to be made whether any bypass route is permanently installed, or whether temporary pipework (e.g. installed between vent points either side of a main line valve) may be used.

[REDACTED]

However, given the additional DVBB hydrogen isolation arrangement required, there is unlikely to be any significant additional cost to providing a permanent bypass valve. This is because, putting in provision for a temporary valve would require two isolation valves on the upstream/downstream side, whereas in a permanent arrangement the bypass valve can be situated between two block valves and need not be isolatable for maintenance itself.

While opening ball/gate valves with significant pressure differences is not usually recommended, and may lead to some seal degradation, this is standard practice in scenarios where there is only a small cavity to be pressurised, since the cavity would pressurise up extremely quickly. For example, there is typically no requirement to pressurise a DVBB cavity before opening one of the block valves, however it should be noted this may not apply in situations where the DVBB cavity may in fact be an entire AGI header or in some cases, a larger pipeline section (as alluded to in Section 4.2 discussions).

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

5. Hydrogen Conceptual Designs

In this chapter, the design justifications outlined in the previous chapter are developed into connection designs for different scenarios for hydrogen pipeline networks. A base case configuration is presented for each of the three major connection types, which is then developed further for different types of sites and connection scenarios.

5.1. Hydrogen (Offtake)

5.1.1. Base Case

Figure 8 shows a basic valve configuration for a “minimum” connection model customer offtake. This would be applicable for either a new-build AGI, or a retrofit future connection within an existing AGI (assuming the AGI has suitable isolation valves upstream to facilitate this). This arrangement would apply where a customer is responsible for the connecting pipework up to the AGI (i.e. where they can route this within their own premises, and the route is short enough that a pipeline connection with pig traps is not necessary). In this case, there are assumed to be no major pipeline inventories either side of the connection (which would require pig launching/receiving facilities, etc.).

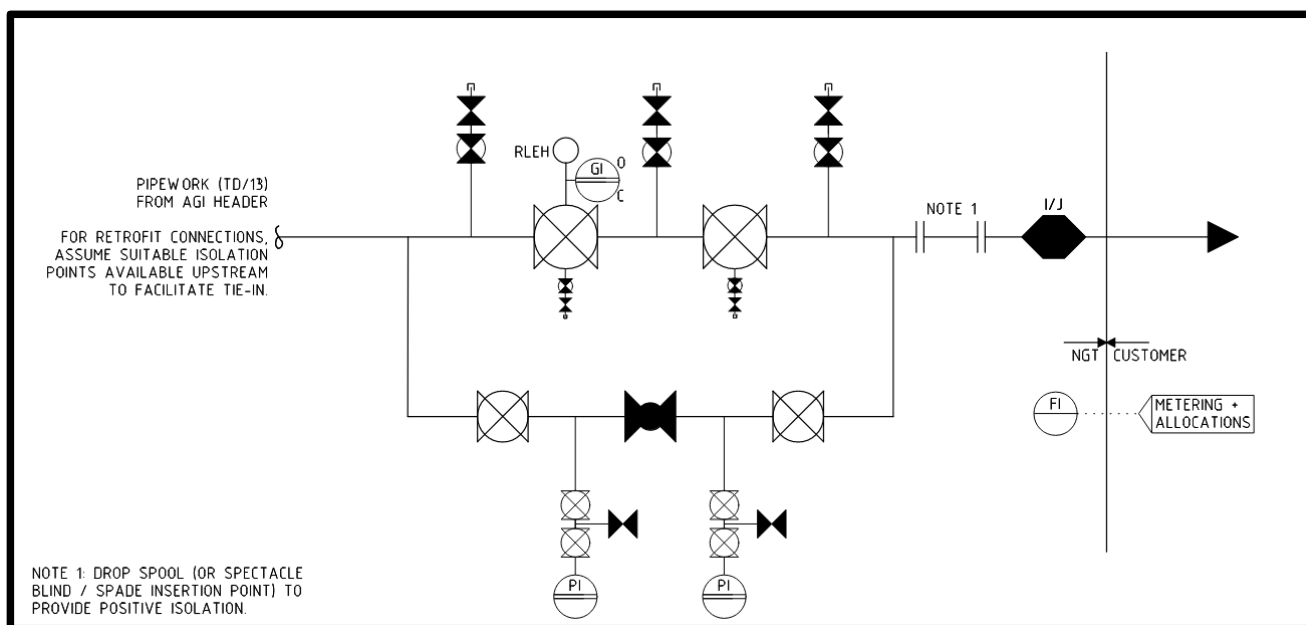


Figure 8: Hydrogen Offtake (Base Case)

The points below provide further justification and background to the proposed configuration.

1. Double valve block and bleed (DVBB) isolation is provided on the mainline and bypass/startup route, with bleed points on both sides to allow the isolation to be applied in either direction. This will:
 - Provide NGT full autonomy to undertake any maintenance / repair works within the AGI or further upstream, with no coordination being necessary with the customer to depressurise their downstream system (which can remain pressurised, if necessary).
 - Provide a high-quality isolation for the customer from the NGT network, to facilitate any tie-in works, intrusive maintenance / inspections, and any disconnection/decommissioning works as needed.

It is expected that the mainline block valves would be trunnion ball valves, with fully welded body, similar to those currently used on the NTS or an equivalent quarter-turn type. For the bypass isolation valves, trunnion ball valves or plug valves may be used.

2. A drop spool (or flanges to allow spectacle blinds / spades to be inserted) is provided to give positive isolation where isolations may be required over longer time periods. This provision should be weighed against the risk of flange leaks, however since this is on the downstream side of the main pipeline isolation point the inventory is limited.
3. A bypass route (of smaller diameter than the main connection) will facilitate purging and pressurisation of the customer connection, and may also be used during with partial/full stroke testing of the mainline valves. A globe valve allows flow to be throttled, which may also be used as an isolation valve if needed.
4. Three vent (or bleed) points are provided in a ball / globe double block valve arrangement. This facilitates:
 - Double block valves to be proved in both directions, local to the isolation point (full NGT control). Pressure build-up gauges can then be fitted at these points to monitor the isolation effectiveness.
 - Can be used as purging (injection) or depressurisation / venting routes for commissioning and decommissioning activities. Alternatively, can be used to attach recompression equipment, if necessary.
 - Some of the vent points could be omitted, if there are others nearby within the AGI or customer pipework.
 - It is assumed that vent points will be nominal 1" or 2" connections, since in this example there are no major pipeline inventories on either side which would mandate IGEM/SR/22 displacement purging be undertaken (i.e. pressure or dilution purging can be used where necessary, at a lower flowrate).
5. Permanent remote and local combined pressure indication available for the upstream and downstream sides of the connection. These could be omitted if other nearby pressure indication is available. As shown, they are situated within the bypass bridge (), which allows them to read both upstream and downstream of the connection when necessary (depending on valve lineup), though could also be installed on the mainline either side of the main block valves.
6. One of the mainline valves is fitted with an electro-hydraulic actuator, giving remote actuation ability for the main line, allowing the NGT control room to quickly isolate the connection without the requirement for an operator to attend the site.
 - The actuator will have a local-mode to allow an operator to operate when in attendance, as well as a manual hydraulic pump (or gear wheel) to allow the valve to be operated if electricity supply is isolated.
 - Attendance at site would always be necessary to enact a full DVBB isolation with the second mainline valve, also disabling the actuator on the other valve.
 - Remote position indication is provided.
7. If trunnion ball valves are used as the DVBB block valves, there may be a small amount of residual pressure trapped within the ball valve cavities. Suitable procedures should be developed to account for this, with cavity vents, shown, opened if necessary (i.e. in addition to the main bleed cavity between valves). If the valve arrangement is above-ground, any vent ports will be accessible, if belowground these may need to be extended.

5.1.2. Pipeline Hot-Tap Connection

Figure 9 shows the same base case connection, but in this case applied to a hot tap connection to an existing pipeline for a similar offtaker connection. As shown, the hot-tap construction valve used to facilitate the hot-tap

procedure and subsequent piping tie-in is ultimately left in a locked open position with flanges encapsulated to limit the potential for any flange leaks.

For the hot-tap construction valve, it would need to be confirmed if a single valve is deemed sufficient to enable the tie-in procedure (e.g. using additional flanges, not shown, to install safety bags) or whether a DVBB construction valve arrangement is needed.

Alternatively, it may be possible to use permanent valves as the construction valves (or swap them over using Lock-o-rings or other types of plugs),

This would only be possible where the connection compound is directly over the pipeline hot-tap (this may not always be possible, where land use is restricted the connection compound may need to be located some distance away from the pipeline).

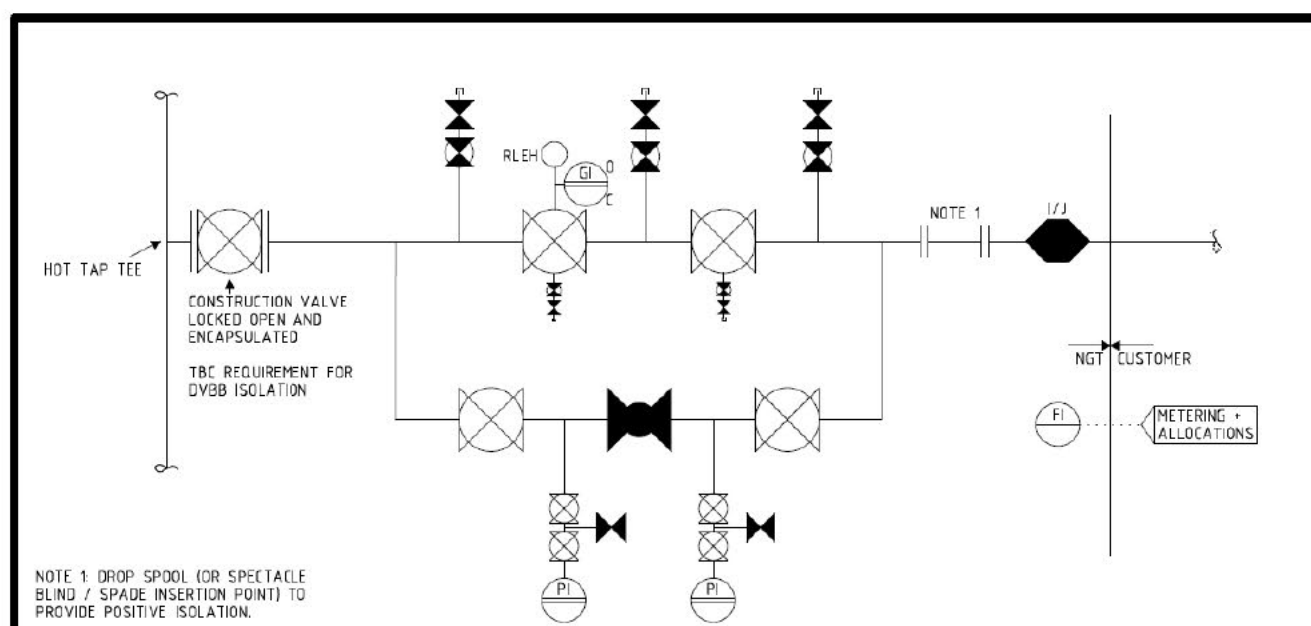


Figure 9: Hydrogen Offtake (Hot Tap)

5.1.3. Block Valve Station

Figure 10 shows an example of the base case applied to a block valve station where, as previously discussed in Section 3.5, for network resilience purposes it is desired to allow the customer to be supplied from east/west pipelines independently (in cases where this is unlikely to be required, e.g. when all storage and entrant sites are along one pipeline, the standard connection arrangement per Figure 8 could be joined to the bypass line).

. As shown, the customer bypass route and the pipeline bypass route are combined in a dual-purpose role (i.e. closed block valve per Note 3 is opened in combination with pipeline bypass globe valve, to facilitate maintenance on the customer ROV). In normal operation, the pipeline block valves are open, so only one customer ROV is needed, with the manual ball valve to the other pipeline normally closed. Note, the two purge/vent valves (Note 2) in this case are sized to IGM/SR/23 to facilitate pipeline purging and pipeline recompression units.

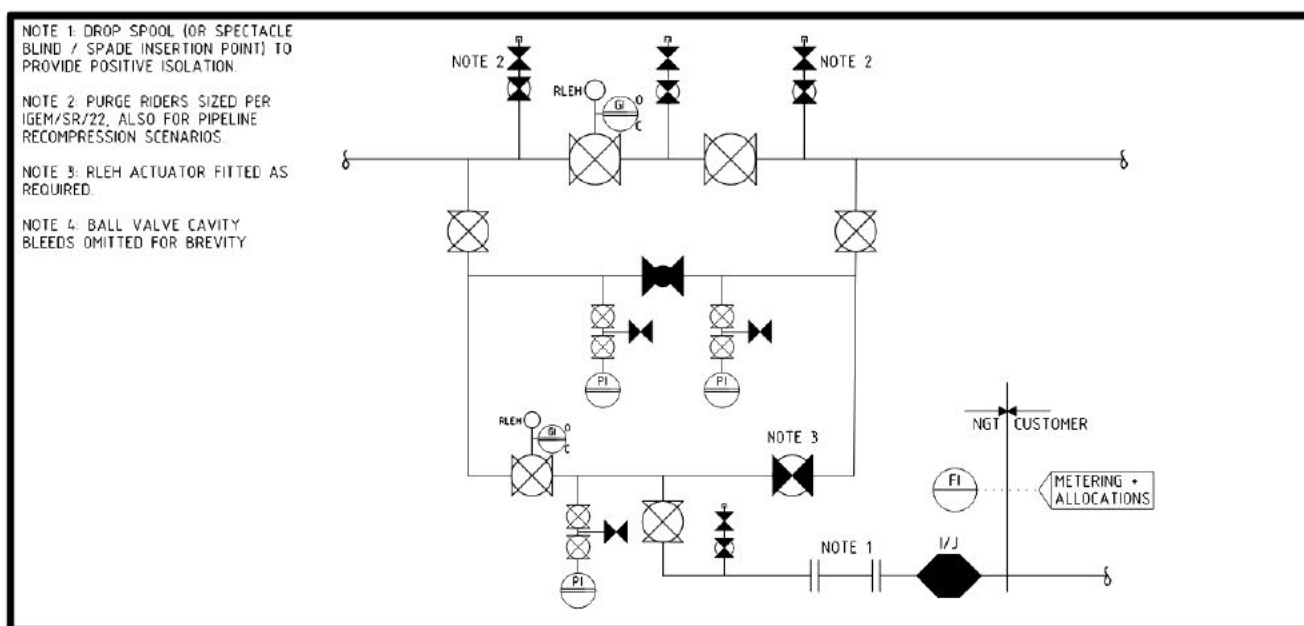


Figure 10: Hydrogen Offtake (Block Valve Station)

5.1.4. Other Configurations

Developing the basic hydrogen connection design from Figure 8 further, Figure 11 gives an example of the standard connection arrangement within a typical, larger AGI header which may contain a pipeline reception area with pig trap (simplified arrangement shown), several other connections to adjacent pipelines and/or other customer offtake / entry points, as well as provision for future expansion. The standardised hydrogen offtake connection design as shown allows the offtaker to be isolated from the AGI header while other pipeline / customer connections remain live.

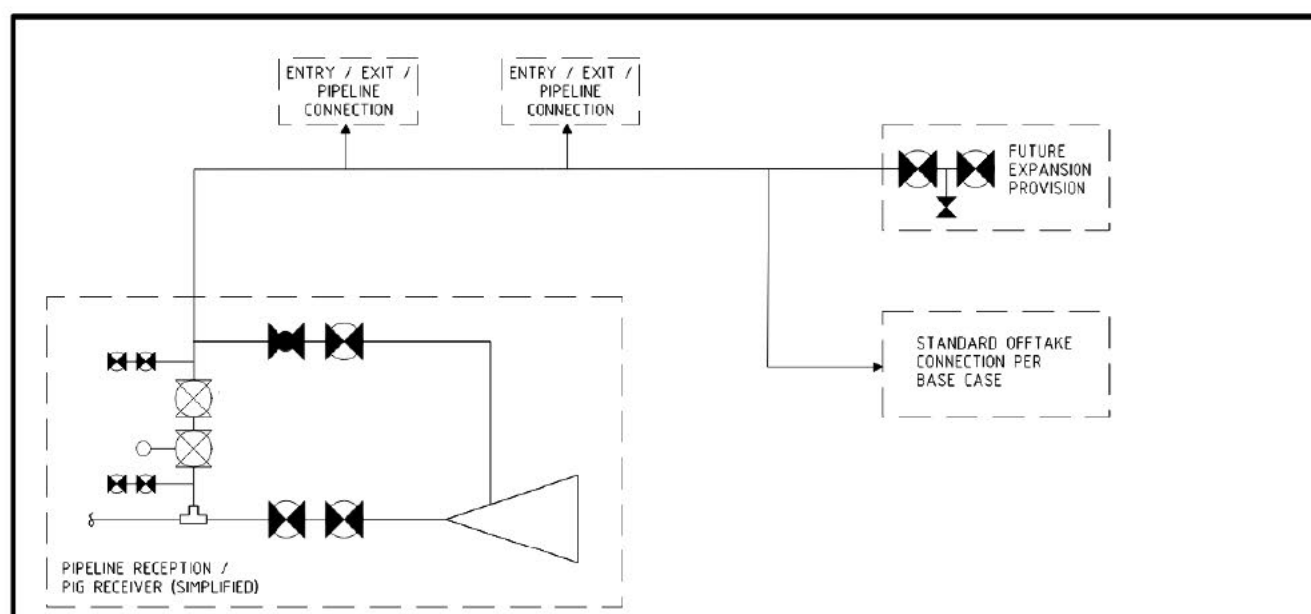


Figure 11: Offtaker Connection with Larger AGI Header

In some cases, provision of a standardised valve arrangement as shown in Figure 8 and Figure 11 may be excessive and lead to duplicate valves and equipment. An example of this would be if NGT is supplying a pipeline connection to a location where there is only a single customer. In this case, it would be possible to combine the offtaker connection with the pipeline isolation valves, in an arrangement similar to that shown in Figure 12.

