Recompression Solutions for a Net Zero NTS WP4: Technical Report

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Technical Summary

National Gas Transmission (NGT) is investigating strategies to minimise venting of hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4) across the National Transmission System (NTS) to support Net Zero objectives. This report summaries key findings from the Recompression Solutions for a Net Zero NTS

The Recompression Solutions project comprises of 4 Work Packages. Work Package 1 Recompressor Management of Change for 12% hydrogen blends conducted by Premtech. This investigated the engineering, performance, safety, and commercial requirements necessary to repurpose the recently purchased *** recompressor units for operation with up to 12% hydrogen blends. Work Package 2 Hydrogen Recompression Solutions and Work Package 3 Carbon Recompression Solutions were combined into one report. These two work packages were completed by Wood. This report aimed to identify current and future venting scenarios across hydrogen-blend networks and the SCO2T CO_2 pipeline. This facilitated the investigation of suitable recompression technologies to minimise or eliminate venting. Furthermore, the report undertook technology overviews, vendor engagements, as well as deployment strategy and business case analysis. Finally, Work Package 4 Reporting presented aims to summarise the key project findings, conclusions, and recommendations.

1.1 WP1 findings

A repurposing review was carried out to assess whether current National Gas recompression units ***** utilised to recompress natural gas can operate under blended hydrogen service. The review considered suitability of use with hydrogen blends of up to 12%, including variability in blend composition, and using the existing ancillary systems. The assessment also evaluates the overall operational performance and safety considerations of the recompression unit when handling blended gas containing up to 12% hydrogen.

The review on the existing ancillary shows that the 100mm and 200mm existing spools can be utilised for hydrogen blends of 2% and 5%. As IGEM/TD/13 Edition 3 Supplement 1 states that where hydrogen blends exceed 10%, the design requirements shall be based on 100% hydrogen. On this basis, the [redacted]mm NB spools with an [redacted] wall thickness are not acceptable for a design pressure of **** barg. Therefore, spools with a wall thickness of [redacted]mm are required for operation with 12% blends.

A review of the existing valves including slamshut and non-return valves concluded that certain materials and processes used in the manufacturing of the existing valves may not be optimal for hydrogen or hydrogen blend service and hence new valves are required for hydrogen blends.

Evaluation of the new RCU engine confirms capability to operate with hydrogen blends of up to 5% volume across the full range of NTS gas calorific values. Operation at up to 12% volume hydrogen is feasible, subject to the natural gas Lower Heating Value (LHV) being ≥ **** MJ/Nm^3 (*** MJ/SCM).

Operational and maintenance procedures will require targeted updates to reflect hydrogen blend service, including alignment with OEM guidance and revised P&ID references. Additional controls are recommended to address hydrogen's higher diffusivity, including enhanced leak detection measures and nitrogen purging requirements. An emphasis on training related to hydrogen hazards is required in conjunction with operation and maintenance updates.

The safety distances for process vents handling hydrogen blends up to 12% were evaluated using the methodology outlined in IGEM SR/23. Thermal radiation distances were found to be lower than those for natural gas vents, confirming that the standard IGEM SR/23 values remain applicable. However, hydrogen blends increase dispersion behaviour, resulting in an overall larger required safety distance.

1.2 WP2 & WP3 findings

A review of operational data and input from the High-Pressure Venting and Flaring project identified four priority venting scenarios: pig traps, ball valve cavities, filter/scrubber maintenance, and temporary CO_2 pipeline venting. Methane operations collectively vent over **** tonnes per year across the first three scenarios, while CO_2 systems are expected to vent just less than **** tonnes annually in small-scale activities and during pipeline maintenance. These volumes present a strong opportunity for mobile recompression deployment.

Market assessment confirmed that hydrogen compression technologies are commercially available, with ***** demonstrating TRL 7–9 readiness for both H_2 and CO_2 applications and recovery efficiencies of around 90%. Hydrogen-capable gas engines remain a limiting factor. Offerings from **** and **** support 100% H_2 operation but there is a gap in the market for gas engines capable of 12%-20% blends

Technical and logistical considerations indicate that mobile units must reliably achieve ~90% recovery across typical ***-to-***-minute venting windows. However, challenges remain around site access (particularly for ball valve cavities), congested sites, and limited space near pig traps. CO_2 pipeline recompression requires significantly larger units capable of up to ****** Nm^3/hr, along with stringent moisture-control measures such as vacuum dehydration to prevent integrity risks.

Ball valve cavities may not be suitable for recompression if they cannot be recompressed quickly enough. Ball valve cavity venting needs to be completed relatively quickly to ensure the ball valve seals are activated. Trials should be completed by NGT to determine if the recompression rates are sufficient to allow the ball valve seals to activate.

CO_2 recompression may be justified by other requirements such as safety. Venting of CO_2 is not straightforward, particularly large pipeline volumes were dispersion is critical. Recompression may be justified as part of an ALARP argument as it could eliminate large, hazardous vents of CO_2. This is covered thoroughly in the CO_2 section of the high-pressure venting study [1].

Overall, recompression technologies for both hydrogen and CO_2 are technically feasible and increasingly available. A key recommendation is to integrate this project findings with the ***** project to determine if CAPEX efficiencies can be gained. Alignment with future RIIO mechanisms (e.g. venting incentive) , and integration within operational protocols will be essential to achieving emissions reduction objectives while maintaining system reliability across future methane, hydrogen, and CO_2 network operations.

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2.0 Project Overview

2.1 Introduction

National Gas Transmission (NGT), owner and operator of the National Transmission System (NTS), has undertaken significant work to explore the potential for transporting hydrogen within the NTS, both as a blend and as 100% hydrogen. In parallel, growing interest in carbon dioxide transport emerged following the UK Government's announcement of large-scale funding for Carbon Capture and Storage (CCS) projects. Recognising the safety and environmental risks associated with venting hydrogen and carbon dioxide, this project aimed to identify strategies to reduce or eliminate venting across Net Zero gas networks. Recompression Solutions for a Net Zero NTS is a project undertaken to gain the technical and strategic understanding around recompression solutions enabling National transmission system to be operated with hydrogen blends, pure hydrogen and CO_2.

The NIA Safe Venting & Recompression of Hydrogen (SVRH) innovation project confirmed that the new recompression units on order were capable of compressing up to 5% hydrogen blends, with potential to handle up to 12% depending on the gas's Low Heating Value (LHV). Building on the findings of this report, NGT identified that there was other potential opportunity for recompression within their network. Therefore, this project investigated how similar technologies could be applied to small scale hydrogen venting as well as future carbon dioxide transportation. This project also assessed technologies and applications for reducing CO_2 venting. This helped establish the rationale and process requirements for CO_2 recompression.

2.2 Scope of Work

The project scope has been divided into four major phases presented below, however, for this report only WP4 will be reported.

1. WP 1 – Recompressor Management of Change for 12% Hydrogen Blends
2. WP 2 – Hydrogen Recompression Solutions
3. WP 3 – Carbon Recompression Solutions
4. WP 4 – Reporting

2.3 Aims of the Work Package

This report aims to summarise all the key results and discoveries made during the project length. It is structured following the chronological order in which the WPs were released to maintain cohesiveness and links between the findings. A technical summary section presented in this document serves to outline final study outcomes and recommendations for hydrogen and CO_2 operation at NTS

2.4 Abbreviations

Table 2-1 : Abbreviation List

Abbreviation	Meaning
Redacted	Redacted
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Abbreviation	Meaning
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3.0 Work Package 1 – Recompressor Management of Change for 12% Hydrogen Blends

National Gas Transmission (NGT) has undertaken substantial work to evaluate the feasibility of transporting hydrogen within the National Transmission System (NTS), both as a blend with natural gas and as 100% hydrogen. Recognising the safety, operational, and environmental risks associated with venting hydrogen, this project was initiated to identify and assess strategies to reduce or eliminate venting across future Net Zero gas network.

New recompression units have been recently procured for natural gas recompression operation on the NTS. The new recompression units are from manufacturer ***, and model is the ***. The procured unit was confirmed by the manufacturer, ******, as suitable for compressing gas containing 5% hydrogen blends and potentially up to 12% hydrogen blends, depending on the Lower Heating Value (LHV) of the gas. This capability represents a significant opportunity for National Gas Transmission (NGT) to offer potential cost savings within a blended gas network.

