CO2 PIPELINE INTEGRITY MANAGEMENT: SUMMARY CLOSE-OUT REPORT

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0	06/03/2026	Draft Summary close-out report	Jacqueline Penn-Morley	Daniel Sandana	Evelyn Freitas

EXECUTIVE SUMMARY

National Gas Transmission PLC (NGT) contracted ROSEN UK Ltd (ROSEN) to collaborate on a research project entitled “Integrity Management of Gaseous Carbon Dioxide Pipelines”. The primary objective of this project was to support the development of an integrity management framework for gaseous CO_2 pipelines.

The project was divided into five Work Packages (WP), each with specific objectives:

- **WP0 – Project management:** covers the project management activities required for the duration of the project.

- **WP1 – Benchmark approaches across other CO_2 pipelines:** presents a comprehensive literature review of current knowledge relating to integrity threats specific to the transportation of CO_2 by pipeline, with a focus on gaseous-phase CO_2 as intended by NGT for use in the National Transmission System (NTS).

- **WP2 – Determine the optimised approach for integrity management for NGT:** provides a technical overview of CO_2 pipeline integrity management, based on expected operating envelopes, stream composition, and design attributes of pipelines intended for transportation of gaseous CO_2. This establishes the basis for an integrity management strategy for the National Transmission System (NTS), enabling the safe and reliable transportation of gaseous CO_2 captured from industrial sources.

- **WP3 – Identify standard updates and provide drafting:** reviews six current NGT procedure documents related to integrity management of natural gas transmission pipelines, and highlights the areas that would require updating should the procedures be applied to gaseous CO_2 pipelines. The documents reviewed are T/PM/OLI/1, T/PM/OLI/2, T/PM/OLI/5, T/PM/P/11, T/PM/P/20, T/PM/DAM/1.

- **WP5 – Non-Pipeline Assets:** assesses the potential impact of CO_2 on existing inspection, assessment, and repair procedures for non-pipeline assets.

- **WP4 – Reporting:** This work package includes the preparation of final reports delivered in Work Packages 1, 2, 3, and 5, as well as the preparation of this final summary report.

This final report provides and overview of, and summarises the key findings from, the final reports delivered in Work Packages 1, 2, 3, and 5.

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1 WORK PACKAGE 1: BENCHMARK APPROACHES ACROSS OTHER CO_2 PIPELINES

Work Package 1 presents a comprehensive literature review of current knowledge relating to key integrity issues specific to the transportation of CO_2 by pipeline, with a focus on gaseous-phase CO_2 as intended by NGT for use in the National Transmission System (NTS).This review includes:

- **Global and European CCUS Landscape**: Mapping of operational and planned CO_2 capture and transport projects, including regulatory frameworks and sectoral trends.
- **CO_2 Stream Sources and Impurities**: Analysis of impurity profiles from various industrial sources and capture technologies, and their impact on pipeline integrity.
- **Phase Behaviour and Transport Implications**: Evaluation of CO_2 phase states and how impurities influence hydraulic performance, pressure drop, and operational constraints.
- **Integrity Threats**: Detailed examination of internal corrosion, environmentally-assisted cracking (EAC), fracture propagation, and material compatibility, with emphasis on impurity driven mechanisms.
- **Integrity Management Strategies**: Review of specifications, inspection technologies, repair practices, and gaps in current standards.

Overall, the absence of robust empirical data regarding the influence of impurities on integrity threats, integrity management practices, and fracture behaviour in gaseous phase CO_2 is highlighted as a risk.

Internal corrosion is identified as a major integrity threat, particularly owing to the risk of formation and drop-out of strong acids that arise from the presence of NO_x and SO_x. Other impurities have been reported to support the formation of sulphuric and nitric acids, including (but not limited to) H_2S and O_2. Substantial research is ongoing to define safe, but also practical specifications to prevent acid formation and drop-out; most research, however, is mainly focused on dense phase CO_2. Some studies indicate that acid formation can happen at lower concentrations of NO_x and SO_x in gaseous phase CO_2.

Acid dropout from SO_x/NO_x creates highly corossive conditions. Aggressive and unstainable corrosion rates (above 10-20 mm/year) could be expected if a separate aqueous phase forms (and is continuously replenished), in both gaseous and dense phase CO_2 environments.

For environmentally-assisted cracking (EAC), hydrogen, H_2S, and CO are the principal concerns: H_2 can reduce toughness noticeably even at low partial pressures (e.g. 0.4 bar). Unlike H_2, H_2S and CO require an aqueous phase to pose a risk of EAC. Safe limits remain to be identified.

Running ductile fracture is considered less of a threat to gas phase CO_2 pipelines compared to dense phase pipelines. For gaseous CO_2 pipelines, the Battelle Two-Curve Method (BTCM) is considered an appropriate approach for determining the arrest pressure, which in turn defines the required material toughness and wall thickness. Further guidance is expected from ongoing EPRG research on fracture control for gaseous CO_2 pipelines on the use of BTCM.