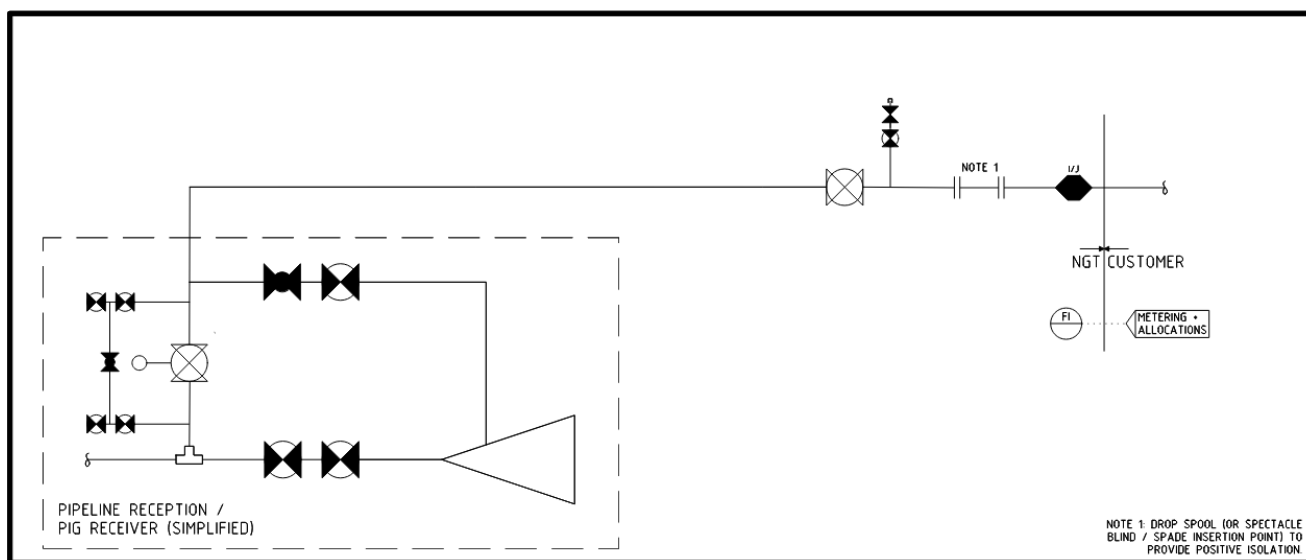


Figure 12: Offtaker Connection – Pipeline Termination / Single Customer (Optimised)

In Figure 12, there is a bridle arrangement at the pipeline reception to facilitate commissioning purging / venting, as well as the pig receiver and kicker line. One of the manual mainline valves is moved to downstream, with suitable vent points to allow purging, venting and pressurisation activities as needed (note, vent and bleed points on the pig trap are not shown, for brevity). The downsides to this “optimised” arrangement include limited ability to expand to include any future connections without a hot-tap, a pipeline settable plug device, or depressuring the entire line (or increasing the size of the valves in the bridle arrangement to provide a future connection point, however in this case the modular base case connection arrangement may as well be provided at the same cost). In addition, the ECV has no permanent pressurisation / bypass bridle.

Figure 13 shows the equivalent single-customer AGI with the modular connection arrangement, which allows the AGI header to be depressurised with DVBB isolation separately from the pipeline and the customer. It also allows the AGI header and downstream customer pipe to be pressurised by permanent startup bypasses (globe valves).

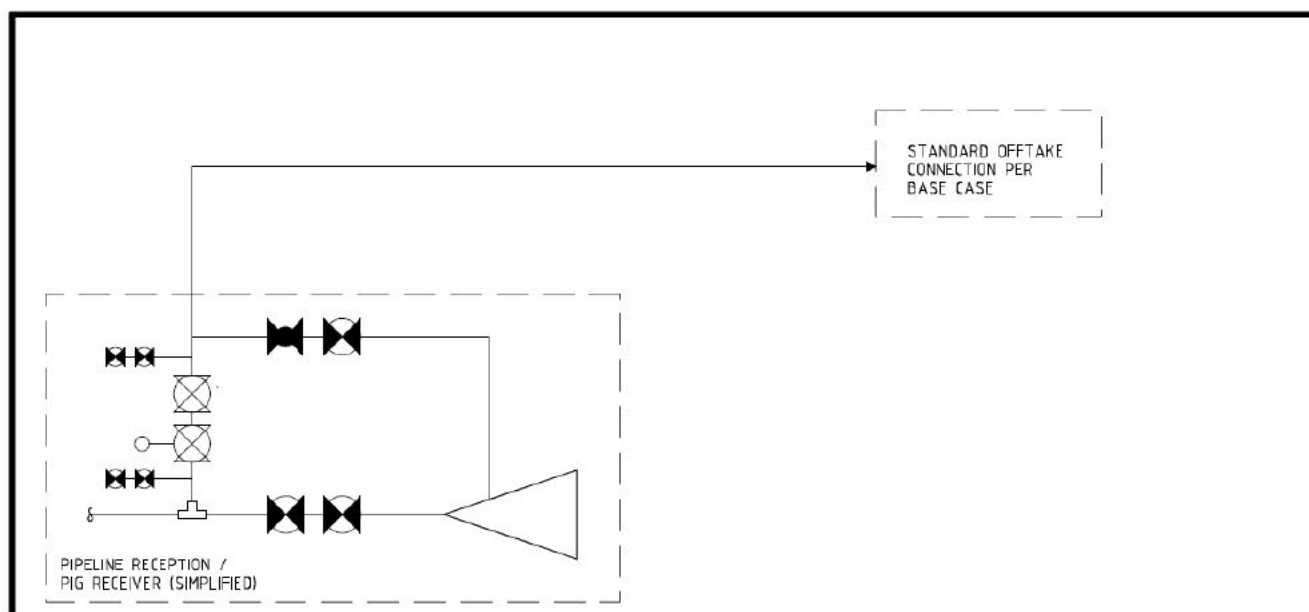


Figure 13: Offtaker Connection – Pipeline Termination / Single Customer (Modular)

5.1.5. Modular Connection Design

The base case valve arrangement shown could be developed as a modular arrangement, either skid-mounted for an above-ground arrangement, or as a pre-built module to be buried under ground. Figure 14 shows an example plan drawing of this, for a DN300 main line and DN150 bypass. With an assumption that Class 600# valves (and Schedule 80 pipe) are suitable, this arrangement weighs about 2.4 tonnes excluding the skid structural steel, and would have dimensions of approximately [REDACTED]. These lengths are based on ASME B16.10 valve end-to-end dimensions (conservative, many valves are shorter) and some additional pipe lengths included (pipe stress analysis not performed at this stage).

Within the confines of UK lorry transportation limits, a practicable size limitation would be to limit the skid size to within that of a 40 ft shipping container ([REDACTED]) with a weight limit of between 21 to 26 tonnes. As such, larger connection sizes up to 16" NB or even larger above could be possible within this limit in a single module. Even larger connections could split the bypass onto a separate sub-module to integrate with the main module on site. Table 6 an estimate of the weight (excluding structural steel) and dimensions for different bore sizes.

Table 6: Modular Connection Skid Size and Weight

Mainline Size	DN100	DN150	DN200	DN250	DN300	DN400
Bypass Size	DN80	DN100	DN100	DN150	DN150	DN200
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]
[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]

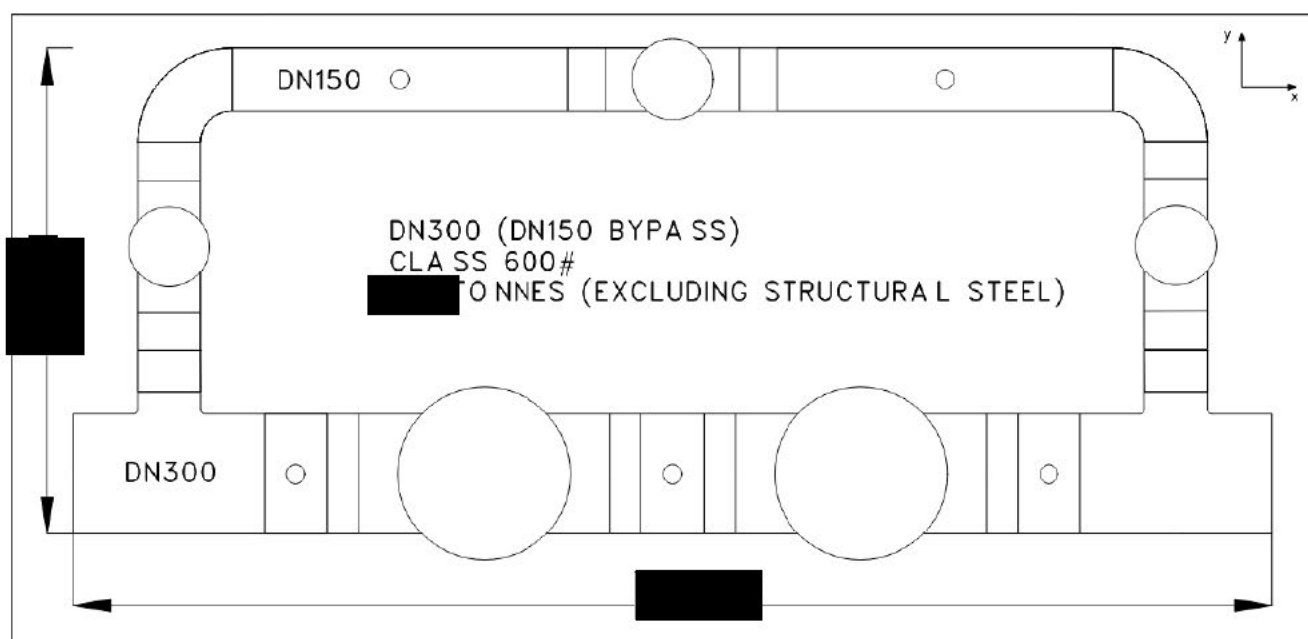


Figure 14: Connection Dimensions (DN300x DN150)

During the framing workshop, some of advantages and disadvantages of using a modular or skid mounted connection designs were discussed, outlined in Table 7.

Table 7: Modular Connection Advantages and Disadvantages

Advantages	Disadvantages
- Modular unit can be assembled, welded, inspected and tested in a factory, in advance of site works. - Overall duration of site works will be minimised, with quicker installation. - Above-ground skid-mounted arrangement provides easy access to all valve body vents, drains, etc. for commissioning and maintenance.	- Onsite welding will still be required to enact tie-ins to the skid, but could also be minimised with pre-fabricated goosenecks / spools to connect to buried piping. - The safety aspects of lack of impact protection and seismic loading may need to be considered for above-ground equipment. - Marginally greater visual impact plus noise. - Module will be significantly heavier than individual components and will require more complex lifting equipment on site. - Access to remote AGIs for an articulated lorry to bring in a module as one piece may be limiting in some cases.

5.1.6. Above/Below-Ground and Welded/Flanged Connections

Per IGEM/TD/1 Section 11.2, all joints between the pipeline and the first valve off the pipeline shall be welded to restrict the potential for leakage which cannot be isolated by closure of the valve. Buried flanges are also to be avoided or minimised to the lowest practicable level. Therefore if the valve and bypass arrangement is provided as a modular skid, it is expected that a butt-weld end would be provided for the pipeline-side tie-in and

golden tie-in weld procedures used to connect to the pipeline (the skid would not be hydrotested with the pipeline).

Otherwise, for tie-ins within existing or new-build AGIs and also the skid internal construction, per IGEM/TD/13 Section 7.9 there is a preference for welded joints compared to flanged connections, where reasonably practicable and economic, to eliminate potential leakage sources. It is proposed that a modular design be fully welded, since this reduces the total number of welds required (i.e. to fit flanges) compared to jointed connections and reduces the risks due to leaking joints.

With regards to whether the connection arrangement itself is above ground or below ground, there are no specific requirement per IGEM/TD/13 standards. Locating equipment above ground provides better access for maintenance activities, and based on discussion during the workshop is generally preferred for hydrogen connections, where maintenance windows may be more critical than on the existing NTS.

5.2. Hydrogen (Entry Point)

Based on the discussions set out in Chapter 4, hydrogen entry points may be facilitated by an identical valve arrangement to the offtake, where the only differences are the inclusion of temperature indication, as well as the gas analyser remote telemetry signal (which in practice are unlikely to be hard-wired at the connection site). One of the two main block valves would be fitted with an electro-hydraulic valve actuator to give ROV functionality, similar to the entry connection. Figure 15 shows an example “minimum” connection model arrangement. The variations in connection arrangement between multi-junction, single-junction AGIs and hot-tap connections would be the same as discussed above for the offtake scenario.

A commissioning strainer is also included in the connection design. This is currently shown as a Y-type strainer, though an open-ended (skirt type) could also be used (refer to IGEM/TD/13 Appendix 6 for further discussion of strainer types).

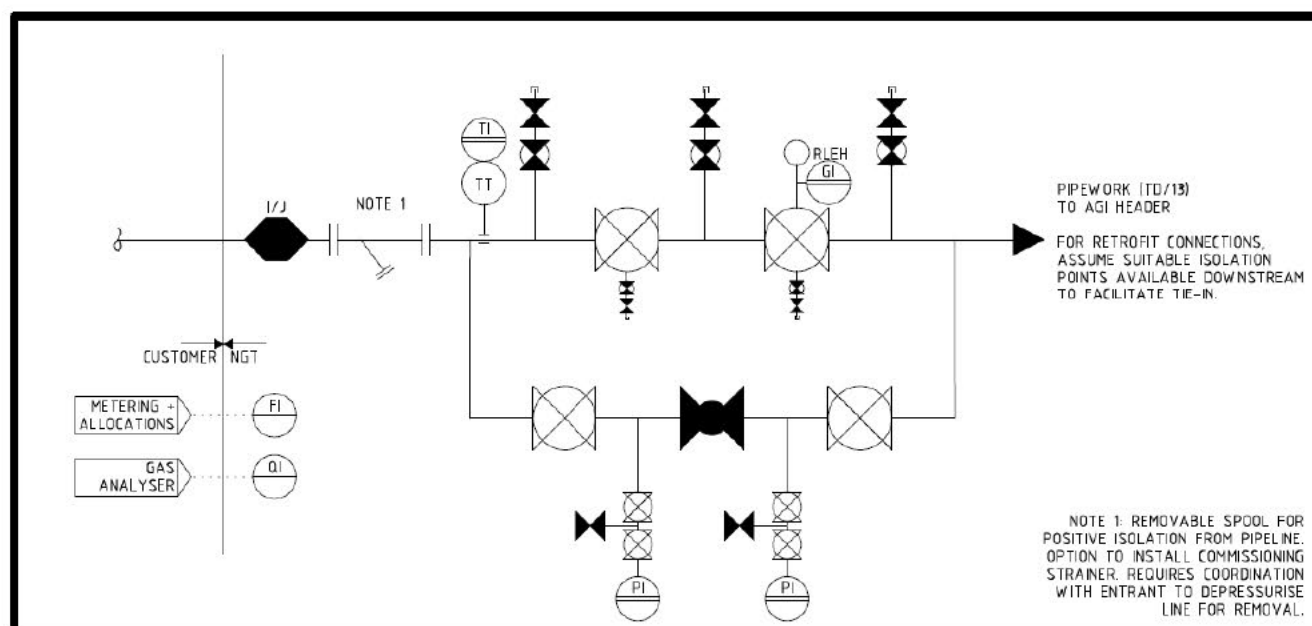


Figure 15: Hydrogen Entry Point (and Combined Entry / Exit Point)

In terms of standardisation, the arrangement proposed above would allow significant efficiencies to be realised for new entry connections, since a modular skid configuration essentially identical to the offtaker connection

could be used. This lack of NRVs, any chemical dosing and additional overpressure protection facilities would need to be confirmed as per discussions in Chapter 4.

5.3. Hydrogen (Combined Entry/Exit Point)

For combined entry/exit points, the arrangement shown in Figure 15 could also be used. Since metering is a customer responsibility, there is no requirement for separate entry / exit streams within NGTs scope and the overall design is bi-directional. The commissioning strainer, if used, should support bi-directional flow.

6. Carbon Connection Design Development

For connections within a carbon dioxide network, many of the considerations will be similar to those outlined above for hydrogen, though there will be some differences due to the nature of the fluid properties. Carbon dioxide is not flammable, but is heavier than air and can present a danger of asphyxiation in areas which are not well ventilated. The threat of sweet corrosion if water is present must be mitigated, and issues associated with liquid drop-out / phase change and low temperatures due to Joule-Thomson cooling upon pressure let-down must also be managed. This chapter discusses these with respect to the connection design, where the focus is on entry points since these will be the most common connection type.

