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Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems

Captage du dioxyde de carbone, transport et stockage géologique — Systèmes de transport par conduites

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

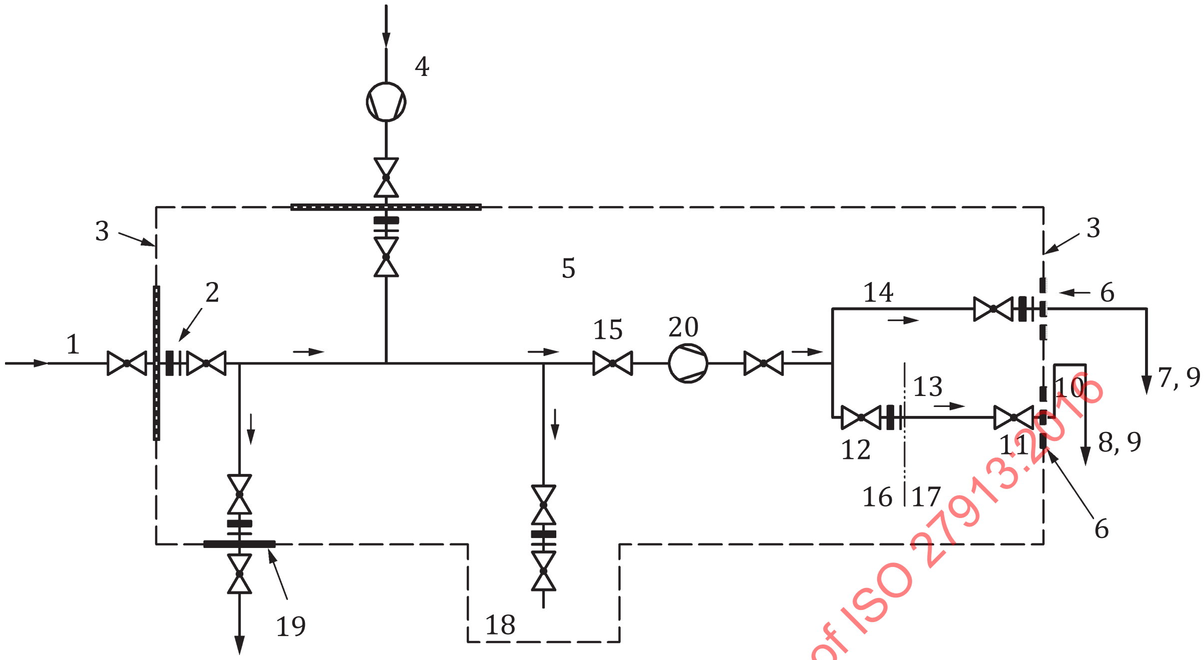
The committee responsible for this document is ISO/TC 265, *Carbon dioxide capture, transportation, and geological storage*.

Introduction

Carbon dioxide (CO_2) capture and storage (CCS) has been identified as a key abatement technology for achieving a significant reduction in CO_2 emissions to the atmosphere. Pipelines are likely to be the primary means of transporting CO_2 from the point-of-capture to storage (e.g. depleted hydrocarbon formations, deep saline aquifers), where it will be retained permanently or used for other purposes [e.g. Enhanced Oil Recovery (EOR)] to avoid its release to the atmosphere. While there is a perception that transporting CO_2 via pipelines does not represent a significant barrier to implementing large-scale CCS, there is significantly less industry experience than there is for hydrocarbon service (e.g. natural gas) and there are a number of issues that need to be adequately understood and the associated risks effectively managed to ensure safe transport of CO_2. In a CCS context, there could be a need for larger CO_2 pipeline systems in more densely populated areas and with CO_2 coming from multiple sources. Also, offshore pipelines for the transportation of CO_2 to offshore storage sites are likely to become common.