Integrity management specifications may need to be tailored to operating conditions and impurity profile, as one-size-fits-all approach could risk unnecessary conservatism. Validation of specifications with sufficient experimental and/or field data would be required. Inline inspection remains essential for managing time-dependent threats. Inspection and repair methods are reviewed in greater detail in work packages 2 and 3.

2 WORK PACKAGE 2: THE OPTIMISED APPROACH FOR INTEGRITY MANAGEMENT FOR NGT

Work Package 2 builds on the findings of Work Package 1 to provide a comprehensive assessment of integrity threats and integrity management system requirements for gaseous CO_2 pipelines operating at 20–35 bar and 5–10°C with impurity profiles typical of post-combustion capture streams.

Internal corrosion driven by acid formation is identified as a serious threat for gaseous CO_2 pipeline systems. Impurities such as SO_x, NO_x, O_2 and H_2S can form strong acids and elemental sulphur even at low concentrations and well below the water dew point. While available evidence suggests that the likelihood of unmanageable acid drop-out is low within NGT's intended operating envelope, the experimental dataset is extremely limited (particularly in gaseous phase and operational envelopes typical of targeted NGT system). Where aqueous acidic phases do form, during specification excursions or operational upsets, extreme corrosion rates can occur. External corrosion risks remain broadly similar to natural gas pipelines, though accidental releases of low-temperature CO_2 may affect coating performance in localised areas.

Work Package 2 also evaluates several environmentally-assisted cracking (EAC) mechanisms. Hydrogen embrittlement and hydrogen-assisted fatigue are considered credible even at very low hydrogen partial pressures, and no safe lower limit has yet been established by industry. Sour service cracking and CO–CO_2–H_2O stress corrosion cracking remain potential threats during upset conditions with aqueous phase formation, with sour service cracking expected to pose a greater risk than CO–CO_2–H_2O stress corrosion cracking. Because most research examines impurities in isolation, current industry limits may be either overly conservative or unsafe when applied to real multi-impurity CO_2 streams. Further data is required to validate specification limits. AMPP MR0175/ISO 15156 is the conventional standard for addressing sour cracking in traditional oil and gas applications. It may be misleading if applied to CO_2 pipelines without due diligence, due to environmental differences. Though it provides a useful starting point, there are key shortfalls that are associated with the difference in environments.

Fracture behaviour in gaseous CO_2 is generally less severe than in dense-phase systems due to lower operating stress. NGT pipelines are expected to operate at ≤30% SMYS, providing a substantial buffer against running ductile fracture. Further guidance is expected from ongoing EPRG research on fracture control for gaseous CO_2 pipelines on the use of BTCM. Preliminary insights suggest that the bounding CO_2 decompression curve, even in the presence of impurities, may correspond to the following worst-case scenario: 100 mol. % at an initial pressure equal to the design pressure and an initial temperature equal to the dew point temperature. Fracture control assessments must consider the effect of impurities on decompression behaviour and the potential influence of hydrogen on material toughness.

Similarly, low-temperature brittle fracture is not expected as a result of low temperatures during controlled blowdown. Temperature is expected to remain above minimum design temperature through controlled depressurisation, though this requires confirmation via engineering assessment. The effect of H_2 on the ductile-to-brittle transition temperature is highlighted as a knowledge gap and should be considered when assessing the risk of low temperature brittle fracture.

Non-metallic materials including elastomers, coatings, and composites show potential susceptibility to swelling, rapid gas decompression (RGD) damage, and impurity-driven degradation in dense-phase CO_2. Though the risk of RGD damage is expected to be lower in gaseous phase CO_2 due to lower CO_2 absorption, material qualification data for gaseous CO_2 is sparse, highlighting a significant knowledge gap.

The proposed integrity management framework presented in Work Package 2 emphasises:

- Robust CO_2 specifications to prevent aqueous phase formation and reduce the risk of EAC.
- Monitoring of water, impurities and operating conditions.
- Defined upset response procedures.
- ILI programmes using MFL, EMAT and data fusion technologies for improved corrosion morphology characterisation.
- Risk-based inspection intervals, with higher frequency early in lifecycle until sufficient data justifies optimisation.
- Established repair methodologies, adapted from natural gas practice but with additional safety and compatibility considerations for CO_2 environments.