6.1. Types of Sites

To consider whether connection types will need to be modified/optimised to suit different entrants, a high-level summary of different entrants is given:

- **Dispatchable Power Generation:** The major power generation emitters will likely be CCGT (of up to 1-2 GW capacity) plants fitted with post combustion carbon capture equipment, producing a rich carbon dioxide stream which is compressed, dehydrated, and exported to the pipeline.
- **Waste to Energy:** Post-combustion flue gas is captured in a similar manner to above.
- **Industrial Decarbonisation:** Various industrial users may implement fuel switching projects and other efforts to capture CO₂ rich streams within existing sites, likely to be relatively steady demand profile.
- **Biomethane:** Biogenic carbon dioxide produced from biomethane sites, typically small scale (e.g. ~10-20 MW), where it will likely be desirable to develop a minimal entry connection, similar to recent for their entry points to the NTS for the biomethane itself. The degree of protections may be lesser than other entrants, for example if the biomethane supply is small and at a particular entry point will be well-diluted by other larger flows, the need for additional protections within NGT scope may not be needed/justified.
- **Direct Air Capture:** Possible future entrants if technology is developed. Many of the current technologies rely on the use the calcium carbonate / calcium oxide mechanism, where there is still a requirement to dehydrate the CO₂ so presents a similar risk to the network.

While the entrants will have different production profiles, all of them have an inherent requirement to dry the produced carbon dioxide stream prior to export, therefore present a potential risk of high moisture content to the network. The risk of other contaminants would require further consideration.

No major drivers for differences in connection design are identified, with the possible exception of minimal connection (i.e. no ROVs) approach for biomethane sites and other small industrial emitters. As noted in the basis for this document, NGT may decide to offer a "maximum" approach to connections to take ownership of the metering, gas analyser, and other parts however this is not considered in detail at this stage.

6.2. Isolation Valve Configuration

Carbon dioxide is not currently defined as a dangerous fluid under PSR and, as such, carbon dioxide pipelines are not classified as Major Accident Hazard Pipelines (MAHPs), however this may be revised in the near future. Gaseous carbon dioxide, per some company's isolation standards would fall under the "hazardous utility" category, which may permit slightly lower isolation standards compared to flammable / toxic fluids (which would include hydrogen).

Per NGT's current T/PM/TR/17 isolation standard Appendix D, both flammable / highly flammable gases and asphyxiants such as carbon dioxide all come under Category 2. The required isolation standard is then determined by the line size, system pressure, and a location factor, which combine to give a release factor. The fluid category and release factor then determines the type of isolation needed: positive, proved, or non-proved. For Category 2 fluids, positive isolation is generally required though proved isolations are acceptable in some cases. T/PM/TR/17 states both DVBB and DIB isolations meet the minimum isolation standard.

However, any new project should consider what isolations it is appropriate to provide in different locations. A type of proved isolation will always be first required as a means to enact positive isolation. With maximum operating pressures expected up to 32-35 barg for the SCO2T Connect project, DIB isolation may be deemed appropriate both as a means of enacting positive isolation and also by itself as a form of proven isolation for shorter intrusive works (particularly in cases where the work itself requires a undoing/making up a similar number of joints to enacting positive isolation).

The risk assessment process for carbon dioxide isolations must take account of the hazards posed by small quantities of gas leakage, and therefore any works being undertaken in confined spaces, low points, or those otherwise not well ventilated may require upgrades (e.g. safety bags, plugs/PITs) and other mitigations (e.g. gas monitors, breathing equipment).

Within this document, it is assumed that DIB isolation is acceptable for normal connections to the network, though this does not preclude DVBB from being used if deemed appropriate. Consideration should also be given to the use of spectacle blinds, spades and drop spools to provide positive isolation where appropriate.

6.3. ROVs

For all carbon entry points, the risk of adverse impact to system integrity posed by off-specification fluid (particularly higher water content) warrants that ROVs be fitted at all locations so that NGT can take action to isolate suppliers when necessary. These are expected to use electro-hydraulic actuators, as discussed in Section 4.3.1, which will require an electricity power supply with each connection AGI, as well as telemetry for the remote control signal (and position feedback plus status information)

6.4. Instrumentation / Telemetry

Similar to hydrogen entry points, gas metering and gas quality monitoring will be necessary and it is expected these would be customer responsibility to install and operate, with independent 3rd party verification, with telemetry mirroring to NGT. However, carbon dioxide presents some additional risks, discussed here.

6.4.1. Water Content

Consideration may be given as to whether additional instrumentation is required at each entry point to verify the incoming composition. For example, this could include dedicated moisture meters which can be supplied either as in-line pipe fittings (threaded or flanged probe which must protrude into the bulk gas flow) or as discrete sampling cabinets which extract a small bleed stream from the pipeline flow (and typically vent this to atmosphere, where it is not practicable to put in a recovery system to return the gas to the pipeline).

Section 6.8.4 of BS-ISO-27913 on carbon dioxide pipelines sets out the reliability and precision of pipeline dehydration, noting that valid calibration certificates should exist for the water monitoring system and calibration should be performed, using two separate water monitoring systems. From a review of vendor offerings, it is expected that moisture meters would require testing and calibration at regular intervals (e.g. 12 – 24 months) and therefore a means of isolating these while the connection remains online would be required.

For the in-line probe types, this would require them to be mounted on duty/standby streams in the mainline gas flow, or alternatively the meters could potentially be located on a separate sampling bypass loop off the mainline however a means of “forcing” gas past the meters would be required by creating a small pressure drop on the mainline. As noted, to avoid any added pressure drop on the mainline, a discrete sampling cabinet is likely preferred which vents the gas.

Following a risk-based approach (per T/PM/GQ/8) to inform the necessary speed of response / action to the detection of “out-of-specification” water content, the network integrity risks and commercial risks need to be taken into consideration. Given the commercial risks held by NGT, NGT may elect to include independent monitoring and trips (which could be designed to meet a suitable reliability level, e.g. for a CIL1 trip).

However, the preference / default position is for entrants to hold responsibility for meeting inlet specifications and take action in the first instance to prevent off-specification fluid onto the network, especially since the

upstream connection pipe may contain a significant inventory of off-specification fluid which would need to be remedied to allow the system to be restarted.

The following approach is proposed to address the risk of off-specification fluid:

- **Client side:** In addition to the client side metering and gas analyser telemetry mirroring to NGT, consideration may also be given to providing an on/off signal as to whether gas is currently being exported into the network. (i.e. this is similar to the diverter valve discussed for hydrogen). This may align with the open/closed position of the export valve on the client side, or to the position of a diverter/recycle valve which prevents forward flow of off-specification material and instead routes this to a vent. This means, in the first instance NGT does not need to take any action if the client telemetry signal indicates they have already prevented further off-specification material from being exported.
- **NGT side:** On NGT side, consideration should be given as to whether commercial/safety risk is sufficient to require additional monitoring within NGTs connection scope, and what response is needed to client or NGT initiators (i.e. whether local ESD system is needed to close the ROV, or whether alarm and remote signals to close from the central control room are sufficient, including consideration of operator response time).
The volume / inventory of off-specification material which could occupy the pipe connecting to the network (which could lead to the necessity to accept a "slug" of off-specification material when the system is restarted again) may also be considered. In some cases it may be acceptable to allow the out-of-specification fluid into the network if it can be sufficiently diluted by other exporters, and displaced by on-specification gas once the problem is resolved, thereby reducing the amount of time the off-specification gas is present in pipelines on the network.

In general, it is expected that NGT will set appropriate alarms based on client and/or NGT monitoring with the ability to remotely close the ROVs by operator command, or potentially via a local ESD panel if a higher integrity level is justified. It was noted during the framing workshop that this issue may need further consideration, and for example in some cases NGT may require the customer to receive a trip signal from NGT to close ROVs as far upstream as possible, in order to minimise the inventory of off-specification fluid within the system.

6.5. NRVs

There is not thought to be any mandatory requirement for NRVs at carbon dioxide entry points. Current pipeline design codes BS-ISO-27913, DNV-RP-F104, and IGEN-TD-1 do not include any requirement for check valves, except for consideration as inventory segregation valves (in combination with block valves), along the pipeline route.

NRVs would provide protection in the event of a leak in the upstream system. It is challenged / proposed that this is not required, on the basis that:

- The customer site will naturally include NRVs at the compressor discharge / metering unit.
- The connecting pipe from the customer premises to the NGT connection is likely to be short piping (unless there is a major customer-operated pipeline).
- While an NRV could be included in the connection design, without suitable isolations to test, inspect and remove for maintenance it is unlikely that any significant claims could be made on the NRV preventing reverse flow.
- If the connection design must allow for NRVs with suitable test, inspection and isolation points, it is likely that duty/standby streams would be needed and the total connection costs would be significantly (200% or more) increased.

Also it may be possible to integrate any backflow prevention capability, if required, into the ROVs.

6.6. Overpressure Protection

Overpressure of pipelines and AGTs is discussed in Section 12.5 of IGEN/TD/1 and Section 8.5 of IGEN/TD/13. Typically, upstream compressors will have controllers to prevent overpressure (modulating compressor speed

and/or recycle valves) as well as other safety layers such as relief valves, high-pressure trips (which close actuated valves and/or shutoff compressor/pump motors), and slam-shut valves. In some cases, it may be possible to avoid such devices if the compressor (or pump) can be demonstrated such as to not pose an overpressure risk (i.e. maximum discharge pressure is less than the pipeline design pressure).

For carbon dioxide entrants, it would be expected that NGT will audit customer sites for suitable overpressure protection measures set at the correct setpoints to protect the pipeline network. This may require a combined HAZOP/LOPA/QRA assessment to ensure the appropriate SIL rating is assigned, taking into account the potential consequences for overpressure of the pipeline network. In addition, following on from discussion on NRV configuration above, it is not expected that NGT would provide NRVs to protect entrants from overpressure due to reverse flow, which per API-521 would typically require dual and diverse NRVs which are tested and inspected.

6.7. Filtration / Strainers

Filters or strainers can be used to prevent foreign object debris (welding slag, construction debris, corrosion products, pig tool parts, etc.) from entering the network, and also to protect sensitive equipment (e.g. valves, metering packages, etc.) from debris material which is naturally generated from within the pipeline network.

The provision of a commissioning strainer has historically been a best practice measure to prevent a range of potential issues during operational life of the pipeline system caused by initial construction debris. For example, debris could affect the operation and sealing effectiveness of valves, could damage internal coatings and other equipment, could hinder pigging, and potentially cause liabilities if debris is transported onwards.

Alternatives to the provision of commissioning strainers could be to put a duty on the supplier to demonstrate appropriate inspection and commissioning methodology / equipment to mitigate the risk of any construction debris entering the NTS. For short connecting lines, this could for example include boroscope inspection or running cleaning pigs with temporary equipment. Where the upstream supply is via pipeline connection, cleaning pigs may be run to the permanent pig traps.

On balance, the following approach is proposed for carbon service:

Commissioning Strainers

- A commissioning strainer may be waived in cases where the upstream connecting pipe is short, and can be demonstrated to be free from debris by other means and/or the risk of debris from the customer site during startup is deemed to be low.
- Elsewhere a strainer should be provided, however the cost impact of providing a strainer would be significantly reduced by:
 - Installing the strainer as the first piece of equipment downstream of the supplier-NGT interface.
 - Coordination would be required with the supplier to depressurise the connecting pipe section and remove the strainer. This would need to be scheduled with a planned outage within the first few years after startup (assuming there is no major differential pressure across the strainer which would necessitate earlier changeout).

Filters

- Filters are not expected to be necessary to protect from solid materials from the supplied gas as a matter of course throughout operational life. Per Section 7.5 of IGEM/TD/13, consideration shall be given to incorporating a filtration system if there is a credible risk of dust or liquid from upstream, and if adopted should not be more stringent than necessary to protect downstream equipment. It is proposed that this may be managed by the gas quality measurement process and audit/assurance of the supplier process.
- The NGT scope does not contain any sensitive equipment which would be critically damaged by solids. Carbon dioxide storage sites typically require a particulates level better than that agreed in the transportation agreement, and often make provision for suitable filters within their site accordingly.

6.8. Pressure-Reduction Stations

Not applicable to carbon dioxide network entry points. Where required at the network exit point(s), it is assumed these would be constructed and operated by the customer.

6.9. Odourant / Chemical Dosing / Analysers

No requirement for chemical injection at the network entry points has been identified.

With regards to analysers, the potential for in-line moisture analysers has been discussed above. No requirement for more extensive full compositional online sampling at all entry points is expected, although this could be considered at some locations (e.g. multi-junction AGIs) for assurance purposes, and based on any requirements identified from risk assessment to T/PM/GQ/8.

6.10. Drain / Purge / Vent Points

6.10.1. Drain Points

Pipeline drain points are not expected to be required as part of the carbon dioxide connection design, since the pipeline network will operate with a sufficient safety margin above the gas dewpoint that no free liquids will be present within the pipeline network which require draining. If drain points are required in some locations to facilitate hydrotesting, it is expected that these would be suitably capped off after use for the operational life. The valves may be removed and replaced with lock-o-ring connections.

6.10.2. Vent Points

_____ and equipment to allow for commissioning, purging, depressurisation (and pressurisation in some cases), as part of normal maintenance, repair and modification activities. These should be fitted with a suitable blind / plug in normal operation. In some cases, vent points may be combined with instrument valves to avoid unnecessary additional small bore connections to the main piping.

All valve body vent cavity drain/vent ports should be accessible, to allow purging/drying of these and provide assurance that water is not present (e.g. following hydrotesting, construction and maintenance activities).

6.10.3. Purge Points

Although carbon dioxide does not require indirect purging practices (since carbon dioxide is not flammable), pipeline displacement purging to IGEM/SR/22 is generally still expected to be followed when commissioning the system to remove air from the system. As such, purge riders are expected to be sized per the existing IGEM/SR/22 standard.

For most AGI pipework, there is no requirement for purge points to be specifically sized to accommodate purging practices (pressure or dilution purging methods can be used, which do not require specific flowrate be achieved). As such, dedicated purge points are not generally necessary and vent points discussed above will suffice.

6.10.4. Recompression Points

While the details of the future regulatory framework are to be developed, it is likely that routine venting of carbon dioxide will not be permitted and therefore recompression equipment should be used as a preference to venting, where possible, for most depressurisation operations (except where the inventory volume is small enough, that the use of recompression equipment is not practicable).

6.11. Pressurisation / Start-Up / Bypass Valves

Pressurisation or start-up valves are typically required to:

- Facilitate controlled purging and pressurisation stages during initial commissioning, and commissioning following maintenance/repairs/modifications.
- To avoid excessive piping forces, noise, and seal damage associated with opening large valves with significant pressures differences present.
- Bypasses may be operated to facilitate maintenance activities on the main line valves (partial/full stroke testing and works on valve actuators).

Similar to hydrogen, it is expected that permanent bypass / pressurisation and start-up valves will be provided for carbon dioxide entry points so that ROVs can be tested while entrants remain online, also noting:

- The design temperature and sizing of the bypass bridle should be confirmed as part of design activities, to mitigate the risk of breaching the pipeline minimum design temperature due to Joule-Thomson cooling.

6.12. Other

At MOP it is possible for carbon dioxide to condense into liquid at temperatures below circa 5°C. Therefore, it is possible that above-ground pipework which is shut-in (not flowing) and allowed to cooldown to ambient air temperature in UK winter conditions will experience some carbon dioxide liquid condensation. The presence of carbon dioxide liquid within pipelines and AGIs has the potential to cause a number of problems if not properly accounted for, such as a risk overpressure (if liquid is shut-in and allowed to heat up), low temperatures (fluid temperatures of circa -87°C if liquid carbon dioxide is depressurised to atmospheric pressure), and slugging in the pipeline (giving rise to mechanical loads the system was not designed for).

The quantity of condensed liquid is likely to be relatively small (limited by the heat transfer rate of the exposed pipework) and, upon restart, it is likely that this would be well mixed and vaporised with warmer fluids. Nevertheless, the connection design and operating procedures should take this into consideration and aim to mitigate the risk of liquid condensation as far as possible (i.e. minimise the extent of above-ground piping, in more extreme cases consideration may be given to fitting insulation for heat conservation to some pipework).

7. Carbon Conceptual Designs

7.1. Carbon Dioxide (Entry)

Figure 16 presents the base case connection design for a minimal entry point into the network, from a local customer site (i.e. not from a pipeline), where the downstream connection will either be directly into a pipeline (hot-tap or tee), or will be internal AGI pipework (e.g. to a pig trap and pipeline entry point). Independent moisture metering is shown with separate analyser cabinet.