The objective of this document is to provide requirements and recommendations on certain aspects of safe and reliable design, construction and operation of pipelines intended for the large scale transportation of CO_2 that are not already covered in existing pipeline standards such as ISO 13623, ASME B31.4, EN 1594, AS 2885 or other standards (see Bibliography). Existing pipeline standards cover many of the issues related to the design and construction of CO_2 pipelines; however, there are some CO_2 specific issues that are not adequately covered in these standards. The purpose of this document is to cover these issues consistently. Hence, this document is not a standalone standard, but is written to be a supplement to other existing pipeline standards for natural gas or liquids for both onshore and offshore pipelines.

Transport of CO_2 via ship, rail and road is not covered in this document.



Key

1 source of CO_2 from capture, e.g. from power plant, industry; see ISO/TR 27912 (capture)
2 isolating joint
3 boundary limit
4 other source of CO_2
5 ISO 27913 (transportation system inside)
6 boundary to storage facility
7 onshore storage facility
8 offshore storage facility
9 EOR
10 riser (out of transport scope)
11 subsea valve (inside transport scope)
12 beach valve
13 offshore pipeline
14 onshore pipeline
15 valve
16 landfall
17 open water/sea
18 third party transport system
19 export to other uses than 7, 8 and 9
20 intermediate compression or pumping

Figure 1 — Schematic illustration of the system boundaries of this document

Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems

1 Scope

This document specifies additional requirements and recommendations not covered in existing pipeline standards for the transportation of CO_2 streams from the capture site to the storage facility where it is primarily stored in a geological formation or used for other purposes (e.g. for EOR or CO_2 use).

This document applies to

— rigid metallic pipelines,

— pipeline systems,

— onshore and offshore pipelines for the transportation of CO_2 streams,

— conversion of existing pipelines for the transportation of CO_2 streams,

— pipeline transportation of CO_2 streams for storage or utilization, and

— transportation of CO_2 in the gaseous and dense phases.

The system boundary (see Figure 1) between capture and transportation is the point at the inlet valve of the pipeline, where the composition, temperature and pressure of the CO_2 stream is within a certain specified range by the capture process or processes to meet the requirements for transportation as described in this document.

The boundary between transportation and storage is the point where the CO_2 stream leaves the transportation pipeline infrastructure and enters the storage infrastructure.

This document also includes aspects of CO_2 stream quality assurance, as well as converging CO_2 streams from different sources.

Health, safety and environment aspects specific to CO_2 transport and monitoring are considered.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3183:2012, *Petroleum and natural gas industries — Steel pipe for pipeline transportation systems*

ISO 20765-2, *Natural gas — Calculation of thermodynamic properties — Part 2: Single-phase properties (gas, liquid, and dense fluid) for extended ranges of application*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
arrest pressure
internal pipeline pressure where there is sufficient mechanical strength to arrest or, there is not enough energy to drive a *ductile fracture* (3.8)

3.2
CO_2 stream
stream consisting overwhelmingly of carbon dioxide

3.3
corrosion allowance
extra wall thickness added during design to compensate for any reduction in wall thickness by corrosion (internal/external) during the design operational life

3.4
critical point
highest temperature and pressure at which a pure substance (e.g. CO_2) can exist as a gas and a liquid in equilibrium

Note 1 to entry: For a multicomponent fluid mixture of a given composition, the critical point is the merge of the bubble and the dew point curves.

3.5
critical pressure
vapour pressure at the *critical temperature* (3.6)

Note 1 to entry: The critical pressure for pure CO_2 is 7,28 MPag.

3.6
critical temperature
temperature above which liquid cannot be formed simply by increasing the pressure

Note 1 to entry: The critical temperature of pure CO_2 is 304,03 K.

3.7
dense phase
CO_2 in its liquid or supercritical phases

3.8
ductile fracture
mechanism which takes place by the propagation of a crack or stress-raising features, linked with a considerable amount of plastic deformation

Note 1 to entry: A “ductile fracture” is sometimes referred to as “shear fracture”.

3.9
flow coating
internal coating to reduce internal roughness, and hence minimize friction pressure loss

3.10
fracture arrestor
additional pipeline component that may be installed around portions of a pipeline designed to resist propagating fractures

Note 1 to entry: Fracture arrestor is also called crack arrestor.