3 WORK PACKAGE 3: IDENTIFY STANDARD UPDATES AND PROVIDE DRAFTING

Work Package 3 (WP3) reviews six current NGT procedure documents related to integrity management of natural gas transmission pipelines and highlights the areas that would require updating should the procedures be applied to gaseous CO_2 pipelines. The recommendations are based on the findings from Work Packages 1 and 2. The procedure documents reviewed in this work package are:

[redacted]

Overall, the core engineering principles underpinning defect detection, assessment, and repair philosophies remain applicable for gaseous CO_2 service. However, the transport of gaseous CO_2 introduces specific considerations which should be reflected in the procedures; key topics include:

- **Safety:** For natural gas service, risk assessments focus on flammability, while for CO_2 the key risks to address are asphyxiation, dermal hazards such as frostbite, and toxicity. Impurities in CO_2 should also be considered.
- **Depressurisation:** Uncontrolled CO_2 decompression can cause extremely low temperatures. Controlled decompression of gas phase CO_2 from 35 bar is not expected to cause temperatures below minimum pipeline or coating design temperatures, but detailed thermodynamic modelling is required for confirmation. The risk of rapid gas depressurisation damage is expected to be low for gas-phase CO_2 pipeline operation and pigging, but further material validation is required.
- **Compressibility and impact on pigging operations:** Gaseous CO_2 is less compressible than natural gas. This means that pig velocity control is better in gaseous CO_2, but there is a higher risk of overpressure if a pig stalls. The risk of such events should be assessed with flow assurance and pigging feasibility studies before deployment.
- **Pipeline integrity:** Aside from pipeline integrity threats that are applicable to any pipeline assets, threats specific to industrial CO_2 transportation are internal corrosion and environmentally-assisted cracking due to contaminants. The impact of impurities such as hydrogen on material properties should be considered.
- **Repair methods:** Methods generally remain applicable to gaseous CO_2. Low temperatures during decompression should be considered for compatibility of repair materials. Hot tap methods remain applicable, longer heat decay cooling times should be considered. Additional care should be taken for dressing and grit blasting due to the greater risk of through-wall corrosion.

4 WORK PACKAGE 5: NON-PIPELINE ASSETS.

Work Package 5 assesses the potential impact of CO_2 on existing inspection, assessment, and repair procedures for non-pipeline assets. The scope of the study includes the following asset types: pig traps, filters above 7 bar, general pressure vessels, high pressure bulk storage, valves, shell and tube heat exchangers, and water bath heaters. Key integrity threats identified for non-pipeline assets in CO_2 service include:

- **Internal corrosion**: both general wall loss and pitting are significant integrity threats driven by the presence of separate aqueous phases, particularly the formation and drop-out of strong acids.
- **Low temperature effects**: Joule-Thomson cooling during rapid depressurisation can lead to several temperature related degradation mechanisms, including temporary reduction in fracture toughness, brittle fracture, and external coating disbondment, which may impact on operational performance and critical defect limits.
- **Hydrogen, H_2S and CO impurities**: Hydrogen may be present as a contaminant depending on the CO_2 source and specifications. Current industry consensus suggests adopting requirements consistent with gaseous hydrogen/blend applications until further research clarifies safe thresholds. In addition, H_2S impurities in the presence of water may result in sulphide stress cracking (SSC), particularly in highly stressed weld regions of pressure vessels. CO can also lead to stress corrosion cracking (SCC) when water is present, and this threat is even more prominent in the presence of oxygen (O_2).
- **Vibration induced fatigue:** Because CO_2 has a much higher density and kinetic energy than natural gas, non-pipeline assets are exposed to increased flow-induced vibration, small bore connection fatigue failures and side-branch resonance. These risks are particularly relevant to pressure reduction installations.

In CO_2 service, the detection and assessment of internal defects becomes essential. As a result, the current approach to integrity management is insufficient for CO_2 service. Recommendations for asset integrity management for CO_2 non-pipeline assets is summarised below:

1) Consideration should be given to designing pressure vessels for CO_2 service, to comply with PD5500 Category 1 or an equivalent design code (e.g. BS EN 13445 or ASME VIII) to ensure comprehensive NDT and stringent quality controls.

2) Materials should be selected with consideration to both internal corrosion risk and sour service compatibility.

3) A corrosion allowance should be defined during design based on expected service conditions, material of construction, CO_2 stream composition and design life of the asset.

4) Cycle variations associated with emitter production should be considered during design to ensure appropriate assessment of cyclic loading.

5) Asset geometry should minimise the likelihood of aqueous-phase accumulation in valves, filters and other components where cavities or low points can trap liquids.

6) Design should also facilitate ease of inspection, with particular emphasis on ensuring access to the underside regions where internal corrosion is more likely.

7) Replacement of cast filters and cast pig trap closures with forged steel alternatives should be considered, where practicable, due to inspection challenges, thickness variation and the higher defect prevalence associated with castings.

8) Fillet welds in pressure zones of forged steel assets remain critical and must meet strict acceptance criteria. Where inspection coverage is limited, the likelihood of defects occurring must be managed through robust quality assurance and quality control during fabrication.