Final report on requirements for the safe operation of repurposed natural gas pipelines for gas phase CO_2 operation

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1 Introduction

National Gas Transmission (NGT) is proposing to repurpose some National Transmission System (NTS) natural gas pipelines for the transportation of gas phase CO_2. This will require full demonstration through preparation of a safety justification that the transportation of gas phase CO_2 by pipelines can be carried out safely.

This document presents the requirements for the safety justification for the repurposing of natural gas pipelines for gas phase CO_2 service. CO_2 is a hazardous substance with complex phase characteristics. The hazardous nature poses safety risks to people, and the complex phase characteristics of the fluid require specialist modelling to assess the hydraulic behaviour on pipeline design and operation.

In the event of a release, the gaseous phase CO_2 will decompress and disperse as a heavy gas. In common with all pipelines transporting gaseous phase fluids, the energy released during decompression influences the fracture behaviour of the pipeline, the formation of a crater and the subsequent near and far field dispersion of the released fluid. The CO_2 collected from emitters will contain impurities which will affect the flow characteristics, hydraulic and decompression behaviour of the fluid, and may also affect the hazard posed to people in the event of a release.

In addition, certain impurities will impact upon the pipe integrity. The extent of these effects requires investigation and assessment as part of the demonstration that the risks associated with the pipeline are acceptable.

1.1 Approach

Gaseous phase CO_2 as a dense gas, the thermodynamic behaviour of the gas needs to be considered, taking account of the effect it will have on the integrity and failure mode of materials in the pipeline system, and the safety consequences of unplanned releases all need to be assessed.

This requires assessment of:

- Thermodynamic characteristics of gaseous phase CO_2,
- Fracture control requirements,
- Quantified risk assessment, and
- Design and integrity requirements.

2 Thermodynamic characteristics of gaseous phase CO_2

This involves the investigation, modelling and analysis of the thermodynamic behaviour of gaseous phase CO_2. This is of particular significance to understanding the behaviour of the fluid in the event of a controlled or uncontrolled release, because the energy released by the decompressing fluid provides a driving force which could possibly cause defects to propagate, and as the fluid is toxic and an asphyxiant, it presents a hazard to people over the range that it disperses.

Requirements are:

- Specification of the composition of the gaseous CO_2 (and impurities).
- Assessment of the thermodynamic and chemical behaviour and the decompression behaviour
- Controls to ensure the maximum allowable levels of impurities are not exceeded.

The thermodynamic characteristics of gaseous phase CO_2 involves: -

- Identification of the CO_2 Specification (including the levels of impurities which may be present)
- Assessment of the Thermodynamic Behaviour of Gaseous phase CO_2 with Impurities
- Chemical Behaviour of CO_2 Mixtures
- Gas Treatment and Monitoring Requirements
- Decompression Studies
- Shock Tube Tests

These characteristics are discussed in more detail below.

2.1 Identification of the CO_2 Specification (including the levels of impurities which may be present)

A worst-case acceptable specification for gaseous phase CO_2 for transmission in CO_2 pipelines has been developed from work carried out by Newcastle University for National Grid [7, 11]. The maximum permitted levels of particular impurities were defined based on

a) safety to people in the event of a release,

b) pipeline integrity, in particular, avoidance of sour conditions, and

c) effect on hydraulic efficiency.

The dryness requirements for gaseous phase CO_2 were also reviewed by Newcastle University for National Grid [11], and the report was also used to define the minimum dryness requirement for gaseous phase CO_2 pipelines to prevent free water occurring in the pipeline. Based on the above, the worst-case acceptable specification of CO_2 to be transmitted by pipeline in gaseous (or dense) phase is given in [ref 6].

[redacted]

2.2 Assessment of the Thermodynamic Behaviour of Gaseous phase CO_2 with Impurities

The thermodynamic behaviour of CO_2 (i.e. enthalpy, entropy and density changes as pressure and temperature conditions vary) is predicted using equations of state (EOS). The EOS are semi-empirical and are based on empirical data. This means that the equations of state are accurate within the experimental error associated with the measured data. Anthropogenic CO_2 contains several different impurities which influence the thermodynamic behaviour and changes the location of the phase boundary. For gaseous phase pipeline transportation of CO_2, this is of particular importance at higher pressures and lower temperatures where two-phase conditions may occur.