3.11
free water
water (pure water, water with dissolved salts, water wet salts, water glycol mixtures or other mixtures containing water) not dissolved in the gaseous or dense CO_2 phase, i.e. a separate water phase

3.12
internal cladding
pipe with internal metal liner where the bond between the line pipe and liner is metallurgical

3.13
internal lining
pipe with internal coating where the bond between the line pipe and coating is mechanical

3.14
maximum design temperature
highest possible temperature to which the equipment or system may reasonably be exposed locally during installation and operation

3.15
maximum operating pressure
highest possible pressure to which the equipment or system may reasonably be exposed locally during installation and operation

3.16
minimum design temperature
lowest possible temperature to which the component or system may reasonably be exposed locally during installation and operation

3.17
minimum operating pressure
lowest possible pressure to which the equipment or system may reasonably be experienced locally during installation and operation

3.18
non-condensable gases
chemical substances that are partially in the vapour state at pipeline operating conditions

3.19
operating envelope
limited range of parameters over which operations will result in safe and acceptable performance of the equipment or system during operation

3.20
pipeline commissioning
activities associated with the initial filling and pressurization of the pipeline system with the fluid to be transported

3.21
pipeline dehydration
process of removing water from a *CO_2 stream* (3.2) to a level below saturation such that the design maxima for the transportation system can be achieved

3.22
pipeline dewatering
removal of water after hydraulic testing of the pipeline system

3.23
rapid gas decompression
phenomenon brought about by a fluid migrating at a molecular level into a polymer, and collecting as a bubble and bursting following pressure reduction

3.24
saturation pressure
pressure of a vapour which is in equilibrium with its liquid at a given temperature

Note 1 to entry: The term “saturation pressure” is also referred to as “saturation vapour pressure”.

3.25
short-term storage reserve
accumulation of the fluid in a pressurized section of a pipeline additional to the fluid that is extracted from the pipeline, for the purpose of temporary storage of that fluid

3.26
threat
activity or condition that alone or in combination with others has the potential to cause damage or produce another negative impact if not adequately controlled

3.27
triple point
temperature and pressure at which three phases (gas, liquid and solid) of a substance coexist in thermodynamic equilibrium

4 Symbols, abbreviated terms and units

4.1 Symbols

C_V	Notched-bar impact value of the pipeline steel (J)
c_{cf}	Correction factor (--)
E	Young's modulus (MPa)
A_C	Test patch = 80 mm^2
σ_f	Flow stress (MPa)
R	Average pipe radius (mm)
t	Minimum wall thickness of the pipe (mm)
σ_a	Arrest stress (MPa)
Ps	Maximum saturation pressure (gauge pressure) in MPag; for pure CO_2 critical pressure = 7,28 MPag
OD	External diameter of the pipe (mm)

4.2 Abbreviated terms

CCS	Carbon dioxide Capture and Storage
EOR	Enhanced Oil Recovery
GERG	Groupe Européen de Recherches Gazières (European Gas Research Group)
IMP	Integrity Management Plan
MAOP	Maximum Allowable Operating Pressure
PIG	Pipeline Inspection Gauge
SCADA	Supervisory Control And Data Acquisition
SI	Système International d'unités (International System of Units)

4.3 Units

All units used in this document are SI units.

5 Properties of CO_2, CO_2 streams and mixing of CO_2 streams influencing pipeline transportation

5.1 General

It shall be considered in accordance with ISO 20765-2 that pure and impure CO_2 have properties that can be very different from those of hydrocarbon fluids and can influence all stages of the pipeline life cycle.

The thermodynamic and chemical behaviour of pure CO_2 can be found in literature (see, for example, Reference [50]). In the usual operating envelope for CO_2 transportation, the temperature and pressure will vary and will be project-specific. CO_2 can be in the gaseous or dense phase. There is a large change in density between gaseous and dense phases when the CO_2 is close to the saturation pressure, and for this reason, operation close to the saturation condition should be avoided.

In case two-phase flow cannot be avoided for any reason, it should be given special consideration during design and operation (see References [25] and [52]).

The following subclauses are intended to inform the designer and pipeline operator on how to decide on the correct parameters to be used to avoid negative impacts on the pipeline integrity.