This work package will assess the technical, safety and operational considerations associated with operating the procured ***** with hydrogen blends of up to 12%, including variability in blend composition using the existing ancillary system. The assessment will also evaluate the overall operational performance of the recompression unit when handling blended gas up to 12% hydrogen.

3.1 Engineering and Design Changes

3.1.1 Mechanical Assessment

A mechanical assessment was completed on the ancillary pipework of the newly procured *****. The assessment included review of pipework, flexible connections, fittings, gaskets and valves associated with recompression operations.

The existing pipework was evaluated using a maximum design factor of [redacted], which is applied for hydrogen service to limit hoop stress to [redacted] for the relevant material grade. The review concluded that the spools typically used in recompression operations are generally suitable for hydrogen blends of 2% and 5%.

However, IGEM/TD/13 Edition 3 Supplement 1 [16] states that when hydrogen blends exceed 10%, design requirements must be based on 100% hydrogen. On this basis, the [redacted] mm NB spools with an [redacted] mm wall thickness do not meet the necessary requirements for hydrogen blends up to 12% by volume.

Table 3-1 : Assessment of Spools for Hydrogen Blend Service

Pipework	Wall Thickness	Design Factor	Applicability to blend of hydrogen
100mm NB	[redacted]mm	[redacted]	2%, 5% and 12%
200mm NB	[redacted]mm	[redacted]	2% and 5%
200mm NB	[redacted]mm	[redacted]	2%, 5% and 12%

The review identified that the fittings currently used by National Gas Services would be suitable for hydrogen blends of 2% and 5% only.

Flexible steel hose assemblies currently used in the recompression unit operation are not suitable for hydrogen blend service; however, suitably rated hoses are readily available on the market.

Gasket materials shall be suitable for the design pressures and temperatures specified of the recompression unit and shall be compatible with hydrogen service, providing adequate leak resistance. It is believed that the raised face flanges within the spools are jointed using graphite spiral wound gaskets in accordance with [redacted] and hence are suitable for hydrogen service applications however, other gasket materials must be changed or assessed for hydrogen compatibility and leak rate.

The valves assessed for hydrogen blend compatibility included double block and bleed arrangement valves, slam-shut valves and non-return valves. In line with recommendations from the valve manufacturers, the current valves on the ***** should be replaced with hydrogen compatible valves.

3.1.2 Electrical Assessment

All new electrical and instrumentation equipment shall be ATEX-rated for Gas Group IIA, which is typically specified for natural gas duty. Gas Group IIA equipment is considered suitable for hydrogen blends up to 25%, as stated BS EN ISO 80079-20-1 [33]

3.1.3 Civil Assessment

The civil elements required for recompression include installation of temporary supports of ancillary pipework and supporting manual vent stack. It is noted that 12% hydrogen blend recompression will have no impact on the existing civil requirements

3.2 Formal Process Safety Assessments

A review of the HAZID and HAZOP guidewords was carried out to assess their applicability to the recompression unit when operating on hydrogen blends of up to 12% volume. Recommendations were developed for each relevant guideword to support future reassessment of hazards arising from the change in gas composition and to ensure all guidewords potentially affected by hydrogen blends are suitably addressed. The key changes identified relate primarily to loss-of-containment scenarios, which will require reassessment to reflect the different severity and consequences associated with hydrogen blends. In addition, new requirements for inert gas purging introduce further considerations, particularly regarding potential purge gas failure scenarios.

3.3 Safe Setting of Work

3.3.1 Hazardous Area Assessments

The gas pipework on the recompression unit has the following forms of release as defined by IGEM/SR/25 [21], these are:

a) Releases from flanges, fittings, screwed connections, and valves

b) Releases from [redacted] relief valve PSV [redacted] and PSV [redacted]

c) Releases from [redacted] mm NB manual vent.

d) Releases from [redacted] mm process vent.

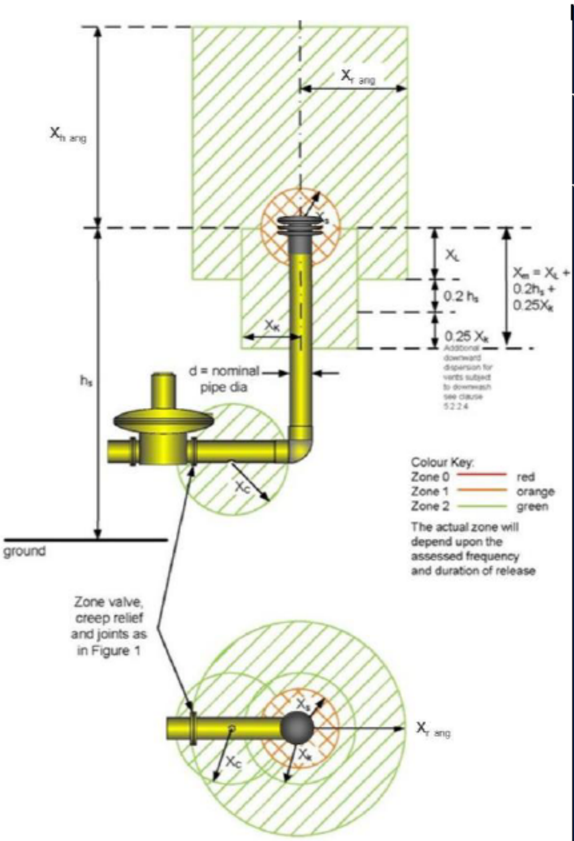
Secondary releases are typically from flanges, fittings, screwed connections and valve glands present on the recompression unit. These would require a zoning distance of [redacted] m if located in an area under normal conditions (Table S1B in IGEM/SR/25 Hydrogen Supplement 1 [22]).

The new ***** is equipped with two [redacted] mm NB relief valves, PSV [redacted] and PSV [redacted], set at 115 barg. As the pressure range is beyond range covered by IGEM/SR/25 Hydrogen Supplement 1, PHAST software was used to model vent flow rates. The flow rates were then correlated with the IGEM/SR/25 Hydrogen Supplement 1 to obtain the extent of release. The horizontal and vertical extent of the hazardous area zone was found to be [redacted] m and [redacted] m respectively, resulting in a larger horizontal hazardous area and slightly reduced vertical hazardous area than the respective distances for natural gas ([redacted] m and [redacted] m).

Two manual [redacted] mm and [redacted] mm vents are present on the recompression unit and may be used periodically for short durations, it should also be noted that the manual vent contains fittings that may produce secondary grade releases. The hazardous area assessments of the vents are summarised in Table 3-2.

Table 3-2: Manual Vents Hazardous Area Assessment Summary

	Zone Distances (m)	
	Mobile Recompression Anciliary Manual Vent – 200mm NB	**Mobile Recompression Anciliary Manual Vent – 25mm NB**
X_s	[redacted]	[redacted]
Zone	[redacted]	[redacted]
X_r	[redacted]	[redacted]
X_h	[redacted]	[redacted]
X_L	[redacted]	[redacted]



X_k	[redacted]	[redacted]
0.2 h_s	[redacted]	[redacted]
X_m	[redacted]	[redacted]

3.3.2 Dispersion and Thermal Radiation Modelling

Venting is required as part of the recompression operation. Typically, IGEM/SR/23 is used to determine the safety zones with regards to natural gas venting from vent stacks. Phast software was employed to determine the safety zones for hydrogen blend venting, the model inputs are summarised in Table 3-3.