The concentrations of impurities are limited to low percentage volumes (typically less than 3% volume) by the specification developed for CO_2 for pipeline transportation. [redacted]

A paper has been prepared to support and justify this conclusion. [redacted]

2.3 Chemical Behaviour of CO_2 Mixtures

Gas phase CO_2 is relatively inert with respect to reaction with impurities (such as oxygen (O_2), nitrogen (N_2), carbon monoxide (CO), hydrogen (H_2), argon (AR), hydrogen sulphide (H_2S), nitrogen oxides (NOx) and sulphur oxides (SOx) which may be present as impurities in anthropogenic CO_2, so assessment of the chemical reactivity of CO_2 with impurities is not required in the gas phase. The only issue in relation to chemical behaviour in the gaseous phase is the reaction of CO_2 and some of the impurities, e.g. H_2S, with water (under a fault condition) and the resultant risk of internal corrosion, and hydrogen which may increase the rate of fatigue crack growth.

2.4 Gas Treatment and Monitoring Requirements

The gas treatment, monitoring and metering requirements must be specified. This requires confirmation whether part or all gas treatment and monitoring equipment will be supplied by NGT or by the CO_2 emitter. The process to ensure the monitoring equipment will remain effective and ensure the gas quality remains within specification will need to be carefully considered and detailed in any agreement between the CO_2 emitter and the transporter. These issues are project dependent and will be developed and agreed as part of specific project design activities.

2.5 Decompression Studies

Theoretical and experimental decompression studies are used to determine the behaviour of the gaseous CO_2 in the event of instantaneous decompression or pressure reduction. In the event of an unplanned release, the decompressing gas will generate a driving force which will affect the fracture initiation and propagation in the pipeline. The objective of decompression studies is to confirm the minimum toughness required to arrest a propagating fracture for defined pipeline geometries and operating conditions.

Specifically, this involves predicting or measuring the changes in physical parameters with time including pressure, temperature and density so that the velocity of the decompression shock wave and the mass flow of fluid released from the open pipe end or hole can be determined. These studies must also include analysis to identify the conditions under which phase changes may occur inside the pipe.

An accurate knowledge of decompression behaviour is required to establish the minimum toughness levels for shear fracture arrest. A three-stage process is required:

- initial calculation of the minimum required toughness,
- establishing high confidence of these initial results, and
- finally, validation of the predictions by shock tube testing.

Specifically, the strategy involves:

(i) Calculation of the minimum toughness using a recognised model e.g. Gasdecom which was originally developed for predicting the decompression curves of hydrocarbons, including natural gas and rich gas [1 – 5]. Gasdecom was developed specifically for use with the Battelle Two Curve Model (BTC model) which is used to obtain the toughness requirements for gas pipelines, and it has now been modified for use with CO_2. The model predicts a decompression curve for the CO_2 which is then input to the BTC model to determine the minimum required toughness for gaseous phase CO_2 pipelines.

(ii) The accuracy of the decompression curve produced by Gasdecom must be assessed using more sophisticated models [8]. The resulting curves are then compared with the curve already produced by the modified Gasdecom to provide high confidence in the calculated minimum toughness requirements.

(iii) Validation of the results using shock tube test data.

2.6 Shock Tube Tests

Decompression characteristics, in terms of pressure and temperature changes with time during decompression, can be experimentally determined from shock tube tests.

A programme of shock tube tests for pure CO_2 and CO_2 mixtures, to investigate conditions relevant to gaseous phase pipelines, has been carried out to provide validation of the decompression curve predictions referred to in the previous section, and also for validation of the phase boundary conditions (pressure and temperature) which have been used to define the maximum operating pressure and minimum operating temperature at which phase change from gaseous to dense phases will occur.

The gaseous CO_2 analytical decompression models developed by Atkins Boreas (A Cosham), UCL and Kingston University have been validated using previous work carried out by British Gas (and others) relating to rich gas in the 1980s and were used in the development of the design specification for the National Grid shock tube tests. In particular, the decompression model developed by UCL (using modern CFD methodologies) has been utilised to assess the potential sensitivity of experimental results to specific physical parameters such as the diameter of the pipe/shock tube and the roughness of the internal surface [8, 9].

3 Fracture Control

Fracture control requires consideration of fracture initiation and propagation behaviour, and pipeline codes require that adequate fracture control measures are in place for all high-pressure gas pipelines, as gas decompression (of any fluid) can provide a fracture driving force which can lead to propagating fractures if the pipe toughness specification is not adequate.