Impurities within the CO_2 stream can result in negative impacts on the pipeline integrity. As a part of the design process, limits shall be specified for the maximum levels of impurities within the CO_2 stream, and robust measurement equipment shall be installed to monitor the composition against this specification prior to its entry into the pipeline. Annex A provides further information on this.

5.2 Pure CO_2

5.2.1 Thermodynamics

The thermodynamic properties of CO_2, particularly the saturation pressure, shall be taken into account because they have a significant impact on the design of the pipeline. If the MAOP is above the critical pressure, then the critical pressure shall be used as the principal parameter in the design. This avoids ductile fracture in the wall of the line pipe unless the operating envelope with regard to pressure and temperature is such that it can be demonstrated that the pressure and temperature at the saturation line are always below the critical pressure and critical temperature. For other parameters, the MAOP shall be used as described in 7.3.

5.2.2 Chemical reactions and corrosion

With pure CO_2, there will be no chemical reactions or internal corrosion in the pipeline.

5.3 CO_2 streams

5.3.1 Thermodynamics

It shall be considered that the phase diagram and the physical and chemical properties will change depending on the CO_2 stream composition, leading, amongst other things, to changed values of the saturation pressure compared to pure CO_2. The highest value of the saturation pressure shall be the principal design parameter to avoid ductile fracture, unless the operating envelope with regard to pressure and temperature is such that it can be demonstrated that the pressure and temperature at the saturation line is always below the critical pressure and critical temperature. This saturation pressure for the specific stream may be determined by use of the GERG formula (see ISO 20765-2) or any other similarly validated formulae or other validated methods which are appropriate for the specific CO_2 composition, e.g. Reference [37].

5.3.2 Chemical reactions

The different impurities within a CO_2 stream shall be taken into account because they have the potential of reacting together to form other compounds. The presence of these other compounds has the potential to affect the thermodynamic properties of the CO_2 stream. The worst case will result in a free water phase, solid deposition or corrosion. These potential effects should be modelled or confirmed experimentally.

5.4 Mixing of CO_2 streams

The connection of new sources to an operating pipeline system could result in the CO_2 stream no longer meeting the previous design specification and shall be subject to a design review to ensure that the changed composition is still appropriate for the pipeline design and operation.

6 Concept development and design criteria

6.1 General

This clause includes requirements and recommendations related to design issues that are specific to CO_2 and that are usually considered as part of the pipeline concept phase.

CO_2 pipelines shall be designed in accordance with industry recognized standards and applicable regulatory requirements.

6.2 Safety philosophy

Safety is ensured in different ways in different countries. Some countries use risk-based and probabilistic design and operation philosophies, others use deterministic concepts. These concepts can be found in existing pipeline standards such as ISO 13623, EN 1594, AS 2885, or other standards (see Bibliography). Hence, for risk assessment, risk management and hazard identification, the designers and pipeline operators should refer to these pipeline standards.

In cases where, in the design of the pipeline, the existing pipeline standards require a classification of the fluid with respect to potential hazards to public safety, the differences in hazards shall be recognized compared to other fluids, e.g. natural gas. It shall be considered that there is limited statistical data relevant to CO_2 pipelines, e.g. Reference [56]. Users should be aware that because of the different design criteria and operational conditions, other pipeline incident databases, e.g. for natural gas pipelines, may not accurately reflect the situation appropriate to CO_2 streams. Therefore, they should be used with caution.

Failure statistics for onshore and offshore pipelines shall be considered separately, particularly in relation to the causes of external third party damage. Statistical databases relevant to the application should be used but if data assembled in a different nation or geographical region are used, appropriate factors shall be applied where there are differences in design approach. For instance, requirements for minimum ground cover of a pipeline can vary from one country to another, as a result of which the frequency or severity of damage to the pipeline by third parties can correspondingly also vary.

The frequency analysis should examine the available historical incident data in detail to extract and use the most relevant data for a particular CO_2 pipeline project. When applying failure statistics, the designer shall consider pipelines designed according to equivalent codes.

Incident data from other relevant pipeline systems may also be consulted and assessed carefully as input to any frequency analysis. Examples could include data from the Bibliography.