Table 3-3: Phast Input Summary

Parameter	Vent Stack	Purge Ejector
Diameter	157 (mm)	200 (mm)
Gas pressure	3.7 (barg)	7.0 (barg)
Gas temperature	5 (ºC)	5 (ºC)
Height of release	10 (m)	3 (m)
Blends considered	2%, 5%, 12%	2%, 5%, 12%
Model	Pressure vessel and elevated short pipe	Pressure vessel and elevated short pipe
Dispersion parameter	Ooms model (α1 = 0.09), early initial air entrainment = 0	Ooms model (α1 = 0.09), initial air entrainment = 0
Weather parameters	1D, 5D, 10D	1D, 5D, 10D
Discharge parameters	Momentum conservation	Momentum conservation
Equation of state	Phast multi-component	Phast multi-component
Consequence height of interest	2(m)	2(m)
Thermal radiation contour	6.3 kW/m2	6.3 kW/m2
Flammability contour	½ LFL	½ LFL
Overpressure contour	140mbar	140mbar
Overpressure	Multi energy model, TNO curve 10, 100% explosion efficiency, 0.3 flammable mass	Multi energy model, TNO curve 10, 100% explosion efficiency, 0.3 flammable mass

Thermal radiation of an ignited vent was used to define safety distances for the process vent and purge ejector which forms part of the ancillary pipework of the recompression unit. Thermal radiation predictions from Phast and IGEM SR/23 show strong agreement, as both methodologies are fundamentally driven by source mass flowrate and thermal power of combustion. The thermal radiation consequence modelling shows a decrease in thermal radiation safety distances with increase in hydrogen percentage; this is likely due to the lower emissivity of hydrogen and can be seen in Figure 3-1 and Figure 3-2. It is noted that windier weather conditions give rise to the largest thermal radiation distances. The thermal radiation derived from IGEM SR/23 can be used to determine safety distances for hydrogen blends up to 12% volume. As summarised in Table 3-4, the horizontal safety distance is driven by the thermal radiation contours.

Figure 3-1 : Phast Model for Thermal Radiation of Ignited Process Vent Containing Natural Gas

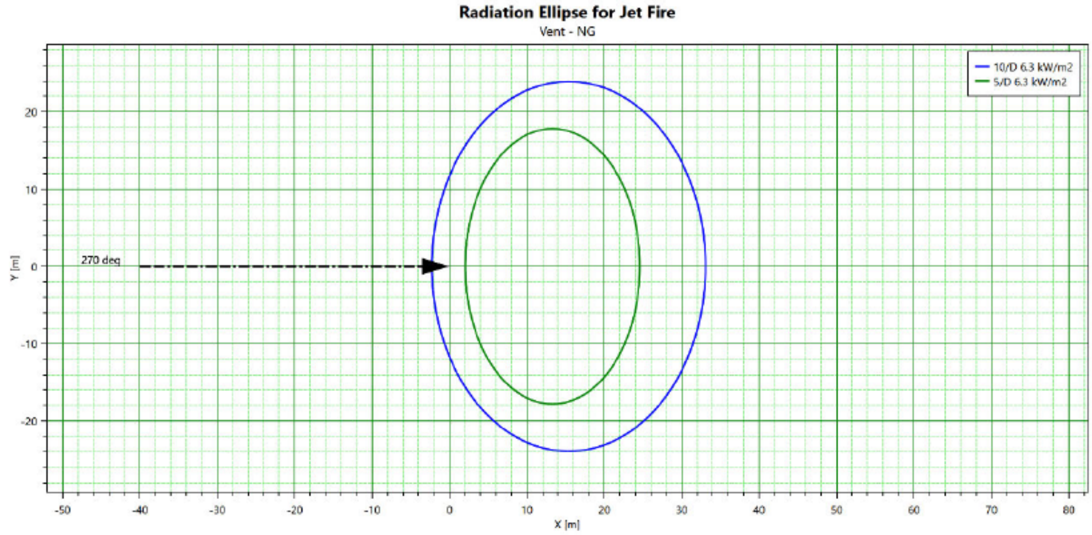
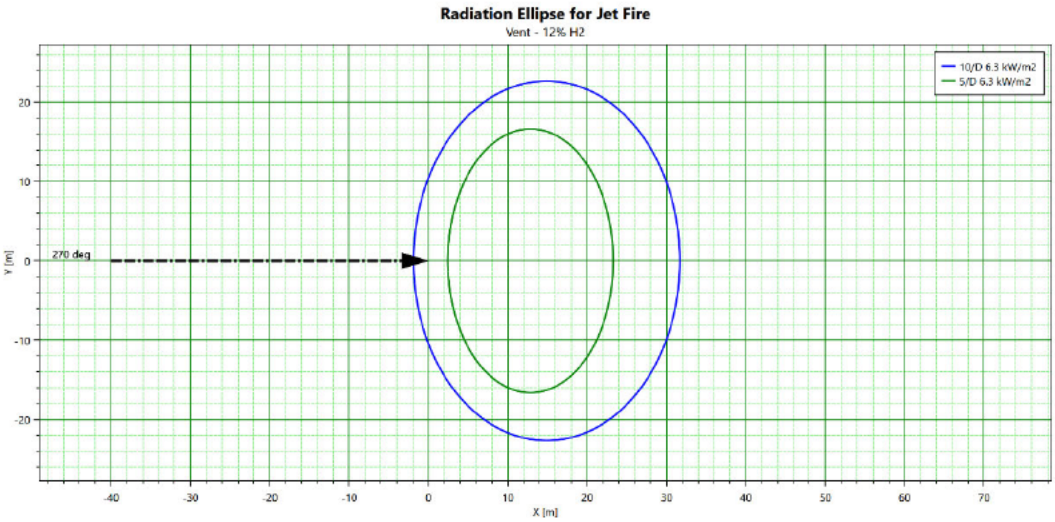


Figure 3-2: Phast Model for Thermal Radiation of Ignited Process Vent Containing 12% Hydrogen Blend



The flammability of the vent plume is defined as the distance to the ½ Lower Flammability Limits and was assessed using a Phast model. Hydrogen blend plumes displayed an increase in vertical and horizontal flammability distances, as represented by Figure 3-3 and Figure 3-4. This is likely due to the wider flammability range of hydrogen. This marks an increase in safety distance due to the hydrogen contained in the blend and particularly impacts the vertical safety distances, as summarised in Table 3-4.

Figure 3-3: Phast Model for Flammability of Process Vent Containing Natural Gas

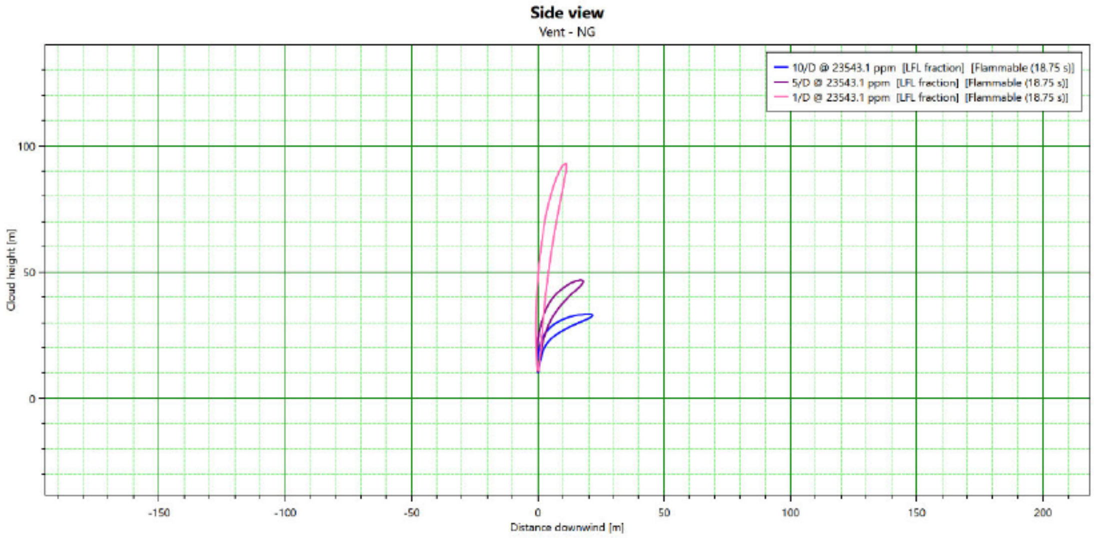
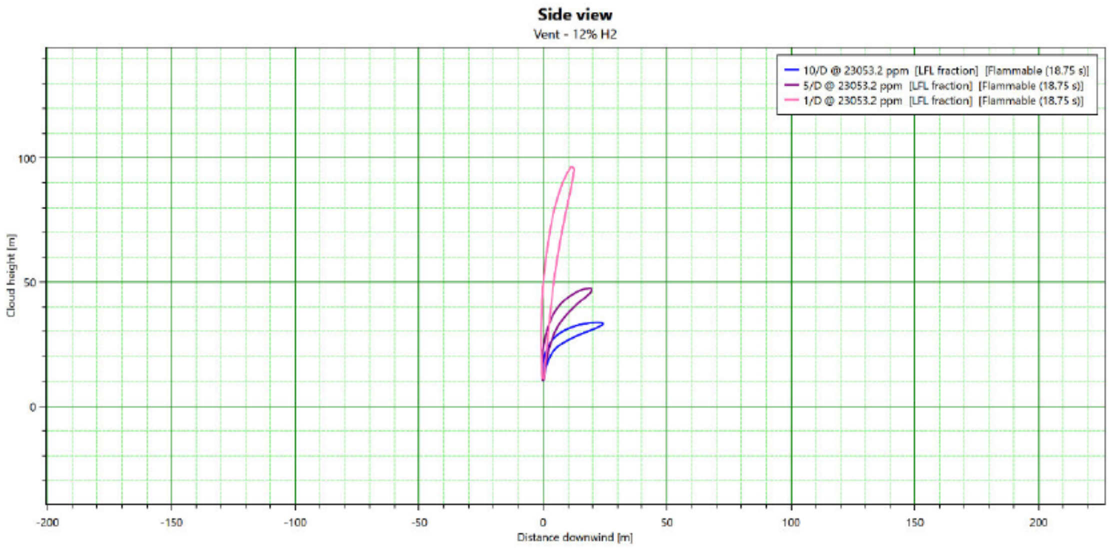