In simple terms the key requirements are: -

i) Ensuring that the material toughness is adequate to tolerate small flaws (specifically material manufacturing flaws acceptable to material Quality Assurance (QA) standards and fabrication workmanship flaws acceptable to workmanship standards). This involves ensuring that the transition temperature of the pipe and component material is known and is below the design and operational requirements.

ii) In the event of a rupture, ensuring that any fracture is ductile. This involves ensuring that in the event of a rupture, operation will be at a temperature above the brittle – ductile transition temperature of the material.

iii) The steel has sufficient energy absorption capacity (toughness) to arrest a ductile fracture. This involves ensuring the pipe material toughness is sufficient to arrest a running ductile fracture.

iv) Having in place an efficient and effective inspection, maintenance and repair strategy which will identify and repair damage (of any type including metal loss, crack like defects, gouges and dents) before it reaches a size which results in initiation and propagation. This involves understanding the defect size and type associated with different damage mechanisms. In general, this relates to sharp, crack like defects, but other defects, such as metal loss due to external or internal corrosion, may result in initiation and propagation if they are large enough or associated with a cracking mechanism. It is essential that such defects are recognised, identified by inspection, assessed and repaired before they may become an initiation/propagation threat.

Fracture initiation is associated with the critical (axial) length of a defect which will result in a rupture, and is dependent upon the pipe geometry, material properties and operating stress. Fracture propagation occurs when the energy released by the decompressing gas drives the fracture.

A fracture control plan is required as part of the design strategy for pipelines and generally involves specifying design requirements in terms of:

a) The minimum Ductile Brittle Transition Temperature (DBTT) of the material. This is confirmed by specifying appropriate Drop Weight Tear Test (DWTT) requirements (i.e.

minimum 85% shear area at the minimum design temperature). This prevents brittle fracture.

b) The minimum toughness requirements (i.e. minimum Charpy impact value) to prevent and/or arrest ductile fracture propagation.

c) Definition of limiting tolerable defect sizes for all potential damage mechanisms.

d) Specification of the inspection strategy to identify defects before the limiting size is reached, and development of defect assessment procedures and defect repair plans.

This involves the investigation of three issues:

- the material properties requirements (particularly the DWTT and Charpy impact energy) to ensure the arrest of a running shear fracture
- the failure mode (leak rupture boundary)
- the assessment of damage mechanisms.

In this respect all damage mechanisms which apply to gas pipeline must be considered including the impact of the risk of internal corrosion, which is not normally considered for natural gas pipelines.

The work programme is described below.

3.1 Material Toughness Requirements

All the previous work carried out world-wide relates to natural and rich gas pipelines has resulted in toughness specifications for line pipe which are selected to prevent extensive propagation of a fracture in the event of a pipeline failure. The DWTT prevents brittle fracture propagation; the Charpy (upper shelf energy level) prevents and/or arrests ductile fracture propagation. In addition to preventing brittle fracture propagation, compliance with the DWTT specification also ensures that brittle initiation will not occur (the DWTT exceeds any initiation requirement). Additional (Charpy) initiation requirements are specified for welds, fittings etc.

Existing knowledge associated with natural gas pipelines can be used to apply DWTT and any additional initiation requirements for welds, fittings etc, because the operating pressure and temperature envelope for gaseous phase CO_2 pipelines falls within that of natural gas pipelines. However, because the decompression behaviour of CO_2 is different to natural gas, a study is required to define the Charpy toughness levels to prevent ductile fracture propagation for gas phase anthropogenic CO_2 pipelines.

Pipeline material toughness requirements are determined using the BTC model [4,5]. The BTC model is an established, validated semi-empirical model for estimating the toughness required to arrest a running ductile fracture. The BTC model is used to compare the gas decompression pressure vs. velocity behaviour to the fracture propagation pressure vs. velocity behaviour and to determine the minimum Charpy toughness requirements for the pipeline.

The fracture propagation driving force is represented by the gas decompression curve which relates the pressure and the velocity of the decompression wave. This depends on the thermodynamic properties of the fluid, and the initial pressure and initial temperature. The resistance to the propagating fracture is represented by the fracture velocity curve which relates the pressure to the velocity of the running fracture. The fracture velocity curve is a function of the strength and toughness of the line pipe steel, and the diameter and wall thickness of the pipe. If there is a pressure condition at which the fracture velocity and the decompression wave velocity are the same, then the pressure at the crack tip remains constant and ductile fracture propagation will occur which means that the Charpy toughness of the pipe is inadequate.