For internal failure mechanisms, such as corrosion, the application of pipeline failure statistics should be made with caution and only be applied on the basis that there is adequate control of the water and acid dew point of the CO_2 stream. The lack of dew point control is expected to increase the potential for failure in the CO_2 pipelines as the internal corrosion rate increases significantly.

6.3 Design criteria

The design specification shall be consistent and aligned throughout the whole process from CO_2 production to storage, e.g. the specification of impurity limits in the CO_2 stream shall be adequately considered.

6.4 Reliability and availability of CO_2 pipeline systems

In assessing the reliability and availability of a pipeline, it shall be considered that the reliability or availability of one part of the process from CO_2 production to storage has design and operational impact on other parts. When assessing the availability of a component within the pipeline system, due attention should be paid to the operational interdependency with other components, because the components of a pipeline system including pumps and valves are necessarily very interdependent. Due attention should also be paid to the provision of redundancy or diversity for key components in order to provide high operational availability and to avoid shut-in CO_2 or the need to vent pipeline volumes between valves.

6.5 Short-term storage reserve

Short-term storage within the pipeline can be used as a buffer to smooth out some variations in CO_2 deliveries and receipts. The extent to which short-term storage reserve and other buffering solutions may be used should be reviewed and optimized against other project drivers both in the design phase of a project as well as during operations.

Consideration should be given to the limited availability of short-term storage reserve in dense-phase pipeline systems. More short-term storage reserve capability is possible in gaseous phase pipeline systems.

6.6 Access to the pipeline system

Any third party access to an existing or proposed pipeline shall conform to the requirements of this document.

6.7 System design principles

6.7.1 General

The general design principles are defined in existing standards for oil and gas pipelines. In addition to these, the following design principles shall apply for CO_2.

6.7.2 Pressure control and overpressure protection system

A pressure protection system shall be used unless the pressure source to the pipeline cannot deliver a pressure in excess of the incidental pressure including possible dynamic effects.

For a pipeline operated in the dense phase, the pressure control system shall be designed to ensure that the dense-phase condition is retained both within the operating envelope (see 3.24), reduced flow rate and in a pipeline shut-in situation.

Unless the materials of the pipeline or pipeline system are selected to accommodate such a situation, the pressure control system should be configured to ensure that there is a sufficient margin to free water formation (see 6.8) in case of a pipeline shut-in condition.

Venting of CO_2 to atmosphere to restore pressure levels within a pipeline is permissible, but the design shall ensure that any venting does not lead to significantly higher exposure of personnel to adverse impacts, or significantly affect the environment. The phase changes of the vented CO_2 and subsequent dispersion of the resultant plume should be modelled as described in Annex B to ensure this.

6.8 Pipeline dehydration — General principles

6.8.1 Particular aspects related to CO_2

It should be taken into account that adequate pipeline dehydration of the CO_2 stream is essential for corrosion control (see 7.1) and to reduce the potential for hydrate formation (see 6.8.3).

NOTE As pipeline dehydration is part of capture process, refer to ISO/TR 27912.

6.8.2 Maximum water content

Water content should be specified in terms of parts per million on a volume basis (ppmv) and the maximum concentration should be determined such that hydrates will not form and corrosion and solids formation will be within design margins. The maximum water content will depend on the operational conditions and should be specified on the basis of relevant field experience, reliable experimental data or experimentally verified models. For further information, see Annex A.

6.8.3 Avoidance of hydrate formation

The potential for hydrate formation both in gaseous and dense-phase CO_2 shall be considered with reference to the water content in the CO_2 stream.

In addition to the potential for forming CO_2 hydrate, the potential for forming hydrates from other non-condensable components shall be considered.

The potential for forming hydrates during pipeline commissioning or re-start shall be considered with reference to the pipeline dewatering procedure and potential for residual water in the pipeline after pressure testing.

The primary strategy for hydrate prevention should be sufficient dehydration of the CO_2 stream prior to it entering the pipeline system. Water content should be controlled and monitored at the inlet of the pipeline system.