Figure 3-4: Phast Model for Flammability of Process Vent Containing 12% hydrogen blend



Overpressure at the vent stack was assessed at pressure levels equivalent to 1% fatality to people outdoors, which is more conservative than the harm criteria used to define the thermal radiation safety distances. The results of the overpressure assessment indicate a horizontal safety distance less than the thermal radiation result.

The results displayed in Table 3-4 represent the recommended horizontal and vertical safety distances proposed for all blends of hydrogen up to 12% volume. It should be noted that the most conservative value has been chosen for both horizontal and vertical safety distances.

Table 3-4: Summary of consequence modelling results

Vent	Mixture	Recommended safe horizontal distance (m)	Recommended safe vertical distance (m)	Driving hazard
Vent stack	All	33	107	Horizontal safety distances are driven by thermal radiation, whereas vertical safety distances are driven by dispersion distances
Purge Ejector	All	50	134	

3.4 Performance Analysis

Assessment of the **** engine shows that it can operate effectively on hydrogen-blended natural gas up to 12% vol. Comparison of the unit's Lower Heating Value (LHV) requirements with the full range of LHVs measured on the NTS indicates that a 5% vol hydrogen blend is fully compatible with maintaining recompression unit performance across all typical calorific values. While blends up to 12% vol are technically feasible, they can only meet the engine's minimum fuel quality requirement of **** MJ/Nm^3 (**** MJ/SCM) when supplied with gas at the upper end of the NTS calorific value range.

3.5 Policy and Procedures

The following policies were reviewed to highlight required changes to account for blends of hydrogen in the NTS and recompression activities.

- NRO Example used [redacted] Decommissioning
- Method Statement 100a (Twin Unit)
- [redacted] - Work procedure for the functional check of critical valves (remote operation)
- [redacted] Work procedure for the functional check of critical valves (local operation)
- [redacted] Work procedure for the functional check of non-critical valves

The recompression unit method statement will require updates in accordance with OEM technical guidance, and all valve identifiers and equipment references must be revised to match the latest approved P&ID. Given hydrogen's higher diffusivity the development of a hydrogen-specific leak detection procedure is also recommended. A major difference between natural gas procedures and hydrogen blend procedures may be the requirement of nitrogen purging of the recompression unit. Asset management related criteria, [redacted] will require revaluation due to hydrogen's distinct acoustic and leakage characteristics.

Overall, the policies and procedures must be updated to account for hydrogen hazards and the associated safeguards. The key hydrogen safeguards involve more stringent control of ignition hazards such as static electricity and appropriate gas and leak detection.

3.6 Training

Hydrogen presents different hazards compared to natural gas resulting in the requirement for additional safeguards. Training must ensure personnel understand hydrogen related risks and are familiar with any changes to equipment, procedures, or operational practices. The table below summarises the key areas in which personnel will require training to operate the recompression units on a hydrogen blend of up to 12% volume.

Table 3-5: Training Requirements for Operation of Recompression Units with Hydrogen Blends

Training requirement	Training description
Fire	Hydrogen blend vent fires should be controlled primarily by isolating the gas supply. Firefighting apparatus must not be aimed directly at the vent, as doing so may obstruct the vent and create additional hazards.
Leak detection	Training related to leak detection methods suitable for hydrogen blends will be required.
Hydrogen gas detection	Hydrogen gas detection requires equipment different from that used for natural gas. Training must cover the correct use, calibration, and maintenance of hydrogen-specific detectors, as well as required actions when hydrogen is detected.
Control of static discharge	Due to hydrogen's higher ignition probability, strict control of static electricity is essential. Personnel must be trained in grounding and other static-control procedures.
Hydrogen hazards	Hydrogen hazards and safeguards differ from natural gas, personnel must have appropriate knowledge and understanding of the risk associated with hydrogen service and the differences in risk between natural gas and hydrogen. Training must be specific to the role and responsibilities of the personnel. All training shall be supported by records.
Indirect purging	Indirect purging is a requirement for ensuring equipment containing hydrogen blends do not contain a flammable mixture.
PPE	PPE which reduces the risk of static generation is required. Personnel must receive training on the correct selection and use of PPE.

3.7 Reverse Compression

Reverse compression refers to the transfer of natural gas from lower-pressure to higher-pressure systems to create artificial demand on the lower pressure system. Reverse compression is typically employed to facilitate the injection of biomethane. Reverse compression is usually required during summer months, when network demand is low. An assessment of the **** found that, although it is effective for rapid bulk pipeline evacuation during maintenance and emergencies, it cannot efficiently handle the low flowrates and pressures required for reverse compression.

Moreover, the summer months are the optimal time for maintenance on the NTS where reduced network demand can facilitate pipeline outages Using the recompression units for reverse compression would conflict with NTS maintenance requirements. Therefore, a dedicated unit designed specifically for reverse compression is recommended to ensure efficient and reliable operation. Since reverse compression is not recommended for natural gas applications, it is also unlikely to be used on a future Net Zero NTS with hydrogen blends.

4.0 Work Package 2&3 – Hydrogen & Carbon Recompression Solutions

4.1 NTS Venting Scenarios

WP2 (Hydrogen Recompression Solutions) and WP3 (Carbon Recompression Solutions) focused on small, vented volumes from hydrogen and CO_2 operations within AGI limits, as well as large-scale CO_2 pipeline recompression. The objectives were to identify relevant recompression scenarios, assess feasible technologies, and outline a supporting business case.

The assessment includes pure hydrogen, blended hydrogen and carbon dioxide across a range of maintenance and operational activities. Large hydrogen-volume cases previously examined in the SVRH project [2] are excluded. The study, therefore, concentrates on recompression opportunities in pig traps, ball valve cavities, and filters/scrubbers for hydrogen blends and pure H_2/CO_2 operation, and on large CO_2 pipeline sections.

Venting scenarios were defined using insights from previous work [redacted] and High-Pressure Venting Demonstration NGT Innovation Project) and engagement with NGT during WP2, considering the applicability to hydrogen and CO_2 operations and aligning with the CH4RGE project scope.