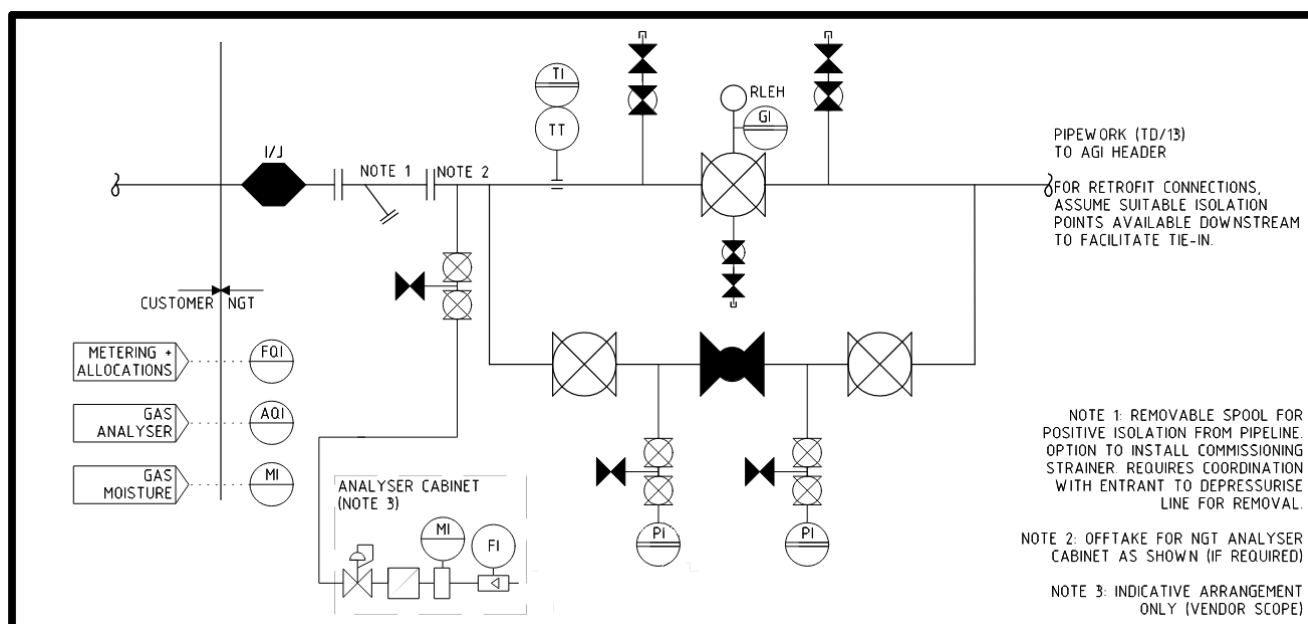


Figure 16: Carbon Dioxide Entry Connection (Base Case)

7.2. Modular Design

Similar to the hydrogen concept, the carbon dioxide design could be provided as a modular, skid-mounted unit installed above-ground. Where situated above-ground, it should be noted in cold winter conditions (e.g. below 0°C), if there is no flow of carbon dioxide through the connection (keeping the pipework warm) then it is possible that some liquid carbon dioxide will condense within the exposed pipework, and flow back into the pipeline (where it may re-vaporise). Whether this cycle causes any significant problems for the network would need further consideration, though a buried design (where fluid temperatures would largely be expected to remain above the dewpoint) would help prevent this.

8. Conclusions and Recommendations

The following conclusions and recommendations are made based upon this study:

[REDACTED]

1. [REDACTED]
[REDACTED]
[REDACTED]
2. [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

Hydrogen Connection

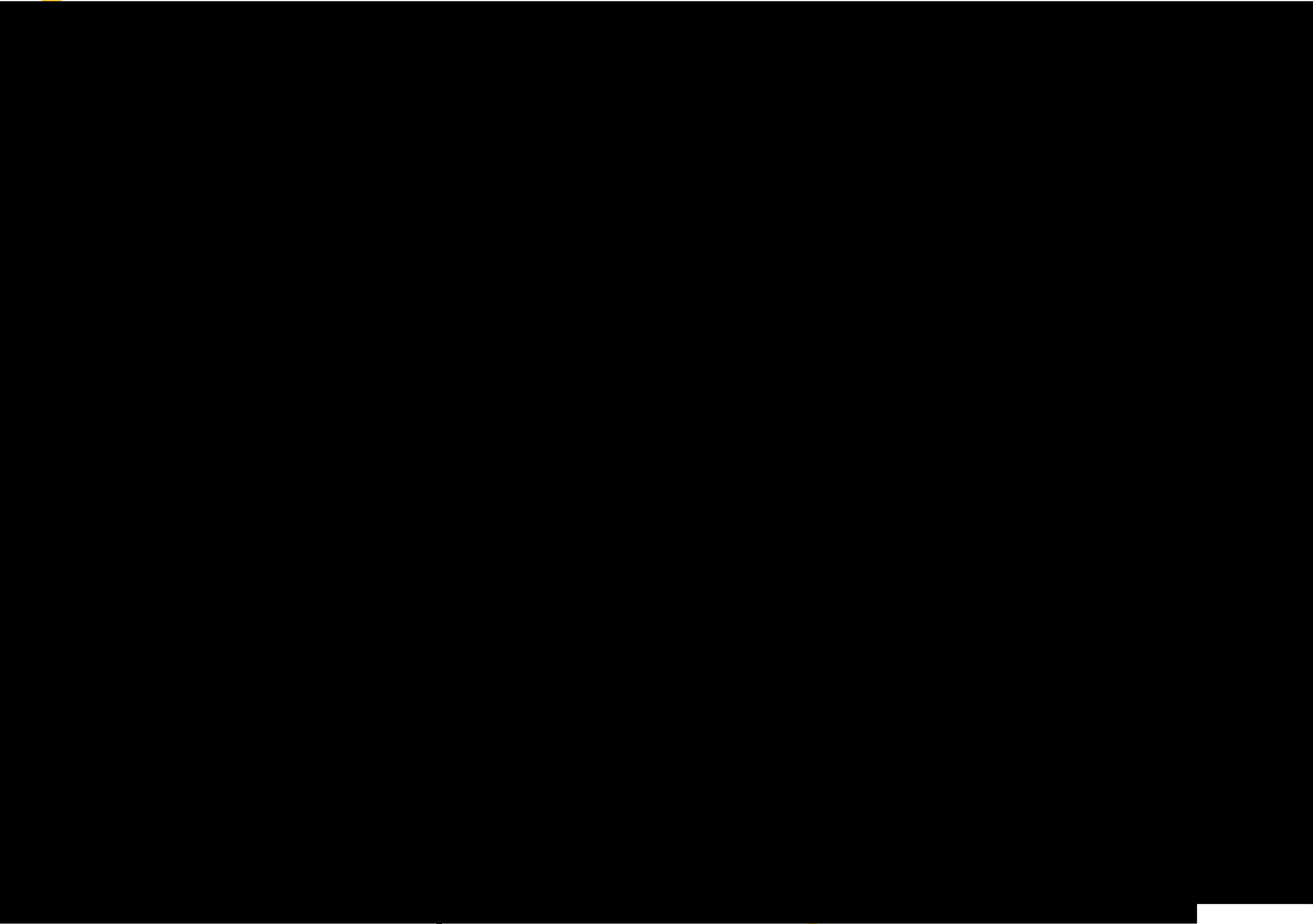
3. It is expected that double valve block and bleed (DVBB) should form the standard provable isolation arrangement for hydrogen, versus DIB isolation which is often used with natural gas.
4. A standardisable, modularisable connection arrangement has been proposed which is transportable and can be fabricated and tested at the factory before shipment to AGI sites. Building upon the development of non-ROV connection designs which have been recently adopted, the standardised valve configuration would be identical in both cases, with the fitment of manual or electro-hydraulic valve actuator to provide ROV functionality to be determined based on process safety / regulatory assessment for each site (and customer preferences).
5. It is noted that a standardised, modular configuration may not be optimal in all circumstances, and at single-customer sites with no future expansion potential there may be (minor) costs savings by only using the pipeline isolation / pig trap valves as the customer isolation points.
6. The impact on connection design for different types of offtaker / producer sites has been considered, and while these would have different supply/demand profiles than natural gas equivalents, it is proposed that connection designs can be standardised and would not need to be different for each type of site. However, the connection agreement with such sites may differ, and in particular the assurances and checks which NGT undertakes is likely to differ, to best represent the risks posed to the network.
7. For entry and combined entry/exit points, it is noted that there will be a disproportionate cost impact to providing non-return valves, filters, and other maintainable equipment and it is proposed that the risks posed by removing these can be mitigated or solved by other means, if necessary. This is likely to require review from safety / commercial perspectives.
8. Based on the above, it is proposed that a significant standardisation and modular design build is possible for hydrogen connections to the network, which can offer a number of advantages in terms of minimising site work durations, improving lead times for customers, and reducing design effort and costs.

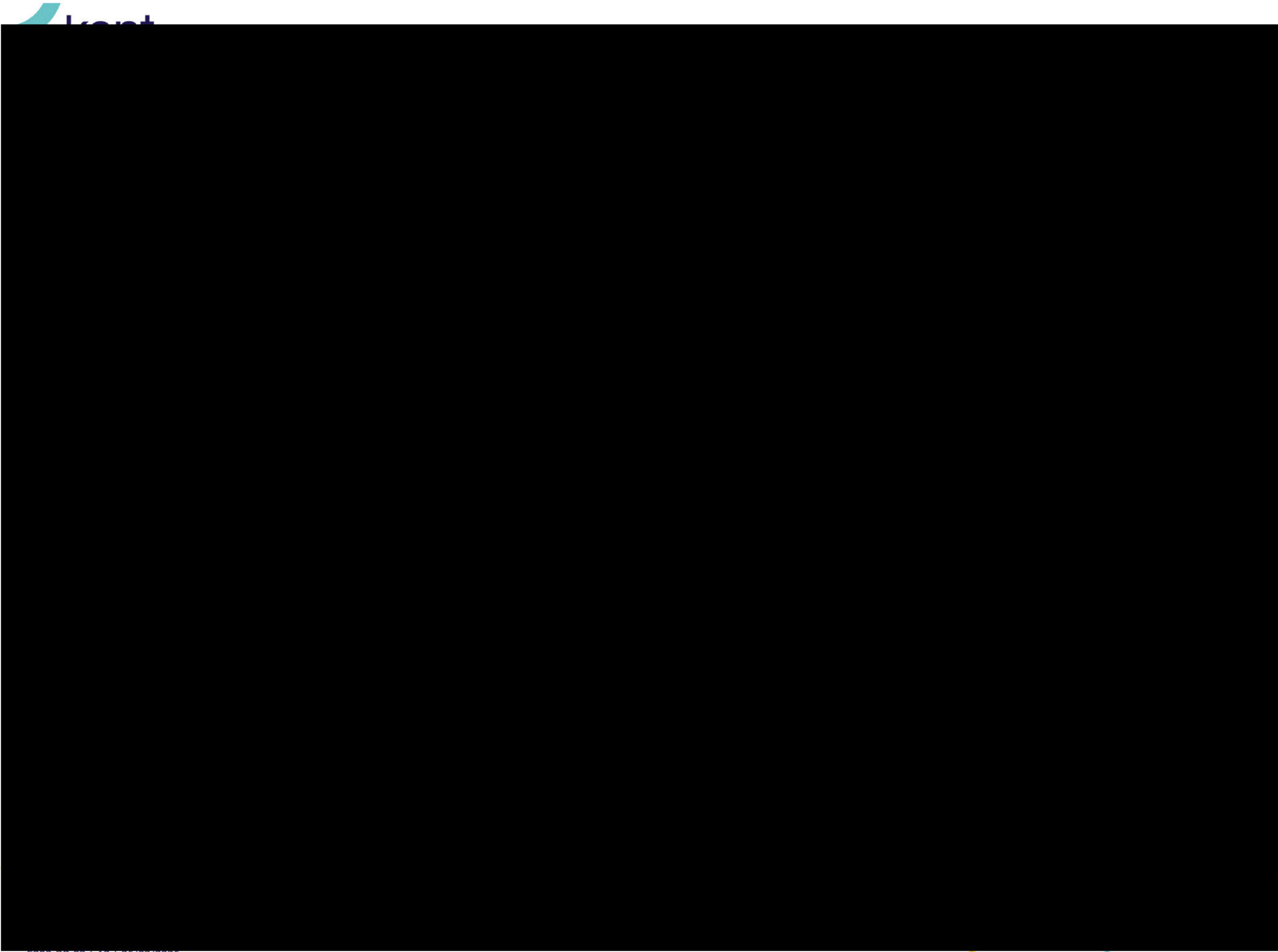
Carbon Dioxide

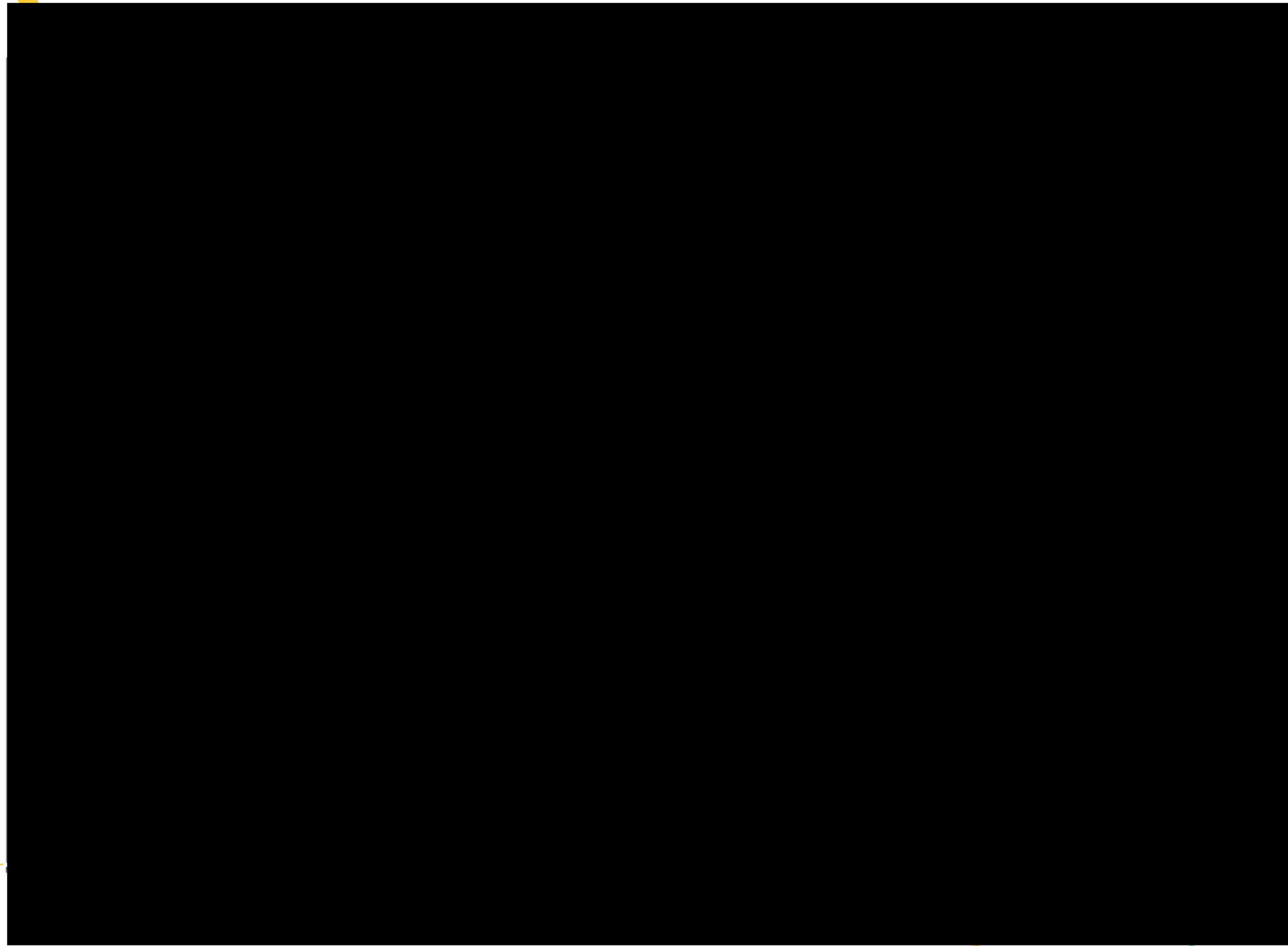
9. For carbon dioxide, a modular entry point connection design has been proposed, similar to that as for hydrogen. As shown, this has been presented with DIB isolation, similar to the existing network, though could incorporate DVBB isolation if required.
10. The differences in fluid properties for carbon dioxide have been considered, namely that carbon dioxide is an asphyxiant gas heavier than air, poses a significant risk of sweet corrosion if moisture content is not suitably controlled, with some risks associated with condensation of carbon dioxide in cold weather and Joule-Thomson cooling resulting in low fluid temperatures.