Initial studies applying the BTC model to gaseous phase CO_2 with and without impurities at relevant operating conditions, have been carried out to predict toughness requirements [9,10].

The results of the decompression studies completed to date confirm there is a discontinuity ("plateau") in the decompression curve, and the pressure at which this plateau occurs and the velocity range it covers are significant in the determination of the required toughness level.

The decompression models which are being used to predict the decompression curve for gaseous phase CO_2 with impurities have been verified against validated predictions for rich gas for which shock tube tests and full-scale fracture propagation tests have been carried out. The required toughness levels derived from the BTC model using the predicted decompression curve for gaseous phase CO_2 (at pressures of 38 bar and below) are like the toughness requirements for natural and rich gas (at pressures for 70 bar and above) for the same pipeline geometries [10].

3.2 Assessment of Low Temperatures due to the Joule Thompson Effect

The low temperatures which may occur on pressure reduction due to the Joule Thompson effect of gaseous phase CO_2 and its impact on material properties is expected to be similar to that for natural gas, and further consideration of the impact of this temperature change for gaseous phase pipelines is not considered necessary.

However, a view has been expressed that leakages in CO_2 pipelines could escalate to a full-bore rupture by a process of repeated brittle fractures occurring due to localised cooling of the material around the leak as the escaping gas expands. It has also been suggested that this also applies to leaks from natural gas and ethylene pipelines, although there is no operational evidence to support the view, despite considerable experience of leaks around the world from operational pipelines. A position paper should be prepared summarising the situation, identifying any work in the public domain relating to the issue and to make recommendations on whether any additional work is required.

3.3 Risk of Internal Corrosion

The damage mechanisms which may result in the range of defects to be addressed by the measures in place for fracture control are like those affecting natural gas pipelines, with the exception of internal corrosion. If water enters the pipeline, carbonic acid will be formed which will present an internal corrosion hazard. The primary control on the impact on pipeline integrity will be achieved by ensuring the CO_2 is dry, and the presence of free water is avoided [12,16]. [redacted]

[redacted]

The specification for dry CO_2 is essential in preventing internal corrosion. It is recognised however that as a result of a system upset, CO_2 gas with a higher water content than specified, may enter the pipeline for a very short period. The likelihood of this occurring will be confirmed as part of the design work but, to be fully informed, a programme of experimental work is to be undertaken to determine the type and rate of corrosion which may occur in such a situation to:

(i) Assess the worst-case internal corrosion which may occur as a result of system upsets over the life of a pipeline.

(ii) Identify issues to be considered and quantified in HAZard IDentification (HAZID) and HAZard and OPerability (HAZOP) studies.

(iii) Identify any specific design requirements relating to minimising the risk of corrosion and requirements relating to the control, management and remediation measures to be implemented in procedures relating to operations and maintenance of CO2 pipelines.

4 Quantified Risk Assessment (QRA)

QRA is required to establish an individual risk based routeing corridor, and to confirm that the risks associated with a CO2 pipeline are As Low As Reasonably Practicable (ALARP) in accordance with the Pipelines Safety Regulations 1996. QRA is also required as an input to the Major Accident Prevention Document (MAPD) and Emergency Response Plan.

NGT has extensive experience in the application of pipeline QRA for the safe management of gas pipelines, an equivalent approach for CO_2 pipelines is required [13,14].

In summary the strategy is:

- To assess the impact of the potential damage mechanisms including internal corrosion on the probability of failure.
- To justify using the source model developed for natural gas.
- To conduct fundamental studies relating to consequences (source model), dispersion, effect of CO_2 on humans, shelter and escape assumptions and the effect of topography.
- To develop the QRA methodology and criteria and required outputs of individual risk and societal risk.
- Allowing the QRA and ALARP evaluations required by the appropriate Codes.

These studies are described below.

4.1 Failure of Gaseous Phase CO_2 Pipelines

Pipeline failures occur because of defects in or damage to the pipeline. Primary causes of pipeline defects/damage, in no order of priority, are:

- Material and construction defects.
- Corrosion (external and internal).
- External Interference.
- Ground movement or environmental loading.
- Other (e.g. overpressure, operator error, fatigue).