Table 4-1 : NTS Venting Scenarios

Venting Type	Reason	Volume	Frequency	Current Practice	Annual Volume	Annual Mass
Pig Trap Venting ($CH_4/H_2/CO_2$)	Pig traps require depressurisation during pigging operations for pipeline maintenance and inspection. Each pigging cycle necessitates venting of the trapped gas volume.	****	Variable, dependent on pipeline maintenance schedules	Full atmospheric venting via temporary pipework	*****	****
Ball Valve Cavity Venting ($CH_4/H_2/CO_2$)	Ball valves require cavity depressurisation for inspection and maintenance of valve seats. This prevents pressure buildup and ensures safe access.	****.	Annual inspection cycle per valve	Full atmospheric venting, typically external vent	*****	****

Venting Type	Reason	Volume	Frequency	Current Practice	Annual Volume	Annual Mass
Filter/Scrubber Maintenance Venting (CH_4/H_2/CO_2)	Filters and scrubbers require routine depressurisation for element replacement and legislative compliance inspections.	*****	Annual to bi-annual	Full atmospheric venting following isolation	*****	****
Temporary Planned Pipeline Venting (CO_2)	Large pipeline sections require depressurisation for maintenance where permanent venting facilities are not readily accessible.	*****	Assumed once a year	Future scenario	*****	****

4.2 Recompression Technology

NGT currently employs **** mobile compression units to recompress gas from isolated pipeline sections back into the operational network, thereby avoiding atmospheric venting. These units are typically deployed for large-volume recompression activities. However, smaller scale tasks, such as recompressing gas from pig traps, ball valve cavities, or filters, were identified as potential use cases.

Consequently, this study investigated technologies capable of enabling small-scale venting mitigation and low-volume recompression. The findings are summarised in Table 4-2 below.

Table 4-2 : Recompression Technology Overview

Technology Researched	Findings
Hydrogen Compressor	Hydrogen compression requires adaptations (e.g., high-tolerance seals), but the technology is mature and widely available, so no supply bottlenecks are anticipated [3]
CO_2 Compressor	Reciprocating CO_2 compressors are commercially available and designed to handle CO_2-specific challenges such as phase change risks, small molecular size, and corrosiveness.
H_2&CO_2 Interoperability Compressor	While shared hydrogen/CO_2 compressor operation is technically feasible with appropriate sealing and corrosion-resistant materials, there is limited evidence on long-term dual-service reliability, this highlights an area of investigation for future projects.
Hydrogen Engines	The hydrogen engine market is expanding, particularly for small capacity units driven by transport industry. However, 100% H_2 engines are still not widely available and no market solution exists for blends between 12% and 20%
Electric drive	Electric drive compressors are common, however, retrofit would need to be undertaken to swap from gas engine driven to electric drive. It is advised that a variable speed drive is used which will require grid connection. Therefore, CO_2 pipeline recompression will still require use of gas engines either in the generator or recompression package itself i.e. bringing external fuel source. Whereas site recompression could be driven by the grid.
Balance of plant	Temporary CO_2 recompression pipework must be rigid stainless steel. For small-scale recompression, flexible hose solutions are available for hard-to-access areas and are rated for NG, H_2, and CO_2.
Valves	No control valves are required. Double block and bleed (DBB) valves provide isolation and venting points, while slam-shut valves act as the automated safety barrier for the recompression skid.
Purging and Evacuation Methods	Nitrogen purging is preferred for H_2 systems, while CO_2 systems require vacuum drying to mitigate moisture related risks.
Vacuum Drying Options	Vacuum drying for CO_2 requires a vacuum pump. As no plant (compressed) air is available on site, an electrically driven unit is most suitable.

Technology Researched	Findings
	• For small scale venting there are suitable commercial options, which can be powered via standard 220 V connections to supply 1 kW. • For large scale pipeline venting available units are limited, these require engine or generator drive and vehicle mounting and are impractical for full pipeline evacuation. Thus, nitrogen purging combined with dehydration is recommended to minimise downtime.

4.3 Basis of Design

Table 4-3 and Table 4-4 present the basis of design (BOD) adopted for strategy development and vendor engagement. Given the feasibility-level nature of the study, BOD parameters were estimated from representative NGT operational activities. Flowrate estimates were calculated using **** evacuation tool together with Wood's engineering experience.

Table 4-3 : H_2 Recompression BOD

H_2 and H_2 Blends	
Parameter	**Value**
Pressure Range	****
Temperature	****
Maximum Unit Diameter	****
Recompressor Flowrate	****
Gas Composition	5% H_2 and 95% NG / 20% H_2 and 80% NG / 100% H_2
Objective	• The system must be capable of capturing gas vented from various AGI activities and reintroducing it into live pipeline sections operating at pressures up to **** barg. • Ideally, the technology should reduce the pressure within the unit to near zero prior to venting, without causing significant delays to the maintenance schedule. • The equipment should be lightweight or mounted on a compact trailer to allow easy transport and operation across uneven surfaces such as gravel or shingle. • The solution must be compatible with various hydrogen/natural gas blends with hydrogens concentrations of 5%, 20%, and 100%, to support future operational requirements.

Table 4-4 : CO_2 Recompression BOD

CO_2	
Parameter	**Value**
Pressure Range	****
Temperature	****
Maximum Pipeline Diameter	****
Recompressor Flowrate	****
Gas Composition	~100% CO_2 (detailed composition provided in WP2&WP3 Report [7])
Objective	• The system must be capable of capturing gas vented from various AGI activities and pipeline operations to be reintroduced back into the live system at pressures up to *** barg. • Ideally, the technology should reduce the pressure within the unit to near zero prior to venting, without causing significant delays to the maintenance schedule. • For smaller duties the equipment should be lightweight or mounted on a compact trailer to allow easy transport and operation across uneven surfaces such as gravel or shingle. • The solution must be compatible with the full CO_2 composition provided in WP2&WP3 Report [7].

4.4 Recompression Market Engagement – section redacted

4.5 Strategy

Following the balance of plant review and vendor engagement, deployment targets for each recompression scenario were defined to establish the technical basis for the business case.

4.5.1 Deployment

Table 4-5 : Ball Valve Cavity Recompression Deployment Strategy

Recompression Deployment Strategy: Ball Valve Cavity Venting	
Category	**Details**
Current Mode of Operation	As part of both scheduled and unscheduled ball valve maintenance activities, it is necessary to depressurise the valve cavity to assess the condition of the valve seats. This

	process results in methane being released into the atmosphere, [redacted]. Current venting approach: full volume venting fast, isolation valve opened quickly. Temporary vent pipe utilised.
Required Changes	Mobile recompression unit would have to be brought close enough for temporary hose/pipe to be connected. Onsite temporary storage of recompressed gas.
Equipment Capacity	*****
New Equipment Needs	Flexible hose/connection will have to be rated to full system pressure>***** barg.
Typical Vessel Volume	*****
Recompression Efficiency	~90%
Duration[1]	*****
Maintenance Planning Considerations	Network has nearly*****ball valves, it will be logistically challenging as the recompression would have to be aligned with yearly valve maintenance schedule.
Compliance and Standard	• ISO 13631:2002 – Petroleum and natural gas industries — Packaged reciprocating gas compressors • BS EN 1012-3 Safety requirements - Process Gas Compressors • BS EN 60204-1 Safety of machinery - Electrical equipment of machines • BS EN 13445 ff / ASME VIII Unfired pressure vessels • BS EN / IEC 60079 series – Explosive atmospheres • ISO/TC 197 standards – Hydrogen systems and components. • BS EN 61508/61511 – Functional Safety Management • UK Road Law – HGV Size • PSSR 2000 • DSEAR 2002
Process Safety Considerations	Seal shocking must be ensured to maintain the valve seals. Therefore, recompression duration stated above could be too long. Trails could be conducted to ensure valve is shocked and majority of gas captured.
Monitoring Requirements	Pressure monitoring for H_2 and CO_2 operation and moisture monitoring for CO_2 operation.
Utility Requirements	*****kW – Gas engine (H_2), Generator (CO_2)
Connection Type	1" – 1.5 "

[1] This duration denotes the time required to move the inventory of gas, it does not include set up and decommissioning.