6.8.4 Reliability and precision of pipeline dehydration

Valid calibration certificates should exist for the water monitoring system. Calibration should be performed, taking the project-specific CO_2 stream into account, as other impurities within the stream may influence the readings. The reliability could be improved by using two separate water monitoring systems.

The speed of response to the detection of “out-of-specification” water content should be defined based on an appropriate assessment of the consequences.

6.9 Flow assurance

6.9.1 Particular aspects related to CO_2 streams

With reference to flow assurance, the following particular issues should be considered:

— effect of CO_2 stream temperature and pressure on flow capacity;

— effect on topographic characteristics, such as elevations for vapour pressure and valleys for overpressure;

— transportation in gaseous or dense phase;

— hydrate formation, potentially causing pipeline blockage or corrosion.

Two-phase flow should be avoided in a pipeline system to reduce the risks associated with unpredictable phase changes taking place. These phase changes can occur at different times or locations along the pipeline route, dependent on the temperature, pressure and composition.

In case two-phase flow cannot be avoided for any reason, it should be given special consideration during design and operation (see References [25] and [52]).

6.9.2 Thermo-hydraulic model

In the pipeline design, an experimentally verified thermo-hydraulic model should be used to investigate

— impacts of topography,

— pressure surge,

— free water drop-out,

— release scenarios — controlled and accidental (venting),

— pipeline shut-in and start-up,

— pipeline depressurization,

— heat transfer to the surroundings,

— part-operating characteristics (pressure losses, potential for phase changes) (see Clause 9),

— variations in ambient temperatures (air, ground and sea, but note lower impact offshore),

— transient and cyclic operation and short-term storage reserve, and

— pressure and performance testing of valves and equipment.

The thermo-hydraulic model should, as a minimum, be able to account for

a) two-phase single and multi-component fluid, and

b) steady-state conditions.

6.9.3 Pipeline design capacity

When determining pipeline capacity, consideration should be taken for any short-term storage reserve strategy for smoothing out upstream or downstream transients, noting that the impact of such pressure fluctuations shall be taken into account when assessing the fatigue life of the pipeline and its associated components.

It shall be considered that increasing the concentration of impurities in the CO_2 stream will generally reduce the flow capacity of the pipeline, depending on the type, quantity and combination of the impurities. This will have implications on the required pipeline sizing (e.g. pipeline wall thickness) or inlet pressure or distance between intermediate pump stations.

Recognized thermo-hydraulic tools and suitable physical property models for the composition of the CO_2 stream shall be applied and documented for determination of the pipeline flow capacity.

The pressure throughout the pipeline system should be optimized during the design phase, as a CO_2 stream arriving at the injection point at a pressure that is significantly above the required injection pressure will result in wasted energy.

6.9.4 Reduced flow capacity

In addition to the designed flow capacity, it shall be documented through thermo-hydraulic analysis that the pipeline is able to operate at a reduced flow without significant operational constraints or upset conditions being experienced.

6.9.5 Available transport capacity

Seasonal, daily and weekly variations in ambient temperature shall be considered in the thermo-hydraulic design process due to its effect on the density of the CO_2 stream.

Effect of temperature (seasonal variations) is likely to be more pronounced for onshore pipelines compared to offshore pipelines, however, depending on geographical location.

6.9.6 CO_2 temperature conditions

Due to the significant reduction in density of a dense-phase CO_2 stream with increasing temperature, the temperature at the upstream boundary limit (i.e. post-compression/pumping) of the pipeline should be minimized. Cooling of the CO_2 stream after intermediate compression can significantly increase the capacity of the pipeline.

6.9.7 Internal lining

Application of an internal lining to reduce pressure drop or for other purposes is generally not recommended due to the following:

— detachment of the internal lining in a pressure reduction situation, due to diffusion of CO_2 into the space between the lining and steel pipe during normal operation or due to low temperature during depressurization. It should be noted that the decompression effects may be gradual, i.e. start as blistering and ultimately cause full detachment;

— damaged lining can be transported to the receiving facilities, causing process upsets or plugging of injection wells;

— the difficulties associated with providing consistent internal lining over site welded joints: inferior linings can lead to preferential corrosion sites being set up.