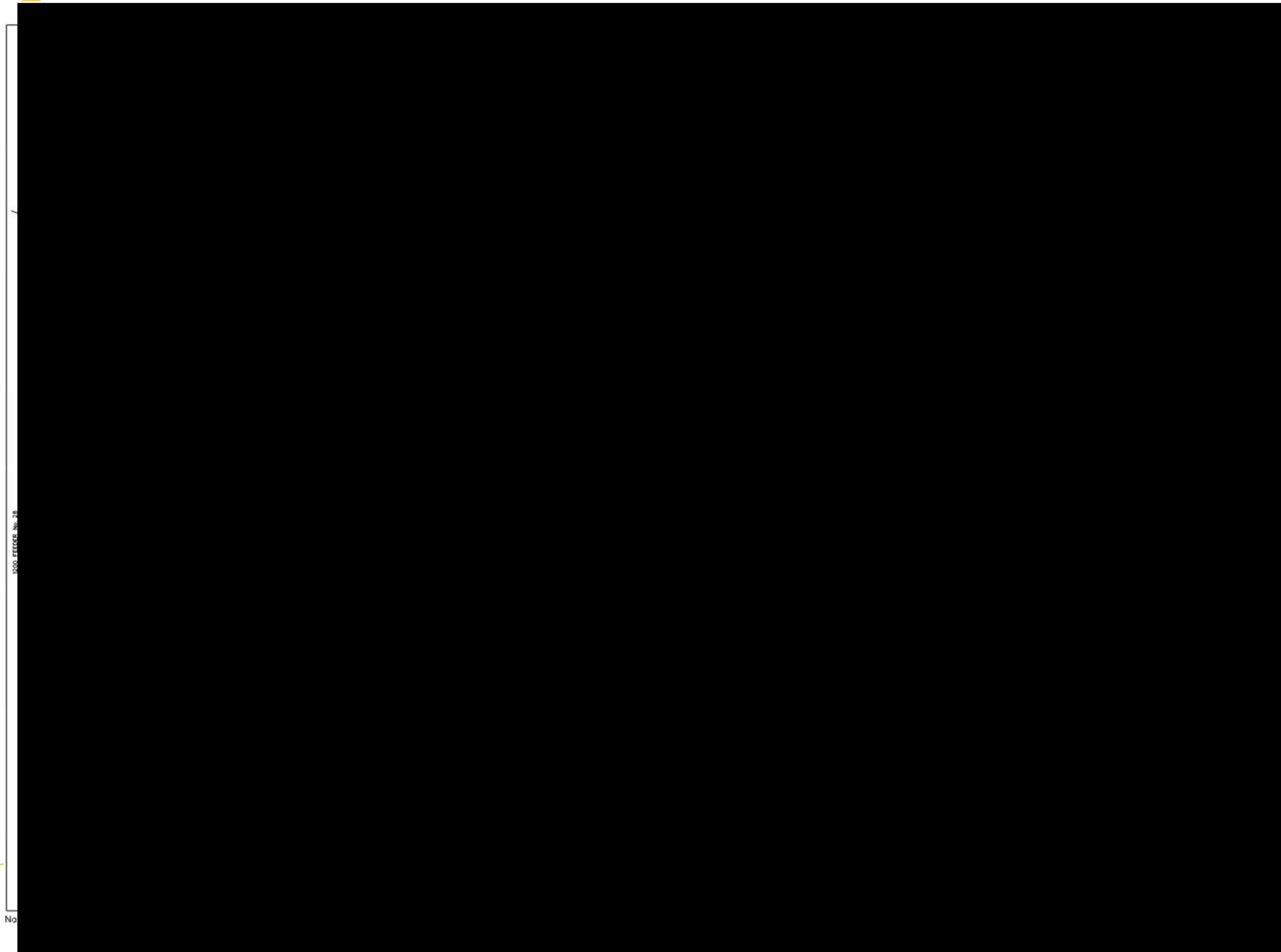
11. It is recommended that consideration be given to independent moisture analysers within the carbon dioxide entry points, following a risk-based approach (per T/PM/GQ/8) to the detection of “out-of-specification” water content. Given the commercial risks held by NGT, independent monitoring and trips could be designed to meet a suitable reliability level, e.g. a CIL rated trip.
12. If situated above-ground, exposed pipework in cold weather conditions is likely to lead to some carbon dioxide condensation and pooling within the pipework, for parts of the network which do not have flow (e.g. emitter temporary outage). This, and the design temperatures required to mitigate the risk of low fluid temperatures caused by startup pressurisation flows, should be considered as designs progress.