Table 4-6 : Pig Trap Recompression Deployment Strategy

Recompression Deployment Strategy: Pig Trap Venting Recompression	
Category	**Details**
Current Mode of Operation	As part of planned pigging campaigns, it is necessary to vent the pig trap several times based on the number of pigging cycles. This process results in methane being released into the atmosphere, [redacted] Current venting approach: temporary *****pipe is attached to vent valve. Pig traps recompressed in < *****mins.
Required Changes	Mobile recompression unit would have to be brought close enough for temporary hose / pipe to be connected. Onsite tie in location identified and within connection range.
Equipment Capacity	*****Nm^3/hr
New Equipment Needs	Small recompression unit, Flexible hose/connection will have to be rated to full system pressure >***** barg.
Typical Vessel Volume	*****
Recompression Efficiency	~90 %
Duration[2]	*****
Maintenance Planning Considerations	Pig trap venting occurs during pipeline maintenance campaigns, therefore, if recompression is added, several process equipment must be scheduled to be present at the same site. The addition of the recompressor adds another level of complexity where availability must be considered.
Compliance and Standards	• ISO 13631:2002 – Petroleum and natural gas industries — Packaged reciprocating gas compressors • BS EN 1012-3 Safety requirements - Process Gas Compressors • BS EN 60204-1 Safety of machinery - Electrical equipment of machines • BS EN 13445 ff / ASME VIII Unfired pressure vessels • BS EN / IEC 60079 series – Explosive atmospheres • ISO/TC 197 standards – Hydrogen systems and components. • BS EN 61508/61511 – Functional Safety Management • UK Road Law – HGV Size • PSSR 2000

[2] This duration denotes the time required to move the inventory of gas, it does not include set up and decommissioning.

	• DSEAR 2002
Process Safety Considerations	Commonly ***** pigging cycles are undertaken during one pigging campaign. This would require multiple venting/recompression cycles which could lead to more likely contaminant ingress. For pigging the drying and evacuation is another consideration on CO_2 systems. Note a recompressor would be required on the launcher and on the receiver for a pigging campaign.
Monitoring Requirements	Pressure monitoring for H_2 and CO_2 operation and moisture monitoring for only CO_2 operation.
Utility Requirements	*****kW – Gas engine (H_2), Generator (CO_2)
Connection Type	1", 2", 4"

Table 4-7 : Filters & Scrubbers Recompression Deployment Strategy

Recompression Deployment Strategy: Filters an Scrubber Venting Recompression	
Category	**Details**
Current Mode of Operation	Filters and scrubbers require routine and statutory inspections. These leads to venting yearly for condition and relief valve checks. Isolations are applied at valves either side of the unit with gas left in the remaining cavity vented out.
Required Changes	Mobile recompression unit would have to be brought close enough for temporary hose/pipe to be connected. Onsite tie in location identified and within connection range.
Equipment Capacity	*****Nm^3/hr
New Equipment Needs	Small recompression unit, Flexible hose/connection will have to be rated to full pressure of system.
Typical Volume of Unit	*****m^3
Recompression Efficiency	~90%
Duration[3]	<*****
Maintenance Planning Considerations	Due to the number of filters and scrubbers on the network, if recompression is to be utilised careful planning of which sites and which units provided the biggest value in compression must be considered.
Compliance and Standards	• ISO 13631:2002 – Petroleum and natural gas industries — Packaged reciprocating gas compressors

[3] This duration denotes the time required to move the inventory of gas, it does not include set up and decommissioning.

	• BS EN 1012-3 Safety requirements - Process Gas Compressors • BS EN 60204-1 Safety of machinery - Electrical equipment of machines • BS EN 13445 ff / ASME VIII Unfired pressure vessels • BS EN / IEC 60079 series – Explosive atmospheres • ISO/TC 197 standards – Hydrogen systems and components. • BS EN 61508/61511 – Functional Safety Management • UK Road Law – HGV Size • PSSR 2000 • DSEAR 2002
Process Safety Considerations	Due to the operational characteristics of filters and scrubbers, excessive differential pressure or high gas velocities across the filter element may cause re-entrainment of captured particulates or liquids back into the gas stream. It is therefore important that the compressor suction is taken from the downstream (clean gas outlet) side of the filter element, ensuring that only gas meeting the required cleanliness specification enters the compressor.
Monitoring Requirements	Pressure monitoring for H_2 and CO_2 operation and moisture monitoring for only CO_2 operation.
Utility Requirements	*****kW – Gas engine (H_2), Generator (CO_2)
Connection Type	1", 2", 4"

Table 4-8 : CO_2 Pipeline Recompression Opportunity

Recompression Deployment Strategy: CO_2 Pipeline Planned Maintenance	
Category	**Details**
Current Mode of Operation	Currently NGT do not operate any CO_2 pipelines. However, it is planned to repurpose some natural gas pipelines for CO_2 operation. NGT also undertaken recompression on these pipelines for NG.
Required Changes	Mobile recompression units must be capable to reach all planned pipeline maintenance sites and must be able to recompress > 90% of the vented CO_2 gas back to pipeline operating pressure.
Equipment Capacity	*****Nm^3/hr
New Equipment Needs	Compared to current pipeline recompression, additional nitrogen purging, vacuum drying and moisture measurement will be required to ensure recompressed CO_2 meets the same specification.

Typical Volume of Unit	Large sections of pipework > *****m^3
Recompression Efficiency	~90%
Duration[4]	*****
Maintenance Planning Considerations	Similar considerations to current natural gas pipeline recompression. The change is on the frequency. Venting of CO_2 is not a preferred due to the challenges around JT cooling and specification control.
Compliance and Standards	• ISO 13631:2002 – Petroleum and natural gas industries — Packaged reciprocating gas compressors • BS EN 1012-3 Safety requirements - Process Gas Compressors • BS EN 60204-1 Safety of machinery - Electrical equipment of machines • BS EN 13445 ff / ASME VIII Unfired pressure vessels • BS EN / IEC 60079 series – Explosive atmospheres • ISO 27913 / ISO 27914 • BS EN 61508/61511 – Functional Safety Management • UK Road Law – HGV Size • PSSR 2000 • DSEAR 2002
Process Safety Considerations	Moisture control of internal components of recompression skid prior to admitting CO_2 is critical to integrity.
Monitoring Requirements	Pressure monitoring for H_2 and CO_2 operation and moisture monitoring for only CO_2 operation.
Utility Requirements	***** kW – Gas engine (H_2), Generator (CO_2)
Connection Type	In line with current pipeline recompression.

4.5.2 Site Layout

- Although the **** can be integrated into AGI configurations, remote siting is recommended due to pigging requirements and ATEX considerations.
- Roadway access is required for skid placement, which is challenging for ball valves and scrubbers.
- For H_2 and CO_2 operation, pressure indicators are needed at both the skid inlet and outlet; for CO_2 only, moisture content must also be monitored. See schematics shown in Figure 4-3 and Figure 4-4.

[4] This duration denotes the time required to move the inventory of gas, it does not include set up and decommissioning.