The failure mode occurs as a leak or a rupture, depending upon the pipeline geometry, material properties and pressure (or operating stress). Failure may be initiated by one of several damage mechanisms. The primary causes of pipeline damage are material and construction defect, external interference, external corrosion and ground movement. Secondary causes are pipeline specific and cover damage mechanisms such as overpressure, fatigue or underpressure connection (hot tap) in error. It is considered that the primary causes of defects/damage and the leak/rupture failure modes for gas phase CO_2 pipelines will be similar to those for high pressure natural gas pipelines, with the exception that internal corrosion is an additional damage mechanism.

Current pipeline failure modelling for high pressure natural gas pipelines is generally applied to gas phase CO_2 pipelines, as the failure frequency of gas phase CO_2 pipelines in the UK will be similar to that of UK high pressure natural gas pipelines providing internal corrosion is controlled. An assessment of the impact of the risk of internal corrosion on failure frequency based on the results of corrosion tests is required, and the reliability of the dryness control system in preventing upset conditions which would potentially allow wet gas into the pipeline and the effectiveness of measures to remove water and dry the gas after an upset has occurred.

4.2 Source Model

The source model relates to the pressure, temperature, velocity and phase of the discharging fluid, the alignment of the pipe ends and the crater size into which the discharging fluid enters and then egresses, and the entrainment of air in this process.

Based on discussions with experts it is considered that the existing source models which have been developed and validated for natural gas will be applicable to gas phase CO_2. [redacted]

4.3 Dispersion Model

[redacted], and the accurate prediction of dispersion behaviour is an input to the consequence model and provides information relating to concentrations of CO_2 and impurities at a distance from the pipeline with time. The information is used to define the safe separation distance from the pipeline to occupied buildings.

Based on expert advice received from industry experts GLIS and the Health and Safety Executive (HSE)) and a review of published literature, heavy gas dispersion models assuming flat earth conditions are being applied in the modelling of consequences of CO_2 releases, as near field obstacles and wind conditions dominate the dispersion. An expert assessment of these assumptions and issues which may affect gaseous phase CO_2 dispersion in the UK, including an independent assessment of the impact of topography [redacted]

[redacted]

4.5 Shelter and Escape Assumptions

The effect of shelter and the likelihood and ability of people in the vicinity of a pipeline failure with a gaseous phase CO_2 release must be considered.

Studies to assess the effect of building standards on the rate of air change within buildings, and the results used to specify the shelter assumptions applied in pipeline QRA.

The likelihood that people will try to escape from the location of a pipeline failure will depend on their awareness of danger. Awareness of danger will relate to the noise and debris throw generated by the escaping gas. The distance over which this will be hazardous is likely to be relatively small, and the need to escape and the effective direction of escape may not be evident. The ability to escape will depend on the exposure of individuals to the toxic effects of CO_2. The initial assumption is that people in the vicinity of a failure remain at that location and are exposed to the CO_2 toxic hazard at that location. This is conservative and further studies may be required.

4.6 QRA Methodology & Criteria

The primary requirements of the QRA methodology are the modelling of consequences including asphyxiation and toxic effects, escape behaviour and the value of shelter and the failure frequencies associated with expected damage mechanisms.

Criteria for individual risk should be as used to define the inner, middle and outer zones of the land use planning consultation distance for Major Accident Hazard Pipelines (MAHPs) (i.e. 10 cpm, 1 cpm and 0.3 cpm) [13, 14].

Regarding the criterion for societal risk, the societal risk FN curve (graph of the frequency F of events causing N or more fatalities) included in PD8010 Part 3 should be applied.

4.6.1 Individual Risk Transect and Minimum Distance to Occupied Buildings

The individual risk transect is the level of individual risk with distance perpendicular to the axis of the pipe. The individual risk transect is constant for constant pipe geometry, material properties and operating conditions. Current pipeline codes (PD 8010 Part 1 and IGEM/TD/1 Edition 5) use the 0.3 cpm (chances per million per year of a fatality) risk level to define the corridor over which the population density is estimated and the area type (R, S as in IGEM/TD/1) or locations (class 1 and 2 as in PD 8010 Part 1) is defined.

Note, initial studies indicated that there is unlikely to be a problem in terms of proximity distances associated with the existing pipeline as the predicted distances for CO_2 operation at 38bar are less than natural gas at 85 bar.