Appendices



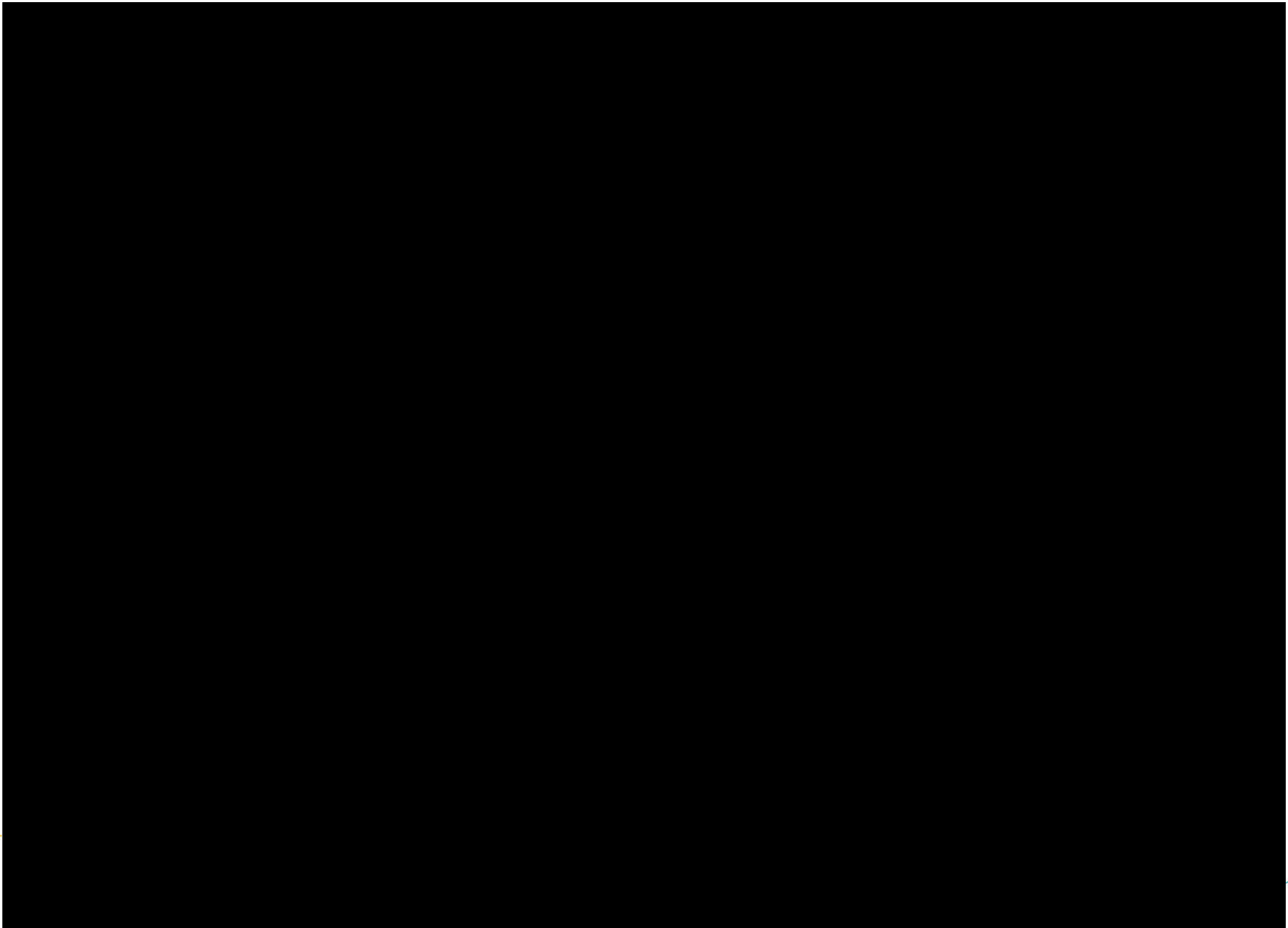


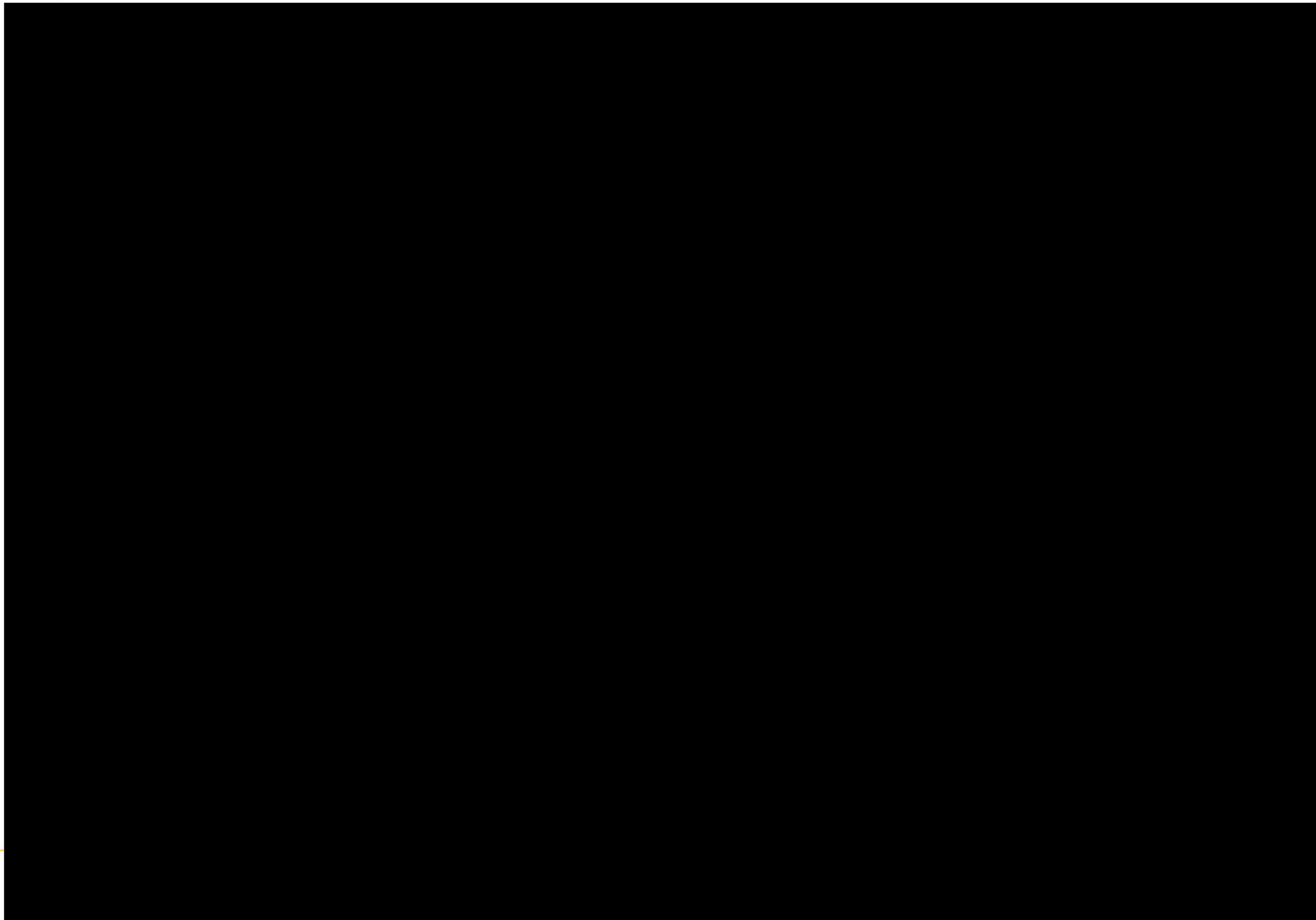


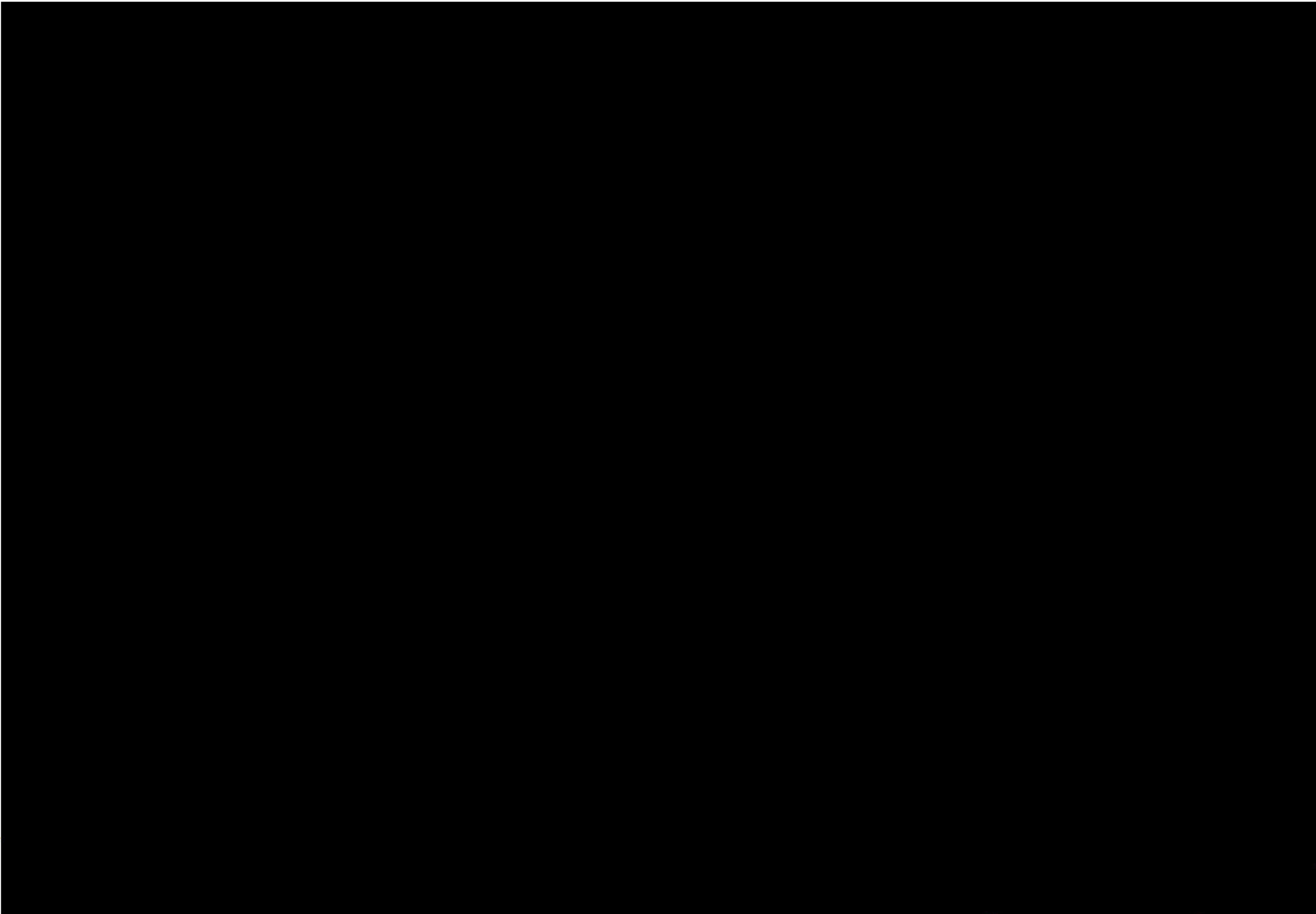


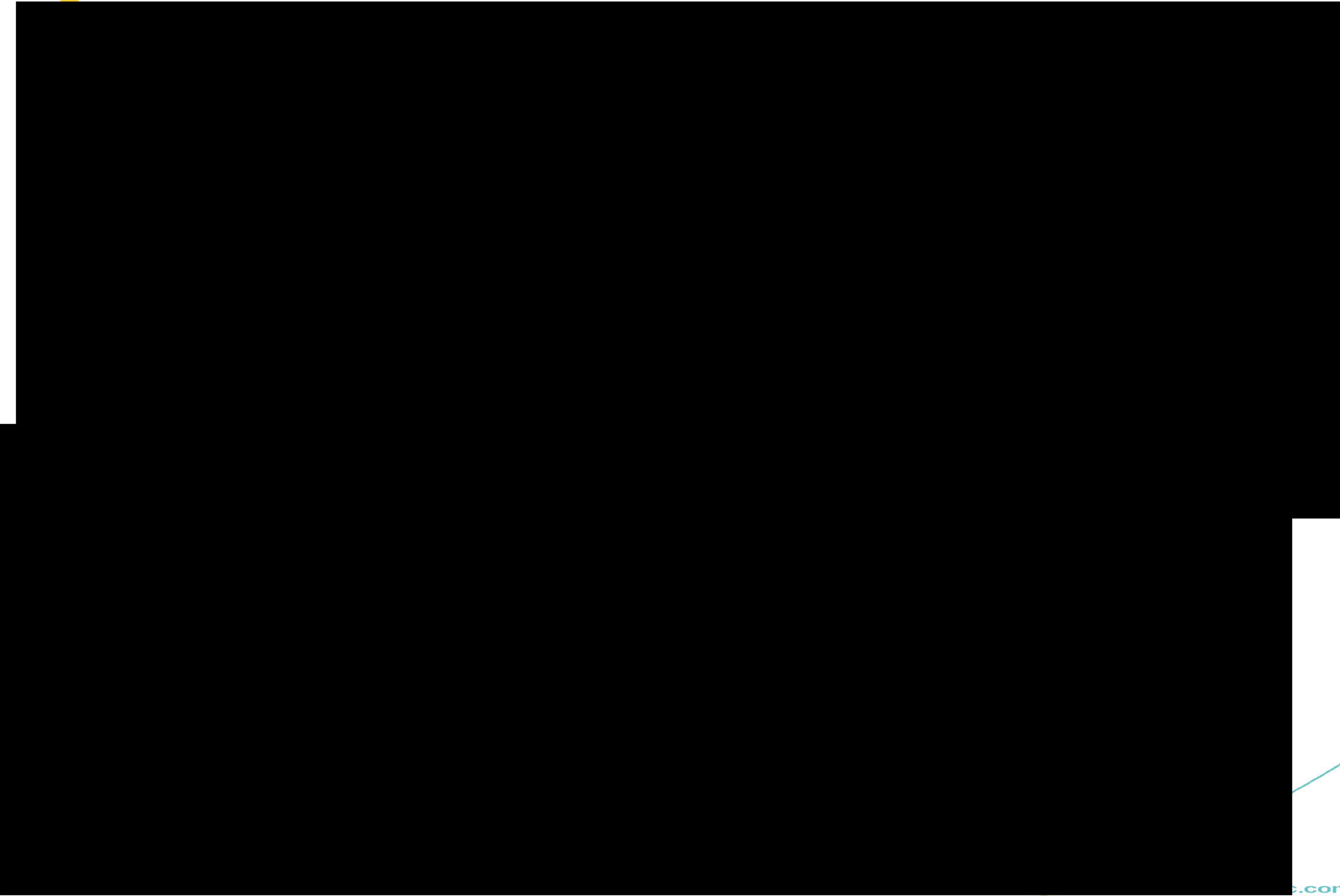
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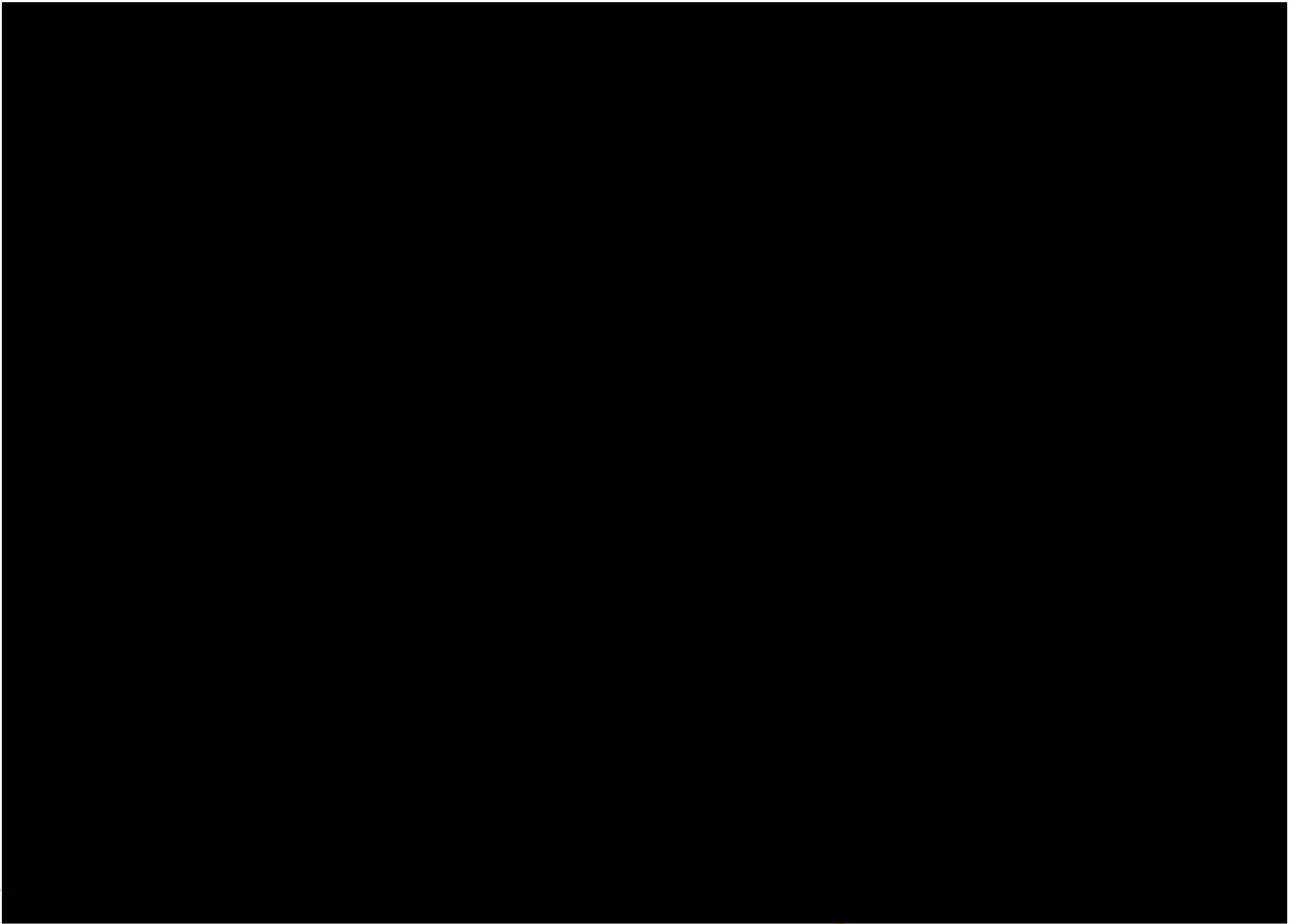
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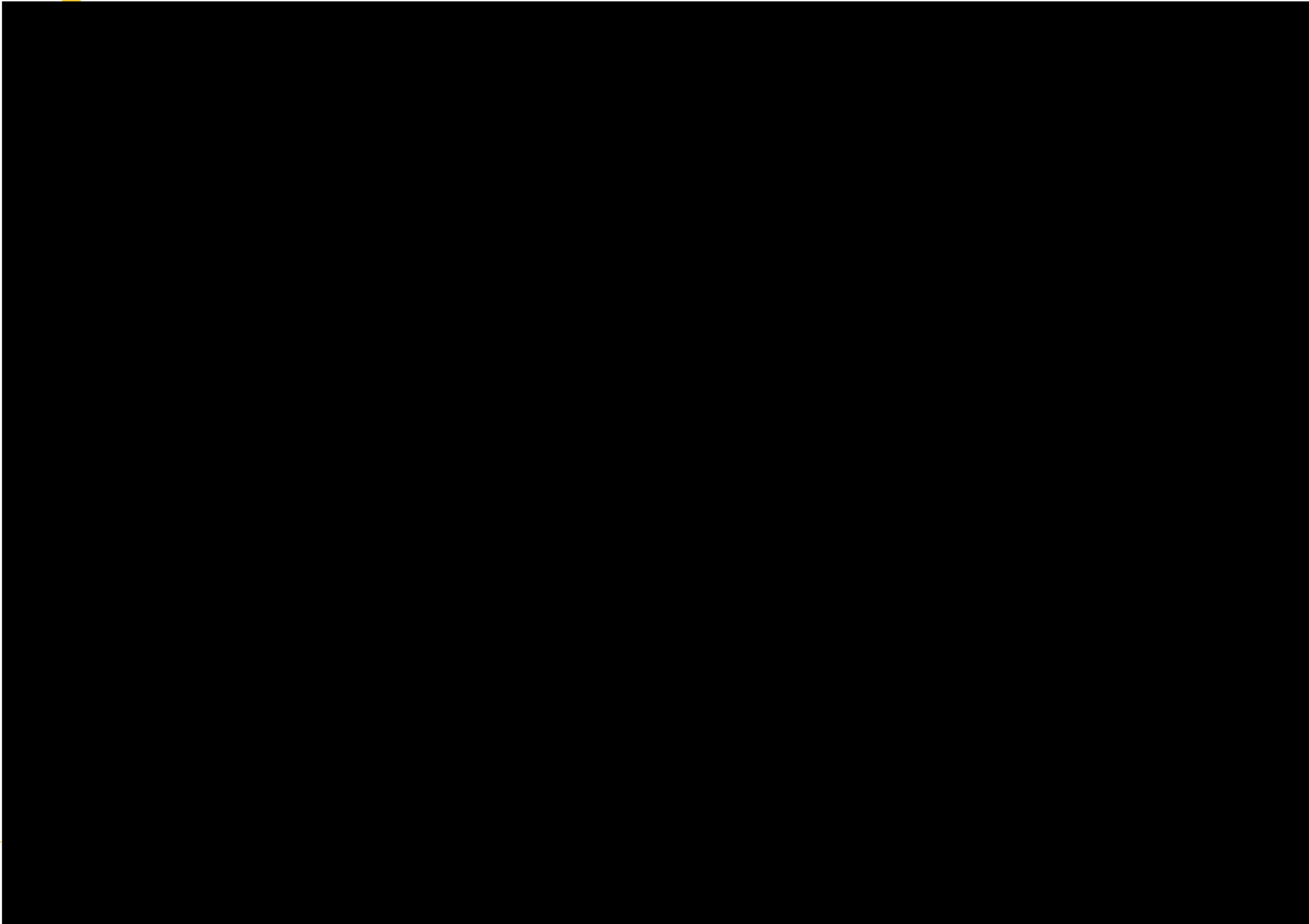












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Pipeline Installation Techniques for Net Zero

WP4 – Summary Report

National Gas

08/04/2026

5300-RP-04

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Figure 1 Strategic Pillars of NGT Supply Chain Development Strategy

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Abbreviations

3-D	Three Dimensional
AGI	Above Ground Installation
AI	Artificial Intelligence
API	American Petroleum Institute
CCUS	Carbon Capture, Utilisation and Storage
DAS	Distributed Acoustic Sensing
DIB	Double Isolation & Bleed
DVBB	Double Valve Block & Bleed
E&I	Electrical and Instrumentation
EPCM	Engineering, Procurement & Construction Management
ESG	Environmental, Social, Governance
EU	European Union
GIS	Geographic Information System
GPS	Global Positioning System
HDD	Horizontal Directional Drilling
HFI/HFW	High Frequency Induction Welded
ILI	Intelligent Line Inspection
LNG	Liquefied Natural Gas
LOSH	Limit Of System Handover
MASIP	Mobile Automated Spiral Intelligent Pipe
MPQT	Manufacturing Procedure Qualification Tests
NB	Nominal Bore
NDT	Non-Destructive Testing
NGT	National Gas Transmission
NTS	National Transmission System
OFGEM	Office of Gas and Electricity Markets
RFQ	Request For Quotation
ROV	Remotely Operated Valve
SAWH	Submerged Arc Welded (Helical)
SAWL	Submerged Arc Welded (Longitudinal)
SCI	Soluble Corrosion Inhibitor
SME	Small & Medium-sized Enterprises
TBM	Tunnel Boring Machine
TRL	Technology Readiness Level
UK	United Kingdom
VCI	Vapour Corrosion Inhibitor
VSM	Vertical Shaft Sinking Machine
WP	Work Package

Executive Summary

National Gas Transmission (NGT) is committed to supporting the government and the broader industry in achieving the Net Zero target by 2050. Carbon Capture, Utilisation and Storage (CCUS), alongside hydrogen, will play a critical role in reaching this goal. Since existing infrastructure was originally designed for methane, adapting it to transport these new gases presents significant engineering challenges. To address this, an extensive research program has been launched to assess the technical feasibility of repurposing sections of the National Transmission System (NTS) for hydrogen and carbon dioxide transportation.

While repurposing existing pipelines will be an essential part of the transition, it will not be sufficient – new infrastructure will be required to support a scalable hydrogen and carbon network. Given the ambitious deployment timelines, meeting these targets will require not only innovative technical solutions but also a holistic strategy that integrates the supply chain and fosters collaboration across the industry.

The construction of new hydrogen and carbon dioxide pipeline sections presents several challenges, including selecting the most effective construction methods and managing commissioning risks. Establishing a standardised process to connect future producers, emitters, and users is also a challenge. The lack of a formalised approach can lead to inefficiencies and potential delays. Through this project, NGT aimed to investigate new construction practices, identify technical requirements and compliance, and address commissioning challenges. The project also aimed to identify a conceptual connection design that will enhance efficiency, reduce costs, and support future network expansion.

The project was divided into a number of work packages to address different aspects of pipeline construction:

- Work Package 1 – Pipeline Construction and Commissioning Techniques for Net Zero
- Work Package 2 – Procurement and Supply Chain Management
- Work Package 3 – Connections Process for Net Zero NTS Customers
- Work Package 4 – Reporting

These work packages identified a number of challenges and opportunities related to pipeline construction that are encountered during different phases of engineering. Key areas are summarised in the Table below.

Table 1 Key Challenges and Opportunities Identified in Different Work Packages

Project Phase	Activity	WP	Main Findings / Recommendations
Design	Pipeline Routing	1A	Use of software tools to optimise route to minimise cost or risk.
	Pipeline Design	2	Investigate potential use of SAWH or HFI materials to broaden supply chain (for large diameter trunklines).
		1A	Investigate potential use of composite pipe for short, small diameter spur lines.
	Connections Design	3	Use of standardised modular connection designs to improve cost and schedule.
	Risk Mitigation	1A	Use of fibre optic cables to provide continuous monitoring capability.
	Data Management	2	Develop plans for data management to ensure systems and supply chain tools are in place.
Fabrication		1A	Update NGT material specifications for pipe, valves etc.

	Supply of long lead items	2	██████████ improve ██████████ such as pipe, valves and compressors. ██████████ where needed.
Construction	Pipeline Construction	1A	Use of advanced multi-torch pipeline welding systems and automated NDT to improve quality and construction efficiency.
		1A	Use of different trenchless installation techniques, depending on terrain / soil conditions.
		2	Develop contracting strategy and maintain pro-active dialog with contractors. Cascade ESG principles into contracts.
	AGI Construction	1A	Use of 3D printed concrete foundations.
		3	Use of factory-built modules or containerised systems to reduce on-site labour and re-work.
Commissioning	Cleaning, drying	1B	Where repurposing a pipeline, ensure that all required pigging operations are carried out while in natural gas service, if possible.
		1B	Recognise the need for more stringent dewpoint specification for CO2 pipelines and engage with vendors to ensure availability of suitable dried air or vacuum pump drying systems.
	Purging, start-up	1B	For hydrogen, indirect purging with nitrogen is required and mobile flares will be needed due to the risks posed by delayed ignition.
		1B	Update NGT procedures where needed to account for different gas properties, e.g. purge velocities.

1. Introduction

1.1. Project Background

National Gas Transmission (NGT) is committed to supporting the government and the broader industry in achieving the Net Zero target by 2050. Carbon Capture, Utilisation and Storage (CCUS), alongside hydrogen, will play a critical role in reaching this goal. Since existing infrastructure was originally designed for methane, adapting it to transport these new gases presents significant engineering challenges. To address this, an extensive research program has been launched to assess the technical feasibility of repurposing sections of the National Transmission System (NTS) for hydrogen and carbon dioxide transportation.

While repurposing existing pipelines will be an essential part of the transition, it will not be sufficient – new infrastructure will be required to support a scalable hydrogen and carbon network. Given the ambitious deployment timelines, meeting these targets will require not only innovative technical solutions but also a holistic strategy that integrates the supply chain and fosters collaboration across the industry.

The construction of new hydrogen and carbon dioxide pipeline sections presents several challenges, including selecting the most effective construction methods and managing commissioning risks. Establishing a standardised process to connect future producers, emitters, and users is also a challenge. The lack of a formalised approach can lead to inefficiencies and potential delays. Through this project, NGT aims to investigate new construction practices, identify technical requirements and compliance, and address commissioning challenges. The project also aims to identify a conceptual connection design that will enhance efficiency, reduce costs, and support future network expansion.

1.2. Document Purpose and Scope

The project is divided into four work packages as follows:

- Work Package 1 – Pipeline Construction and Commissioning Techniques for Net Zero
- Work Package 2 – Procurement and Supply Chain Management
- Work Package 3 – Connections Process for Net Zero NTS Customers
- Work Package 4 – Reporting

Deliverables within each Work Package were as follows:

- Technical Report 1A – Pipeline Construction Technologies [1]
- Technical Report 1B – Pipeline Commissioning and Decommissioning [2]
- Technical Report 2 – Procurement and Supply Chain Management [3]
- Technical Report 3 – Connections Process for Net Zero NTS Customers [4]

This document is Technical Report 4 and aims to provide a technical summary of the work carried out in each Work Package along with the main conclusions and recommendations.

Sections 2-5 of this report provide summaries for each of the four technical reports listed above. Section 6 then provides an overall summary.

2. Pipeline Construction Technologies

Work Package 1 included a number of market reviews of technologies associated with pipeline construction and recommendations for potential improvements to current practices. Technical Report 1A [1] presented a detailed assessment of different technology areas associated with pipeline construction. Full details of this work and supporting references are given in the report. The sections below present a high level summary of the main findings.