If an internal lining is applied, the material shall be qualified for compatibility with CO_2 streams and the ability to withstand relevant pipeline decompression scenarios.

6.9.8 External thermal insulation

It should be taken into account that for a pipeline, the heat ingress from and egress to the surroundings is determined by the difference between the ambient temperature and the temperature of the CO_2 inside the pipeline, combined with the insulation properties and burial depth of the pipeline. In case the temperature difference is too large, thermal insulation might be considered necessary to protect the environment or the CO_2 stream.

The implications of thermal insulation on minimum pipeline temperature in a depressurization situation should be considered.

6.9.9 Leak detection

Wherever applicable, a leak detection system is recommended, unless justified otherwise by a safety evaluation. Automated pipeline monitoring is the most widely used technique for leak detection. These methods use flow, pressure, temperature and other data provided by a SCADA system, and can be divided into five main types:

— flow or pressure change;

— mass or volume balance;

— dynamic model based system;

— pressure point analysis;

— temperature change.

6.10 Pipeline layout

6.10.1 Valve stations

The pipeline layout and facilities for depressurization shall be considered in the design phase of the valve stations.

6.10.2 Block valves

For onshore pipelines, the location and performance requirements of intermediate block valves should be based on local legal requirements (if any).

6.10.3 Check valves

The pipeline layout and facilities for depressurization shall be considered in the design phase of the valve stations. Rapid closing (automatic) check valves (if any) may assist in reducing the volume of released product during a release event, but can cause hydraulic shocks.

6.10.4 Pumping and compressor stations

Dependent on local conditions along the pipeline route, intermediate compressor or pumping stations could be needed as a part of the pipeline system (see Figure 1). For a natural gas pipeline, the transported fluid can act as a source of chemical energy for compressor or pump stations. This is, however, not the case for CO_2 pipelines, but the pressure energy within the CO_2 stream could be used, e.g. to remote control valves. It should be understood that power and signal/control availability can influence the optimal location of pump and compressor stations.

6.10.5 Pigging stations and pigging

CO_2 pipelines shall be designed such that in line inspection (pigging) is possible, and pipeline standards available elsewhere should be used in the design to ensure that this is the case (e.g. ensuring minimum bend radii). PIG launchers or traps may be either temporary or permanent. The primary purpose of the PIG launcher/trap is to enable pipeline dewatering and fingerprinting during pipeline commissioning and internal inspection during operation. A particular aspect related to CO_2 streams is materials selection (see Clause 7). Atmospheric vents from the PIG station shall be designed in such a way that ground level concentrations of CO_2 and any associated impurities do not reach harmful levels during depressurizing operations (see 9.2.3).

6.10.6 Onshore vent facility design

At every onshore valve station, permanent vent facilities should be installed where appropriate for operational flexibility.

As a minimum requirement, one permanent vent facility shall be included to depressurize the pipeline system. As a general recommendation, each vent facility should have the capacity to depressurize the volume between block valves, also taking into account the integrity of the pipeline and any other safety considerations related to the release of CO_2.

Vents should be designed and located in a way that their operation does not result in unacceptable impacts to personnel or the environment.

The vent stack may be equipped with a flow control valve connected to a temperature gauge. The set point for the control valve should be selected with a sufficient margin to the minimum pipeline design temperature so as to prevent the pipeline being exposed to the sub-design temperature during venting.

An alternative to temperature control is pressure control since the temperature relationship with pressure can be determined.

Dominant wind directions and topography effects should be considered when selecting the location and orientation of vent stacks.

The height of a vent stack should be assessed based on

— operational means,

— health and safety issues,

— environmental impacts (including noise), and

— geographical location.

Consideration should be given to the vent tip design so that air mixing at the vent tip is maximized.

It is recommended that pipeline blow-down valves should be remotely operated and opened slowly such that adverse effects as a result of Joule-Thomson cooling are avoided. Pipeline metal temperatures should not be allowed to fall below the minimum temperature recommended by material standards.

Seal materials and lubricants should be selected in accordance with the recommendations given in 7.2.3 and 7.2.4.