4.6.2 Societal Risk

CO_2 pipelines should be assessed in accordance with the requirements of PD8010 Part 3 and assessment of societal risk will be carried out using the FN criteria curve included in the code.

4.6.3 QRA Report and ALARP Demonstration

CO_2 pipelines will be operated in accordance with PD 8010 Part 1. This pipeline code requires that a QRA is carried out as part of the code requirements for the safety evaluation required for all pipelines transporting dangerous fluids. The purpose of the safety evaluation required by PD 8010 Part 1 (Annex E) is to demonstrate the risks are acceptable and ALARP.

The QRA report for the safety evaluation of a specific pipeline will refer to the individual risk transect which is to be developed for the pipeline and will present the results of a societal risk assessment of any infringements which have been identified. Where the risk analysis results indicate mitigation measures should be considered, an ALARP assessment will be carried out.

5 Pipeline Design and Integrity

The assessment of the pipeline design and integrity involves the development of the required criteria, standards, specifications and operational requirements which are essential to the safe design and operation of the pipeline which need to be referenced in the safety justification and MAPD.

5.1 Routeing Guidelines

Routeing guidelines are a basic requirement for any hazardous pipeline and involve determining the population density within a corridor centred on the proposed pipeline route, and the application of a minimum distance to occupied buildings (which may also be referred to as a separation distance). The route corridor over which the population density will be assessed will be defined by the 0.3 x 10-6 risk level, as specified in PD 8010 Part 1 and this will be calculated using the QRA methodology as described above. Population densities less than or equal to 2.5 persons per hectare will be defined as class 1 areas, population densities greater than 2.5 persons per hectare will be defined as class 2 areas. The separation distance will be defined based on an assessment of risk, hazard and engineering judgement.

5.2 Environmental Considerations

Environmental considerations involve the potential damage to the environment arising from CO_2 leaking from a pipeline, in gaseous or dense phase operation, and in particular the impact on flora, fauna, water resources and animals.

5.3 Block Valve Spacing and Leak detection

As mentioned previously, the QRA methodology and criteria are being developed in order to allow demonstration that the risk levels satisfy code requirements. This will involve using the results of the estimates of dispersion and hazard distances using existing flat earth CO_2 models and developed consequence models based on these distances to calculate the distances from the pipeline at which individual risk levels of 10 cpm, 1 cpm and 0.3 cpm will occur.

This is in turn linked to the spacing between pipeline intermediate block valves and the volume of CO_2 that would be released in the event of a major pipeline failure. QRA and dispersion results will be used to estimate block valve separation distances for new pipelines transporting both gaseous and dense phase CO_2 and to assess the need for remote actuation of block valves.

5.4 CO_2 Network Model and Hydraulic Analysis

A CO_2 network flow model is needed to analyse the volumes, flow rates and load profiles of CO_2 to be transported and to identify certain design requirements such as pipeline diameter and ideal operating envelope. Network analysis of gas phase CO_2 pipelines and pipeline networks using existing network heavy gas analysis tools (the Pipe Flow Expert package) on the basis that the CO_2 behaves as a heavy gas, and that transmission properties are not significantly affected by impurities.

Specific hydraulic analysis studies have also been carried out by Newcastle University for National Grid (ref published paper) using the specialist hydraulic analysis software packages PIPESYM and OLGA to assess transients and the impact of impurities on flow efficiency, and to provide benchmark results for the checking and verification of the network flow analysis. Predictions obtained using this software confirmed that the accuracy of the network analysis software referred to above is adequate for the level of analysis of steady state gaseous phase CO_2 pipeline networks required for feasibility studies.

5.5 Gas treatment and Monitoring Requirements

Treatment and monitoring requirements are directly related to the potential for internal corrosion arising from the presence of water and impurities which can combine leading to a risk of corrosion, and also to toxicity and consequential safety and environmental implications. An initial corrosion review has concluded that internal corrosion in gaseous phase and dense phase CO_2 pipelines can be eliminated if dry operation is maintained, and this will require treatment, monitoring and emergency shutdown facilities. Studies are required to assess the likelihood and rate of corrosion should water enter the pipeline because of a process equipment malfunction.