2.1. Overview of Current State of The Art

As National Gas develops plans for major construction projects such as Project Union and SCO2T Connect, there are opportunities to take advantage of new technologies to deliver improvements in efficiency, safety or environmental impact. Major pipeline construction projects involve many stakeholders and a number of engineering disciplines. Kent has carried out a series of state-of-the-art technology reviews focussing on the following areas:

- Novel methods for optimisation of pipeline routing
- Trenching and trenchless methods for pipeline installation
- Automation of welding and non-destructive examination of welds
- Alternative fabrication methods, materials and coatings
- Modular construction methods
- Novel methods for pipeline risk mitigation

The reviews present a description of what is considered state-of-the-art. In this instance, deployment on projects would not require technology development. However, the technologies may need to be discussed with service providers and described in relevant contracts to ensure adoption. Recent advances that are considered to offer the potential for significant impact include the following:

(The type of benefit / impact is characterised as cost, safety/integrity, environmental or operational as applicable)

- Use of software tools for optimisation of pipeline routing during project engineering. These tools automate the route corridor optimisation process using GIS datasets and specially designed weighted scoring algorithms to determine the “optimum” route, subject to multiple constraints such as cost, safety or environmental impact. Tools can be tailored to incorporate a variety of different datasets such as existing infrastructure (pipelines, roads, railways, power lines etc.), terrain information, social and population data, hydrology and flood risk areas, and ecological or special cultural heritage sites.

Cost

Environment

There are a number of tools with similar functionality such as [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED] ducts are in-house tools while others are commercially available software products.

[REDACTED]
[REDACTED]

- Appropriate use of different trenchless installation techniques, including recent developments such as Direct Pipe® and Pipe Express®, depending on terrain, soil conditions and other requirements.

Safety / Integrity

Environment

Although no major step-change innovations have emerged in recent years, incremental advances in equipment design, guidance systems, and digital control have substantially

improved reliability, achievable drive length and installation accuracy. Modern systems can now accommodate a broader range of soil types and geotechnical conditions than was previously possible. The use of biodegradable drill fluids and electric rigs can also help achieve Net Zero compliance.

The selection of an appropriate method should follow a structured option appraisal, considering the technical feasibility, cost, environmental impact, and socio-economic factors of each viable alternative. A detailed assessment of site constraints, ground conditions, groundwater regime, and environmental sensitivities must be undertaken to determine the most suitable technique for each crossing.

A summary of the advantages and limitations of each technique is provided in Table 2 Comparison of Trenchless Pipeline Installation Techniques below.

Table 2 Comparison of Trenchless Pipeline Installation Techniques

Method	Advantages	Limitations	Max. Length / Diameter (m)	Relative Cost
Horizontal Directional Drilling (HDD)	Long crossings (>1,500 m), minimal surface impact; widely available contractors	Geology dependent; requires laydown area	1,500–2,000 / 1.5	Moderate
HDD (intersect)	Extends crossing length (>3,000 m possible); reduced pullback forces; shorter programme	Risk of frac-out; geology dependent; requires laydown areas; requires two rigs/shafts; precise bore alignment required	2,000–4,000+ / 1.5	Moderate–High
Microtunnelling	Accurate, urban-suitable; minimal settlement risk	High mobilisation cost; shafts required	<2,000 / 3+	High
Pipe Jacking	Low cost for short drives; minimal surface disruption	Limited length; dewatering often needed	<500 / 3	Moderate–High
Auger Boring	Low cost for short drives; minimal surface disruption	Non-steerable; Limited length	<100 / 1.2	Low
Pipe Ramming	Low cost, simple, robust in many soils	Non-steerable; vibration; obstruction risk; suitable as a sleeve/casing	<80 / 1.5	Low
Direct Pipe®	Bore stability; continuous install; handles groundwater	High cost	1,000–1,500 / 1.4	High
Pipe Express®	Narrow corridor, continuous laying, lower spoil volumes	Limited cover depth (~2.5 m); soil-dependent	1,000–2,000 m / 1.5	Moderate
Tunnel Boring Machine (TBM)	Very long crossings (>5 km); multi-utility potential	Very high cost, long programme duration	2,000–>5,000 / Unlimited	Very High
Vertical Shaft Sinking Machine (VSM)	Safe, mechanised shaft construction under groundwater	Specialist, high cost	Depth up to 250 / 4.5 - 18	High

- Use of advanced automated internal and external multi-torch welding systems and line-up clamps. When used together with laser pipe end measurement systems and other digitalisation tools, these systems improve both production efficiency and weld quality. Pipe welding and subsequent inspection and coating can account for a significant fraction of total pipeline construction costs. This includes both materials/consumables for the welding operations as well as associated labour. A reduction in the time taken to complete each girth weld has a significant impact on the associated cost, so welding contractors have developed narrow gap welding processes that improve efficiency.

Automated methods for non-destructive testing have also been developed to enable similar efficiencies, rather than relying on manual methods that are typically employed in smaller construction or fabrication projects. Automated ultrasonic inspection systems often incorporate a range of different sensor types to allow detection of critical defects in different areas of the weld and in different orientations. The use of these systems is usually accompanied by a project specific qualification or validation activity to demonstrate adequate detection and sizing capability. [REDACTED]

Cost

Safety / Integrity

- Factory-built modules, containerised systems, and 3-D-printed concrete foundations for AGI infrastructure elements to reduce on-site labour and re-work. Modular construction and off-site fabrication are increasingly adopted in UK energy and utility infrastructure. For pipeline and Above Ground Installation (AGI) projects, modularisation provides an opportunity to reduce on-site construction duration, improve quality control, and lower safety risks. These methods align with NGT's Net Zero strategy by enabling low-carbon, high-efficiency delivery and facilitating repeatable, standardised designs.

Recent progress in modular pipeline delivery has focused on integrating prefabricated structural, mechanical, and electrical assemblies to reduce site labour, improve quality assurance, and shorten construction schedules. Across the UK and European gas sectors, a range of modularisation strategies are being implemented, from factory-built skids and containerised systems to precast and 3-D-printed civil components.

Skid-based AGI pipework modules allow repetitive assemblies of various components to be fully fabricated and pre-tested off-site. This reduces on-site welding, non-destructive testing, and permit durations. Containerised E&I (Electrical and Instrumentation) systems are now common within AGIs and compressor stations, providing plug-and-play functionality and simplified commissioning.

At the civil and structural interface, precast trench and cover modules offer repeatable protection systems that minimise excavation, spoil disposal, and reinstatement effort. 3-D-printed reinforced concrete elements, such as foundations, valve plinths, and AGI bases, are emerging as sustainable alternatives to traditional formwork, achieving significant material and carbon savings. The convergence of these technologies supports a scalable, standardised approach to pipeline infrastructure delivery, enhancing safety, constructability, and long-term maintainability.

- Fibre-optic cables installed along the pipeline length to provide continuous monitoring capability for leak detection, third party interference and ground movement at high risk locations. For new-build pipelines, the construction phase provides an opportunity to embed smart monitoring systems from the outset. Fibre-optic sensing cables installed alongside the pipeline can continuously detect vibration, temperature, gas leakage or strain changes that signal interference or movement.

Safety / Integrity

Demonstrated applications of this technology include [REDACTED] detection, European long-distance monitoring on the 55 km Berlin brine pipeline, and large-scale DAS deployment along the TANAP gas transmission corridor into Europe. Geotechnical sensors placed in backfill or at critical slopes can track settlement or groundwater variation, while smart coatings and remote cathodic-protection sensors improve corrosion control. Including spare ducts or conduits for future sensors and communications ensures the asset remains upgradeable. Installing these systems during construction minimises future retrofit work and establishes a digital-ready pipeline from commissioning.

- Alternative materials for pipeline fabrication. Gas transmission infrastructure is predominantly manufactured from carbon steel pipe and fittings. For large diameter pipe this is usually Longitudinal Submerged Arc Welded (SAWL) although Helical Submerged Arc Welded (SAWH) material is also available and High Frequency Induction Welded (HFI or HFW) pipes are available for diameters up to approximately 26 inch.

Cost

[REDACTED]
[REDACTED]
[REDACTED] as the use of SAWH pipe would significantly widen the potential supply chain, it is recommended that discussions are held with potential vendors to discuss the capabilities of modern mills (which may be better than historical norms) and define qualification requirements. These could involve material testing to demonstrate adequate fracture toughness properties in high pressure hydrogen, and provision of historical fabrication statistics for critical geometry parameters such as pipe ovality.

Reinforced thermoplastic pipe may also be suitable for small diameter spurs / tie-ins. These products are available on reeled spools for pipe diameters up to 7.5 inch. For these applications, the technology provides a means of significantly reducing installation costs, as reels of 1-4 km can be procured, with no need for welding or associated NDT. Reduced susceptibility to corrosion would also provide an operational benefit.

2.2. Updates to Standards or Specifications

During the course of this work, it has become apparent that a number of NGT standards or specifications would need to be updated prior to use of some of the technologies discussed in the dedicated report. Details of these instances are collated here for reference:

- [REDACTED]
[REDACTED]
- [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
- [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
- [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

2.3. Areas for Technology Development

Where technologies are yet to have reached the level of maturity to be widely implemented in projects, an indication of Technology Readiness Level is provided.

However, in some cases, the necessary technology development is considered more feasible. Examples of the latter instance include:

- Autonomous excavation and lowering systems (where terrain and soil type is appropriate). Recent innovations in machine control and automation include GPS-guided excavators and trenchers with automatic grade control and digital data capture for excavation precision and construction quality. AI-driven systems are reported to improve fuel efficiency and reduce emissions by up to ~30% in specific industrial applications, and similar gains may be achievable for trench excavation operations.

Safety / Integrity

Environment

Benefits of automation include improved efficiency, reduced operator fatigue, reduced environmental footprint, and more accurate as-built documentation. Emerging technologies promise future AI-driven autonomous trenching, robotic pipe lowering, and integrated digital twin monitoring enabling high productivity and low-carbon construction.

- Battery electric or hydrogen powered trenching equipment (current practice is mainly diesel with some hybrid plant)
- More radical alternative materials for pipeline fabrication such as MASiP pipe as an alternative to conventional carbon steel linepipe. This consists of a polymer liner and a spirally wound overlapping high strength steel strip with a patented interlock. Environmental coatings are then wound over the steel reinforcement to provide corrosion and mechanical protection. The end product is similar to other steel reinforced composite pipes, but the system is designed to be manufactured on site, rather than being delivered on reels. This would potentially make it feasible to construct larger diameter pipelines where reels would become impractical.

Environment

Cost

At present the technology has only been demonstrated for small/medium pipeline diameters that would only be applicable for NGT spurs or tie-ins. However, the main potential benefit of significantly reduced cost would only be realised on longer pipelines, which for transmission infrastructure is likely to be of larger diameter. A significant technology development and demonstration programme would therefore be needed in this instance.

3. Pipeline Commissioning and Decommissioning

Work Package 1 included a study to develop a high-level procedure for decommissioning legacy natural gas assets and commissioning repurposed or new assets for hydrogen or carbon dioxide service. Technical Report 1B [2] presented a detailed assessment of critical aspects of this procedure. Full details of this work and supporting references are given in the report. The sections below present a high-level summary of the main findings.

3.1. Overview

In this part of the work, Kent has developed a high-level procedure and summary of the expected activities necessary to decommission an existing pipeline currently in natural gas service, and suitably prepare it for repurposing to either hydrogen or carbon dioxide service. Such a procedure is required since existing practices are typically focussed on decommissioning for short term repairs/maintenance, mothballing, or abandonment and not for a change of service. The procedure also outlines relevant considerations for testing and commissioning both new-build and repurposed pipelines for hydrogen or carbon dioxide service.

3.2. Decommissioning

Many of the activities and considerations during the decommissioning phase are similar for hydrogen and carbon dioxide. Before the existing natural gas system is taken out of service, it will be important to undertake surveys and condition assessments to gather the data necessary to underpin the re-qualification process and determine the nature and extent of repair and modification works required. All necessary pig runs (for inspection and cleaning) should also be completed at this stage, if possible, while there is a ready source of motive fluid. Some of the techniques, emerging technologies, and challenges with conducting integrity assessments are presented as well as a suggested methodology/approach to the issue of contaminants and requirement to clean the pipeline.

Once the pipeline is taken out of service and disconnected from adjacent natural gas infrastructure, the necessary intrusive works to repair, modify / divert, replace equipment, and enact tie-ins can commence. A summary of the expected activities and considerations for the timing and phasing of tasks is presented. Getting the right systemisation boundaries and sequencing of tasks will be important to avoid unnecessary extra stages and temporary equipment. The requirement to put in place preservation measures to prevent degradation of the pipeline internals/externals during the shutdown period is also discussed.

3.3. Testing and Commissioning

The expectations for hydrostatic/pneumatic strength testing, pre-testing of pups/assemblies, and leak (tightness) testing for repurposed assets are set out. Strength testing repurposed pipelines will not be a mandatory requirement but may be deemed necessary as part of the requalification process, particularly for hydrogen pipelines, where a high level hydrotest could help in demonstrating adequate integrity of welds. If necessary, strength testing will generally be in accordance with current natural gas practices though for repurposed pipelines the selection of appropriate test envelopes will need careful consideration to take into account road/rail crossings, and modifications to the network since the original hydrotesting was completed.

A review of drying technologies is presented, where the threat of sweet corrosion of carbon dioxide pipelines may require both a more stringent dewpoint specification and procedural steps to give a high confidence there is no free water present in deadlegs, valve cavities, and similar hard-to-reach areas. Compressed, dried air and vacuum pump drying techniques will be most suitable, each with particular advantages and disadvantages. The equipment is readily available on the marketplace for these technologies however it is recommended that NGT engage with the UK supply chain to ensure suitable contractors / hire equipment vendors have appropriate packaged units available.

Aspects related to the safe introduction of fluids to the system during purging, startup, pressurisation, and the need to dispose of gas via venting / flaring are summarised. Much of the supporting engineering, modelling, and

laboratory testing of these aspects for hydrogen have been covered by other studies and are summarised at a high level. For carbon dioxide, there were some gaps in knowledge around phase change / Joule Thomson cooling and purge velocities which were raised and these have been resolved by calculations presented in the report.

3.4. Conclusions and Recommendations

The key conclusions and recommendations made in the pipeline decommissioning and commissioning report are summarised below:

1. Efforts should be made to run all required pigging operations (i.e. cleaning, swabbing and ILI tools) while the pipeline remains in natural gas service. Inspecting for girth weld defects may be required to support hydrogen or carbon dioxide re-qualification assessments [REDACTED]
[REDACTED]
[REDACTED]
2. A pre-cleaning assessment should be undertaken, to determine the current condition of the pipeline and highlight any testing or inspections necessary to inform the development of a cleaning plan for the decommissioning works. The subsequent development of a cleaning plan should take into account the product specifications, contaminant behaviour and interactions, and practicability/safety aspects (i.e. can all pig runs be done in while in natural gas service, or will these need to be done after shutdown).
3. A base line cleanliness level equivalent to that needed to run an ILI tool (i.e. removal of all bulk debris from the pipeline, deposits removed to as close to metal surface as possible, removal of all ferrous debris) is proposed as a readily achievable objective for repurposing. This may need to be combined with more aggressive mechanical cleaning tools or a chemical cleaning programme if necessary, which may need to be done after shutdown (done immediately after shutdown, while system remains mechanically complete). It is understood that there is an ongoing study to investigate NTS contaminant types, behaviour, interactions, and removal techniques which should help to inform the cleaning requirements.
4. Isolation, depressurisation, and purging for decommissioning are expected to be in line with current practices.
5. A preservation plan should be developed to manage external / internal corrosion and set out the necessary preservation measures and monitoring regime during the mothball period. This should take into consideration the phasing and duration of works as well as the commissioning date. Establishing a positive pressure nitrogen blanket (and dewpoint specification) may be considered on a section-by-section basis, before or after intrusive repair/modification works are undertaken. The use of corrosion inhibitors (SCIs/VCIIs) could also be considered if the risk of product contamination is acceptable.
6. [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
7. Early consideration of systemisation and LOSH boundaries, and the sequencing of works and testing / commissioning stages, will be important to avoiding unnecessary additional stages and optimising the location / usage of temporary equipment packages resources such as pigging facilities, drying / purging equipment, and so on.
8. Hydrostatic strength testing will typically not be necessary for repurposed pipelines (though there may be a benefit in some cases for hydrogen pipelines), however all replacement pipe sections should be pre-tested and golden weld tie-in procedures implemented. New pipe runs and assemblies should similarly be strength tested separately prior to tie-in. Hydrotesting for new-build pipeline sections should be in line with current practices for natural gas pipelines.

9. The dryness specification for carbon dioxide is expected to be more stringent compared to natural gas and hydrogen [REDACTED] and is also likely to require additional procedures to prove that low points, branch lines, small bore piping and valve cavities have been adequately dried. Both dried air and vacuum drying techniques are capable of achieving this specification, and both may be appropriate but come with their own strengths and weaknesses. While the necessary equipment is readily available on the market place, and specialist contractors have demonstrated case studies of meeting this specification, it is recommended that NGT engage with the supply chain to ensure local contractor/ hire equipment vendors have appropriate packaged units available. Drying procedures for carbon dioxide systems should consider the requirement to prove dryness at all vent/drain points and valve cavities.
10. The purging and venting / flaring requirements for hydrogen have been studied by numerous other works. The theory, modelling, and testing of hydrogen purging (which requires indirect purging with nitrogen) is largely settled, pending larger scale testing, while testing work suggests that mobile flares will be required for commissioning and contingency depressurisation scenarios due to the risks posed by delayed ignition.
11. For carbon dioxide, issues with introducing the fluid during commissioning has been considered. Since the NGT pipelines will operate in the gaseous phase [REDACTED] liquid/solid phase dropout and low temperatures issues are less severe compared to systems operating with dense phase fluid. Nevertheless, a small fraction of liquid [REDACTED] [REDACTED] can occur when depressurising from [REDACTED] and these risks should be captured within the commissioning procedures.
12. The minimum purge velocity for carbon dioxide has been calculated in line with works for hydrogen, [REDACTED] [REDACTED] While less critical for carbon dioxide since it is not flammable, ensuring this purge velocity is maintained will help ensure air/nitrogen is evacuated efficiently and will minimise the quantity of carbon dioxide which needs to be vented.
13. With respect to current NGT standards, the [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED] Other specific points for consideration have been outlined within the report. It is also recommended that standards or guidance documents be created to cover pre-cleaning assessment, preservation assessment, and drying procedures.