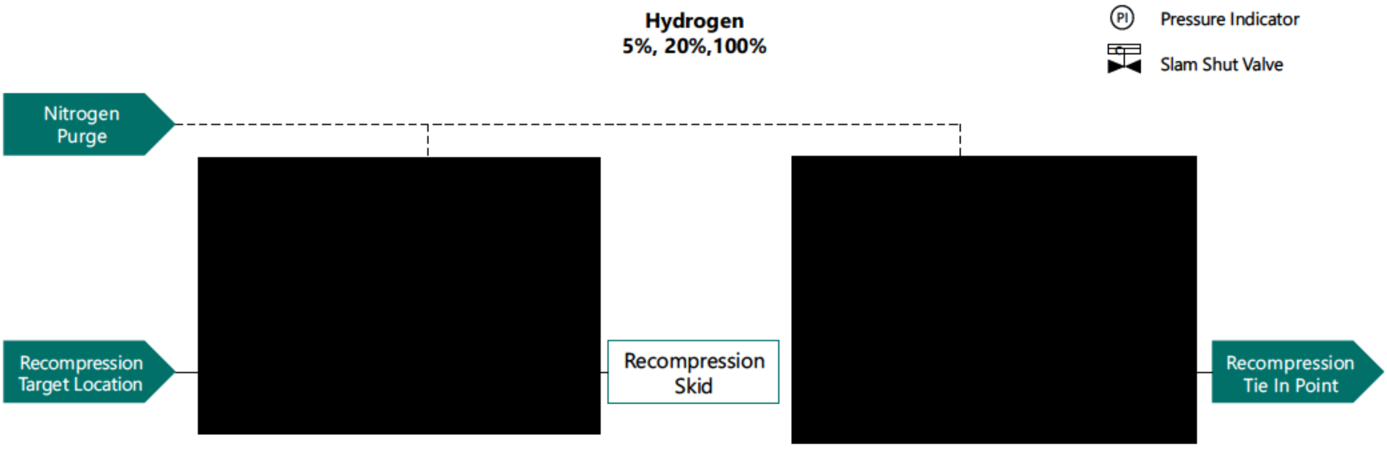


Figure 4-1 : Hydrogen Recompression Arrangement

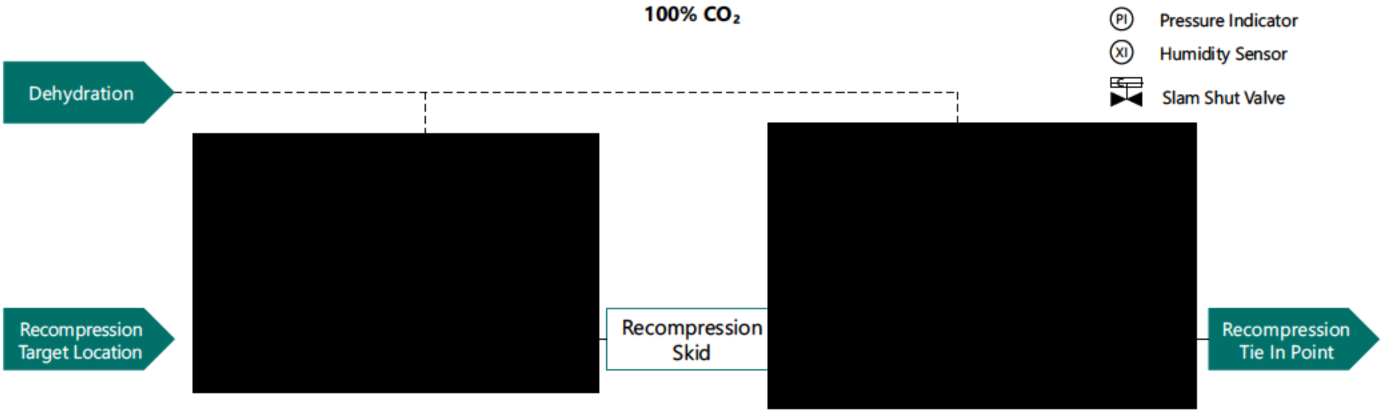


Figure 4-2 : CO_2 Recompression Arrangement

4.5.3 Gas Storage

- Using a temporary ~*** m^3 gas storage vessel or a tube trailer with similar capacity could avoid repeated tie-ins during small-volume recompression, enabling multiple cycles before reinjection, but on-site storage introduces hazards that require assessment. This may also resolve the issue of ball valve venting being too slow to activate the seals if a trail proves this is a concern.

4.6 Business Case – section redacted

4.7 CH4RGE Alignment

Given the scope of the CH4RGE project, several recompression solutions capable of servicing the entire AGI network were evaluated. The key options explored include:

- Flare Gas Recovery Units (FGRUs) which were assessed for applicability but found unsuitable due to the presence of CO_2 in the gas stream.

- Extended CH4RGE compression units, specifically larger compression units, designed for use to capture compressor casing vented gas, are deemed suitable for the recompression duties outlined in this report.
- Ejectors for locations where additional compression is required, vented gas could be used as the motive fluid to drive ejectors, thereby reducing the load on mechanical compressors.

Additionally, three AGI integration options were developed for these proposed solutions, each accompanied by schematic representations.

4.8 Mixing Off-Spec Gas in a Single Feeder

CO_2 storage offtake operators are very sensitive to off-spec gas, therefore, NGT must ensure this does not occur to avoid paying penalties. During a call with ***** it was mentioned that off-spec gas control responsibility will be placed on the gas producers, [redacted] A summary of these has been provided in the table below.

Table 4-9 : CCUS Upset Scenarios

CCUS Upset	Cause	Impurities	Likelihood	Comments
Amine System Upsets (Capture Plant)	Solvent degradation, foaming, or thermal reclaimer malfunction in amine absorbers.	H_2S, SOx, NOx, amine carryover.	Medium	Amine systems are widely used and historically prone to operational upsets and corrosion issues. Incident reviews show frequent leaks and contamination events in absorber units [8].
Dehydration Unit Failure	Glycol or molecular sieve malfunction, poor regeneration, or bypass during maintenance	Excess water → hydrate formation risk	Low	Water control is critical to avoid hydrate formation [9].
Oxygen Ingress During Maintenance	Air leaks during shutdown/start-up or poor isolation.	O_2, N_2 → corrosion acceleration.	Medium	Documented in pipeline integrity studies; often linked to human error during isolation.
Compressor Seal Failures	Mechanical seal degradation or improper lubrication.	Hydrocarbons, lubricants.	Medium	Seen in CCS transport systems; can cause phase behaviour changes and fouling.
Adsorber/Filter Breakthrough	Saturation or channelling in	SO_2, NO_2, trace hydrocarbons.	Medium	Occurs when maintenance intervals are extended or monitoring is inadequate. In

	adsorbent beds.			the presence of volatile organic components (VOCs) the lifetime of the carbon bed, if activated carbon is selected as CO_2 impurity removal technology, is reduced to 1-2 years [10].
Loss of Containment/Blowdown Events	Emergency depressurisation or rupture.	Phase segregation, dry ice formation, hydrate risk.	Low but high consequence	Rare but catastrophic; Satartia pipeline rupture (2020) is a key example.

Allowable impurity levels in CO_2 and the methods used to manage them depend on both the impurity type and the equipment in service. In practice, two major challenges arise when blending off-spec CO_2 to meet offtake specifications:

1. Because the allowable limits for reactive impurities such as H_2S, SO_x, and NO_x are extremely low, even small concentration fluctuations can result in immediate specification failures. Avoiding these breaches often necessitates blending with substantial volumes of compliant gas, which may not always be operationally practical.
2. Accurate impurity metering, particularly online, is difficult, making real-time management of off-spec conditions challenging and increasing the risk of unintentional spec excursions.

A summary of how these impurities affect recompression and venting decisions is illustrated in Figure 4-8 below.