5.6 Metering Requirements

Pure CO_2 has been transmitted successfully in the USA for over 25 years and the process has involved metering of the gas for fiscal purposes. The specification of the CO_2 gas to be transported in NGT pipelines is different and it is necessary to investigate and demonstrate whether the presence of impurities in the gas in terms of the worst-case specification will impact on the metering efficiency. This could also, although it is considered unlikely, lead to the need for additional gas treatment to reduce or remove impurities. An initial study on metering issues carried out by GLIS concluded there is little experience in metering CO_2 and recommends that further work to assess the various technologies is carried out.

5.7 Control Philosophy

The pipeline control philosophy must be established and documented. The philosophy will need to satisfy the legal, safety and operational responsibilities and requirements of the pipeline operator. It is anticipated at this stage that the control philosophy will, as a minimum, satisfy the following requirements:

a) Control and responsibility interfaces including ownership and location of control room and pipeline control staff.

b) Limits of operating conditions, including gas specification, pressure, temperature and flow.

c) Pipeline alarms and associated procedures.

d) Ownership, operation and monitoring of gas treatment (including standby/redundancy provisions, duplicate signals etc).

e) Type, location ownership and operation of safety devices and systems.

f) Shutdown procedures and arrangements.

Full details of the control philosophy for a pipeline or a pipeline network will be developed as an integral part of the project design and recorded as part of the design record.

5.8 Material Specifications

Initial studies indicate that pipelines transporting gas phase CO_2 at 38 bar will have similar fracture control requirements to natural gas pipelines designed for 75-85 bar operation. [redacted]

In using existing natural gas assets to transport gaseous phase CO_2, the fitness for purpose of all other materials and equipment including bends, tees, sweepolets, weldolets, valves, pig traps, pig alerts etc. must be assessed. The assessment will need to assess fitness in terms of strength and toughness and also in terms of resistance to corrosion and/or operation involving a very dry gas, and will be used to confirm the specification required for such components for new pipelines.

5.9 Engineering Standards and Specifications

It is anticipated that NGT's existing suite of engineering standards and specifications, including those relating to welding, will be acceptable for application to gas phase CO_2 pipelines, but a full review should be carried out to confirm this.

5.10 Coating Requirements

[redacted]). It is assumed the coating on existing pipelines which may be used for the transmission of gas phase CO_2 are acceptable.

Special requirements relating to internal coating are unlikely to be required if the risk of internal corrosion is low. This assumption depends on the assessment of the reliability of the water removal process to be installed and the results of experimental work relating to corrosion rates should water be passed into the system as part of a short duration process failure.

5.11 Major Accident Prevention Document (MAPD)

The MAPD deals with the operator's aims and principles of actions for the control of all aspects of design, construction and installation, operation, maintenance and final decommissioning which have a bearing on the health and safety arrangements with respect to the control of major accident hazards.

NGT has an MAPD and safety management system(s) in place for its high-pressure natural gas pipelines and it is anticipated that many aspects will be equally applicable to CO_2 pipelines, but a specific CO_2 MAPD will need to be drafted. It is noted that design issues which have safety implications have already been identified (see above).

Operation and maintenance issues will need to be reviewed, in particular the following areas will require attention:

a) Identification of all hazards with potential to cause a major accident

This will be obtained from the pipeline QRA.

b) Specifications and Procedures

Assessment of the adequacy of existing National Grid specifications and procedures including safety requirements and the need for the implementation of amendments and/or new procedures.

c) Operations and Maintenance

Assessment of the adequacy of the existing philosophy applied to natural gas pipelines and identification and implementation of any required amendments and/or additions.

d) Integrity Monitoring including Assessment of In Line Inspection (ILI) Tools

Assessment of the adequacy of the existing philosophy applied to natural gas pipelines is required and identification, including internal and external corrosion control arrangements and ILI arrangements and implementation of any required amendments and/or additions.

e) Repairs Methods and Materials

Assessment of the suitability of existing procedures relating to categorisation of damage and defect acceptance levels, the suitability of repair methods applied to natural gas pipelines and the availability of any special materials or emergency repair equipment. Particular attention to the requirement for repair of leaking pipelines which may have internal corrosion is required.

f) Emergency Plans and Procedures

Development of CO_2 specific emergency plans and procedures. These must be in place prior to commissioning of the pipeline to gas phase CO_2 service.

g) Organisation, Competence and Training

Assessment of organisational needs, including competence and training requirements required in connection with the safe management and control of CO_2 pipelines, including all routine and emergency operations.

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