A summary of the key differences for hydrogen and carbon dioxide pipelines is also given in the table below.

Table 3 Key Differences for Hydrogen / Carbon Dioxide Commissioning

Hydrogen	Carbon dioxide
- ILI (girth weld defects) - Cleaning repurposed lines (gas quality specification) - Re-Strength testing of repurposed pipelines - Indirect purging (with nitrogen) - Use of flares during commissioning (vs. cold venting) - Leak (tightness) testing requirements	- Drying specification / methods more stringent (sweet corrosion) - Low temperatures / liquid drop-out require consideration in procedures, and design of temporary bridles, etc.

4. Procurement and Supply Chain Management

Work Package 2 included a study to develop a high level supply chain strategy to support procurement activities across major hydrogen and carbon dioxide construction projects. Technical Report 2 [3] presented a detailed assessment of critical elements of this strategy. Full details of this work and supporting references are given in the report. The sections below present a high level summary of the main findings.

4.1. Overview

The scale of new pipeline construction projects will be a significant shift from the current maintenance and operations works required to keep the existing infrastructure operating safely. Supply chains will therefore need to be developed to provide greater resilience and this will be key to the effective delivery of products and services. This supply chain development activity requires activity and decision making at a strategic level.

Kent have worked with National Gas to develop a strategy for this supply chain transformation. A series of workshops have been held with NGT's procurement team to define the main challenges and priority actions.

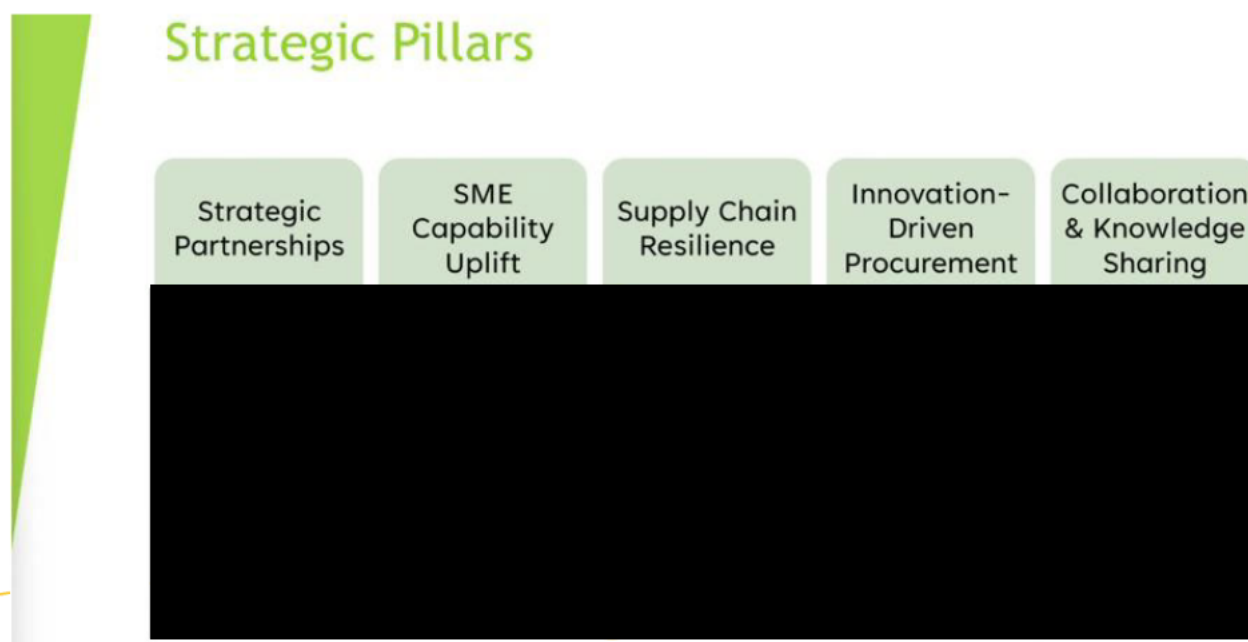
4.2. Strategic Risks

A resilient supply chain will be key to effective delivery of products and services and requires management of risks at a strategic level. The risks the projects will face over the long time frames of the projects will change and will need to be regularly reviewed. The overarching approach to supply chain risks management that encompasses all the intended pipeline projects will drive horizontal consistency across the projects.

[REDACTED]

[REDACTED] [REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

During the project workshops, NGT presented a summary of its Strategic Supply Chain Position and the Strategic Pillars for its development, as summarised in the Figure below.



Kent has suggested some additional strategic elements that should be incorporated within this framework as follows:

- [REDACTED]
- [REDACTED]
- [REDACTED]
- [REDACTED]
- [REDACTED]
- [REDACTED]

4.5. Recommendations

The key conclusions and recommendations made in the procurement and supply chain management report are summarised below:

[REDACTED]

- [REDACTED] ■
- [REDACTED] ■
- [REDACTED] ■

- [REDACTED] ■
[REDACTED]
[REDACTED]
[REDACTED]
- [REDACTED] ■
[REDACTED]
- [REDACTED] ■
[REDACTED]
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[REDACTED]
- [REDACTED] ■
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]
- [REDACTED] ■
[REDACTED]
[REDACTED]

5. Connections Process

Work Package 3 included a study to develop standardised conceptual connection designs for hydrogen producers / offtakers and carbon dioxide emitters. Technical Report 3 [4] presented a detailed description of critical areas and opportunities for efficiencies. Full details of this work and supporting references are given in the report. The sections below present a high level summary of the main findings.

5.1. Overview

Kent has developed conceptual connection designs for hydrogen producers / offtakers and carbon dioxide emitters, to facilitate their connection to the NTS (or equivalent) in a way that is safe and minimises time, cost and complexity. The starting points or reference cases are the current connections process and connection designs which currently exist across the NTS. These have been reviewed and consideration is given to the modifications necessary to support hydrogen or carbon dioxide service, and also where additional optimisation / streamlining can be achieved.

There are three overarching types of connection: entry, exit, and combined entry / exit, for which a generic base case connection design is proposed for both hydrogen and carbon dioxide. A typical hydrogen offtake connection and carbon dioxide emitter connection will be most numerous on each network and these would be the best candidates for efficiency savings from standardisation.

The base case design is further developed with (non-exhaustive) examples for different types of foreseeable sites / tie-in locations across the pipeline network. The objective is to propose a standardised connection arrangement which can be applied to the majority of foreseeable scenarios, though it is also recognised that site-specific factors will always need to be taken into consideration which are likely to require some modifications. In addition, a risk-based approach to assessing impacts from e.g. off-specification fluid is recommended, which may lead to differences in the mitigation measures needed for different entrants / locations.

With respect to the interface and division of responsibility for equipment build/operation between NGT (the transporter) and 3rd parties, the concept of "maximum" and "minimum" connection models is discussed. The proposed connections designs are mostly in accordance with the "minimum" model, based on discussions with NGT as there are a number of inherent efficiencies to the connections process with this approach. [REDACTED]

The main conclusions and recommendations made in the connections process report are summarised below.

5.2. Hydrogen

1. [REDACTED]
2. A standardisable, modularisable valving arrangement for connections has been proposed which is transportable and can be fabricated and tested at the factory before shipment to AGI sites. Building upon the development of non-ROV connection designs which have been recently adopted, the standardised valve configuration would be identical in both cases, with the fitment of manual or electro-hydraulic valve actuator to provide ROV functionality to be determined based on process safety / regulatory assessment for each site (and customer preferences).
3. It is noted that a standardised, modular configuration may not be optimal in all circumstances, and at single-customer sites with no future expansion potential there may be (minor) costs savings by only using the pipeline isolation / pig trap valves as the customer isolation points. Other parts of the installation may also be modularisable, for example where there is a pig trap by the connection point the pig trap itself with

associated isolation valves, and kicker line, etc., therefore each installation and connection point may be constructed of modular parts.

4. The impact on connection design for different types of offtaker / producer sites has been considered, and while these would have different supply/demand profiles than natural gas equivalents, it is proposed that connection designs can be standardised and would not need to be different for each type of site. However, the connection agreement with such sites may differ, and in particular the assurances and checks which NGT undertakes is likely to differ, to best represent the risks posed to the network.
5. For entry and combined entry/exit points, it is noted that there will be a disproportionate cost impact to providing non-return valves, filters, and other maintainable equipment and it is proposed that the risks posed by removing these can be mitigated or solved by other means, if necessary. This is likely to require review from safety / commercial perspectives.
6. Based on the above, it is proposed that a significant standardisation and modular design build is possible for hydrogen connections to the network, which can offer a number of advantages in terms of minimising site work durations, improving lead times for customers, and reducing design effort and costs.

5.3. Carbon Dioxide

7. For carbon dioxide, a modular entry point connection design has been proposed, similar to that as for hydrogen. [REDACTED]
[REDACTED]
[REDACTED]
8. The differences in fluid properties for carbon dioxide have been considered, namely that carbon dioxide is an asphyxiant gas heavier than air, poses a significant risk of sweet corrosion if moisture content is not suitably controlled, with some risks associated with condensation of carbon dioxide in cold weather and Joule-Thomson cooling resulting in low fluid temperatures, [REDACTED]
[REDACTED] at equivalent upstream conditions which may require particular consideration in the design of bridle arrangements around isolation valves. These issues may require small changes in the valve configuration and connection arrangement compared to hydrogen, which should be further developing during FEED/detailed design.
9. [REDACTED]
[REDACTED]
[REDACTED] It is noted that trip setpoint settings may need further consideration, given the commercial risks held by NGT, and independent monitoring and trips could be designed to meet a suitable reliability level, e.g. a CIL rated trip.
10. If situated above-ground, there is a risk that exposed pipework in cold weather conditions will experience some carbon dioxide condensation and pooling within the pipework, for parts of the network which do not have flow (e.g. emitter temporary outage). This, and the design temperatures required to mitigate the risk of low fluid temperatures caused by startup pressurisation flows, should be considered as designs progress.

6. Conclusions

The construction of new hydrogen and carbon dioxide pipeline sections presents several challenges, but also a number of opportunities.

Some challenges are technical, such as those associated with design of a network where the physical properties of the gas are significantly different to natural gas, or material compatibility issues require the adoption of new technologies. Others are commercial or organisational, such as the need to diversify a supply chain in anticipation of a step change in the scale of construction activity.

Supply chain challenges can be mitigated by developing a strategy for engagement with suppliers of critical product types such as linepipe, compressors and valves. Diversification of the supply chain is critical in building resilience, so plans should be developed for vendor qualification programmes in critical areas.

Other key elements of a supply chain development strategy include:

- Collaboration and knowledge sharing.
- Definition of commercial contracting approach.
- Integrating ESG principles into purchase orders and contracts.
- Logistics planning for large scale transport and storage.
- Data and information management tools.
- Competency and skills development.

Technical challenges can be mitigated by engineering design, facilitated by the development of appropriate codes, standards and procedures. The different Work Package reports summarised above have highlighted specific instances of where this is required.

Decommissioning of legacy natural gas pipelines and associated commissioning of new hydrogen or carbon dioxide pipelines requires a procedure to be followed during a repurposing project. The Work Package 1B report summarised above provides an overview of the technical steps involved and addresses the specific circumstances where the change in fluid type has a significant influence. It is envisaged that this guidance can be used to ensure a consistent approach across projects as detailed project-specific plans are developed.

The adoption of new technologies or practices provides an opportunity for significant improvements in efficiency, that can reduce cost and support future network expansion. Numerous technical disciplines are involved in pipeline construction and technology reviews have been carried out to identify areas where technology readiness is at a level where it may easily be incorporated into projects. Those judged to offer the most significant impact include:

- Software tools for optimisation of pipeline routing during project engineering.
- Appropriate use of different trenchless installation techniques, depending on terrain and soil conditions.
- Use of advanced automated internal and external multi-torch welding systems and line-up clamps, together with laser pipe end measurement systems and other digitalisation tools, as well as automated methods for non-destructive testing.
- Use of factory built modules, containerised systems, and 3-D-printed concrete foundations for AGI infrastructure elements to reduce on-site labour and re-work.
- Fibre-optic cables installed along the pipeline length to provide continuous monitoring capability for leak detection, third party interference and ground movement at high risk locations.
- Alternative pipe fabrication processes such as SAWH or HFI carbon steel pipe (for medium to large diameters) and reinforced thermoplastic pipe (for small diameter spurs or tie-ins).

In some areas, further technology development is needed before widespread use on a project could be envisaged. Examples of this include:

- Autonomous excavation and lowering systems (where terrain and soil type is appropriate).
- Battery electric or hydrogen powered trenching equipment (current practice is mainly diesel with some hybrid plant)
- More radical alternative materials for pipeline fabrication such as MASiP pipe as an alternative to conventional carbon steel linepipe.

Significant efficiencies can also be realised by adopting standardised designs for different connections. The Work Package 3 report summarised above includes conceptual designs for hydrogen producers / offtakers and carbon dioxide emitters. A standardisable, modularisable, connection arrangement has been proposed which is transportable and can be fabricated and tested at the factory before shipment to AGI sites. The best candidates for efficiency savings from standardisation would be offtake connections for hydrogen and emitter connections for carbon dioxide due to number of connections expected.

For hydrogen, it is expected that double valve block and bleed (DVBB) should form the standard provable isolation arrangement. The variant for carbon dioxide has been presented with double isolation and bleed (DIB), similar to the existing natural gas network, and could incorporate DVBB isolation if required.

For entry and combined entry/exit points, it is noted that there will be a disproportionate cost impact to providing non-return valves, filters and other maintainable equipment. It is proposed that the risks posed by removing these can be mitigated or solved by other means, if necessary.

Site-specific factors will always need to be taken into consideration; a standardised, modular configuration may not be optimal in all circumstances, and at single-customer sites with no future expansion potential there may be (minor) costs savings to optimise the base case.

The special properties of carbon dioxide have been considered. To mitigate risks, consideration should be given to provision of independent moisture analysers within the carbon dioxide entry points, and design should consider exposed above-ground pipework and design temperatures required to mitigate the risk of low fluid temperatures caused by startup pressurisation flows.

The different work packages described above have identified a number of challenges and opportunities related to pipeline construction that are encountered during different phases of engineering. Key areas are summarised in the Table below.

Table 4 Key Challenges and Opportunities Identified in Different Work Packages

Project Phase	Activity	WP	Main Findings / Recommendations
Design	Pipeline Routing	1A	Use of software tools to optimise route to minimise cost or risk.
	Pipeline Design	2	Investigate potential use of SAWH or HFI materials to broaden supply chain (for large diameter trunklines).
		1A	Investigate potential use of composite pipe for short, small diameter spur lines.
	Connections Design	3	Use of standardised modular connection designs to improve cost and schedule.
	Risk Mitigation	1A	Use of fibre optic cables to provide continuous monitoring capability.
	Data Management	2	Develop plans for data management to ensure systems and supply chain tools are in place.

Fabrication	Supply of long lead items	1A	Update NGT material specifications for pipe, valves etc.
		2	Broaden supply chain [REDACTED] in key areas such as pipe, valves and compressors. [REDACTED] d.
Construction	Pipeline Construction	1A	Use of advanced multi-torch pipeline welding systems and automated NDT to improve quality and construction efficiency.
		1A	Use of different trenchless installation techniques, depending on terrain / soil conditions.
		2	Develop contracting strategy and maintain pro-active dialog with contractors. Cascade ESG principles into contracts.
	AGI Construction	1A	Use of 3D printed concrete foundations.
		3	Use of factory-built modules or containerised systems to reduce on-site labour and re-work.
Commissioning	Cleaning, drying	1B	Where repurposing a pipeline, ensure that all required pigging operations are carried out while in natural gas service, if possible.
		1B	Recognise the need for more stringent dewpoint specification for CO2 pipelines and engage with vendors to ensure availability of suitable dried air or vacuum pump drying systems.
	Purging, start-up	1B	For hydrogen, indirect purging with nitrogen is required and mobile flares will be needed due to the risks posed by delayed ignition.
		1B	Update NGT procedures where needed to account for different gas properties, e.g. purge velocities.

7. References

- [1] Pipeline Installation Techniques for Net Zero - WP1A Report - Pipeline Construction Techniques, Kent Report No. 5300-RP-01A Rev 01, November 2025.
- [2] Pipeline Installation Techniques for Net Zero - WP1B Report - Decommissioning, Testing and Commissioning, Kent Report No. 5300-RP-01B Rev A3, January 2026.
- [3] Pipeline Installation Techniques for Net Zero - WP2 Report - Procurement and Supply Chain Management, Kent Report No. 5300-RP-02 Rev A4, February 2026.
- [4] Pipeline Installation Techniques for Net Zero - WP3 Report - Connections Process for Net Zero NTS Customers, Kent Report No. 5300-RP-03 Rev A2, February 2026.

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