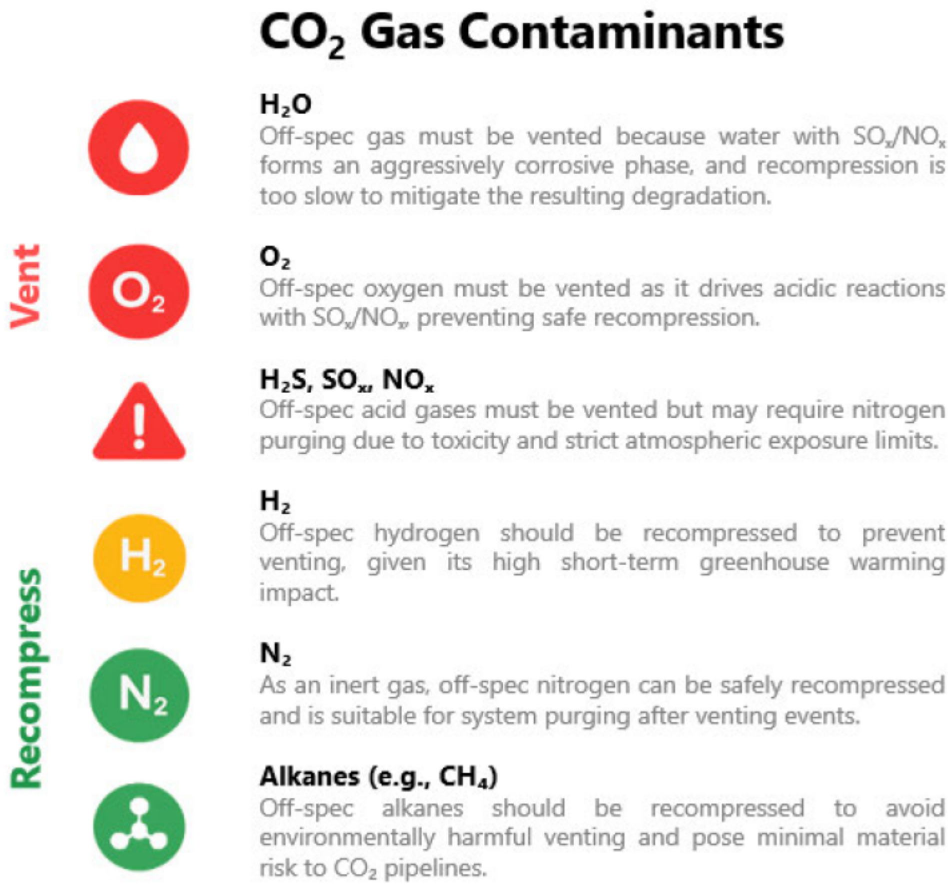


Figure 4-3 : Recompression and Venting Options for CO_2 Contaminants

5.0 Conclusion

5.1 WP 1

Through engineering, safety and operational assessments carried out on the **** it was determined that the recompression unit can be operated, without major modification at hydrogen blend levels up to 5%. Thicker wall pipework spools ([redacted]mm thick) and new valves are required to facilitate operation with 12% blends, subject to the LHV being ≥ *** MJ/Nm^3 (*** MJ/SCM). To enable safe and compliant operation at these blend levels, the following changes are summarised:

- Replacement of hoses and valves that come into contact with hydrogen-blend service.
- Revision of hazardous area classifications associated with operation of the recompression unit.
- Adjustment of safety distances related to venting activities during recompression operations.
- Updates to policies and procedures to address hydrogen-specific hazards and asset management requirements.
- Changes to operating practices to introduce indirect purging procedures.
- Updates to training programmes to ensure personnel understand hydrogen hazards and the associated safeguards.
- Reverse compression has been evaluated and is not considered an efficient or strategic application of the *****. It is therefore recommended that a dedicated stand-alone unit be procured for reverse compression scenarios.

5.2 WP 2&3

Through a scenario assessment based on NGT operations and previous Ofgem funded projects, 4 venting scenarios were identified as potential recompression candidates: (1) pig trap venting, (2) ball valve cavity venting, (3) filters/scrubber venting, (4) pipeline venting (only for CO_2 operation).

- Options are available in the market for 100% H_2 and 100% CO_2 compressors over a wide range of flowrates for recompression. On the other hand, suitable gas engine solutions remain limited, with only a small number of commercially available units capable of meeting the **** energy requirements (***) for 100% hydrogen operation. For 100% CO_2, electric driven could be the way forward, however, site supply will be the limiting factor.
- As part of the market engagement undertaken, *** provided full quotes suitable for all hydrogen recompression scenarios as well as the small-scale CO_2 cases. **** also confirmed design and build of pipeline CO_2 offering. Other vendors were found to have more limited capability or scale, particularly for pure hydrogen or CO_2 service.
- For the evacuation of hydrogen systems, nitrogen purging is required to ensure safe inerting prior to maintenance. In contrast, CO_2 recompression systems require vacuum pump-based dehydration to achieve the strict moisture control necessary for reliable operation.
- Site layout and gas storage must also be considered as typically the location of the equipment that relate to the recompression scenarios are in congested AGI locations.

- Options to extend CH4RGE could provide financial and environmental benefits without additional justification and challenges of mobile recompression options.
- Recompression could be utilised in an off-specification CO_2 event. However, in very few scenarios this would be safe as the majority of potential contaminants have disastrous effect on CO_2 pipelines.

6.0 Recommendations and Next Steps

6.1 Recommendations

- It is recommended that the HAZOP and HAZID undertaken for the new RCU are formally reviewed at the earliest opportunity to ensure hydrogen blends are fully considered and any additional safety implications are identified and addressed.
- Where reasonably practicable, future procurement of pipework and associated equipment for recompression should specify materials suitable for both natural gas and 100% hydrogen service. This will support long-term asset resilience and alignment with Net Zero objectives.
- It is recommended that dispersion modelling results are independently verified using Computational Fluid Dynamics (CFD). CFD analysis should also be used to assess potential downwash effects and impacts on nearby buildings and structures, particularly where the recompression unit may be located within more complex site layouts.
- Given that mobile hydrogen recompression is economically justified, delivers material emissions reductions, and remains robust under uncertain hydrogen blending trajectories, it is recommended that the project progresses to Pre-FEED as the next stage of development, in partnership with shortlisted technology vendors and in close engagement with NGT. A decision to proceed to FEED should be contingent on Pre-FEED confirming project economics and technical feasibility at a level of definition sufficient to support a robust investment decision.
- The Pre-Feed should ensure that integration of recompression and CH4RGE is rigorously investigated to ensure CAPEX is deployed efficiently.
- The findings indicate that recompression should be adapted as the technical solution for small scale venting of methane and hydrogen where operationally practicable. For CO_2 operations, recompression should be adopted as the preferred engineering solution to minimise emissions and operational complexity, despite negative standalone economics.
- Focus near-term procurement and technical development on vendors with demonstrated TRL 7–9 capability, particularly **** for hydrogen and CO_2 recompression. Continue market scanning to track advances in gas engines, electric drives, and moisture-management technologies.
- Evaluate opportunities to integrate mobile recompression with CH4RGE-type initiatives, site-wide compression concepts, and future RIIO mechanisms, ensuring consistency across emissions mitigation measures.

6.2 Next Steps

1. Revisit the HAZOP and HAZID undertaken for the new RCU to ensure hydrogen blends are fully considered and any additional safety implications are identified and addressed.
2. Procurement of new pipework and associated equipment (valves etc.) should be completed for recompression of blends up to 12%. Procurement activities should specify materials as suitable for both natural gas and 100% hydrogen service.
3. Training should be arranged for operations personnel involved in recompression activities to provide context and understanding of hydrogen hazards and how they differ to natural gas.

4. Progress to Pre-FEED in partnership with shortlisted technology vendors and NGT. Initiate a Pre-FEED study to refine the process design basis, validate capital and operating cost estimates to AACE Class 3 accuracy, confirm equipment specifications and procurement strategy, and establish the regulatory and permitting pathway. Vendor engagement during Pre-FEED should specifically address hydrogen material compatibility, compressor and seal specifications across variable blend concentrations, and the tube trailer collection model. The Pre-FEED should conclude with a defined recommendation on whether a pilot deployment is warranted prior to full FEED commitment, and if so identify the preferred pilot location and scope.
5. Conduct a pilot deployment on a selected site subject to Pre-FEED conclusions, by deploying a pilot recompression unit on a selected AGI to validate operational assumptions, gather empirical data on recovery efficiency, deployment duration, and gas quality management, and test the interface and permitting process with NGT. Operational learning from the pilot should be used to update the OPEX and logistics assumptions and to refine the deployment model, including the tube trailer collection concept, before wider rollout is sanctioned.
6. Develop a detailed CO_2 recompression design basis to improve understanding of venting scenarios, technical risks, and dehydration requirements specific to CO_2 streams. This workstream should be progressed in coordination with related initiatives including SCO_2T Connect to avoid duplication and ensure alignment on technical approach and commercial framing.
7. Engage with Ofgem on incentive alignment to explore how hydrogen and CO_2 recompression can be positioned as credible, scalable emissions reduction measures under future RIIO mechanisms. This engagement should be initiated in parallel with Pre-FEED so that the evolving technical and commercial case can inform regulatory discussions, and to ensure that any incentive structures being considered by Ofgem are reflected in the project business case as it develops.

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8.0 Appendix A

The TRL (Technology Readiness Levels) which has been used is shown below:

1. TRL 1 – Basic principles observed and reported
2. TRL 2 – Technology concept and/or application formulated
3. TRL 3 – Analytical and experimental critical function and/or characteristic proof of concept
4. TRL 4 – Component and/or system validation in laboratory environment
5. TRL 5 – Component and/or system validation in relevant environment
6. TRL 6 – System/subsystem model or prototype demonstration in a relevant environment
7. TRL 7 – System prototype demonstration in an operational environment
8. TRL 8 – Actual system completed and qualified through test and demonstration
9. TRL 9 – Actual system proven through successful mission operations