Consideration should be given to the potential for the noise produced during venting operations to affect people living or working in close proximity to the vent facilities. In addition, consideration should be given to the potential effects of noise attenuation equipment on the exit velocity and dispersion of the CO_2 stream.

Additional onshore vent facilities may either be permanent or temporary. Temporary vent facilities may be portable for the purpose of depressurizing sections of the pipeline for inspection, maintenance or repair.

6.10.7 Offshore vent facilities

If it is necessary to vent down completely a subsea pipeline, consideration should be given to do this from the upstream end (i.e. land), where control is easier to exercise.

7 Materials and pipeline design

7.1 Internal corrosion

CO_2 pipelines should be designed for corrosion to be within design margins under normal operational conditions. For upset conditions, a corrosion management plan shall be developed as part of the design. Its scope shall include a plan to recover from failure of the control. Failures can occur upstream of or within the pipeline system. For additional information, see Annex C.

7.2 Line pipe materials

7.2.1 General

The selection of materials should be as described in ISO 3183 or other applicable standards and be compatible with all phases of the CO_2 stream.

Candidate materials need to be qualified for the potential low temperature conditions that could occur during pipeline system commissioning, operation, decommissioning or recommissioning.

7.2.2 External coating

The design of the external coating of CO_2 pipelines shall be designed in the same way as that for natural gas pipelines.

After any incidental or uncontrolled depressurization, the external coating of the pipeline should be examined to ensure that its design integrity has not been compromised, and the effectiveness of the cathodic protection should also be confirmed.

The insulation properties of the external coating, including burial depth, should be considered as part of the overall pipeline heat transfer coefficient. Effect of coating on the temperature for the CO_2 stream should also be considered for planned or unplanned depressurization of the pipeline (see 6.9.8).

7.2.3 Non-metallic materials

For the selection of non-metallic materials, it shall be considered that high partial pressure CO_2 streams cause different types of deterioration mechanisms, in particular, rapid gas decompression of some non-metallic materials in contact with the CO_2 stream (e.g. O-rings, seals, valve seats, PIGs) when the pressure is reduced from the dense phase to the vapour or gaseous phase of the CO_2 stream. Non-metallic materials shall be qualified to ensure

— ability to resist rapid gas decompression,

— chemical compatibility with the CO_2 stream (see Clause 5) without causing decomposition, hardening or significant negative impact on key material properties, and

— resistance to the design temperature range.

With respect to elastomers, both swelling and rapid gas decompression damage shall be considered.

7.2.4 Lubricants

For the selection of lubricants, it shall be considered that lubricants can dissolve in dense-phase CO_2. Petroleum-based greases and many synthetic types of grease used in pipeline components, such as valves and pumps, can deteriorate in the CO_2 stream. The compatibility of the lubricant shall be documented for the specified CO_2 stream composition and operating envelope in terms of pressure and temperature.

7.3 Wall thickness calculations

7.3.1 Calculation principles — Design loads

The highest and lowest internal pressures, as well as the pressure gradient for the worst case operational mode, shall be calculated for the whole pipeline. This calculation shall consider the flow rate, the physical properties of the CO_2 stream, as well as the topographical profile for the pipeline route.

For calculation of the design load, the highest internal pressures and potential negative pressures transient operational modes (e.g. switching and controlling operations at compressor and pumping stations, valves, branch lines or start-up and shut down of the pipeline) shall be taken into account. This is also relevant for operational interruptions which can cause pressure increases or negative pressures (e.g. due to unintended valve closure or stoppage of compressor or pumping stations). The possibility of pressure pulses shall also be considered.

The highest calculated internal pressures for pipelines transporting CO_2 streams in the gaseous or dense phase shall be drawn to scale for the pipeline route profile.

The minimum and maximum values of system test pressures shall be defined on the basis of the topography.

While designing a pipeline system, the maximum and minimum temperatures present during all operations shall be taken into account including those associated with compression and decompression of the system.

7.3.2 Determination of minimum wall thickness

For the determination of the minimum wall thickness required for CO_2 pipelines, three different calculations shall be applied. In particular, these calculations contain the determination of the minimum wall thickness against

— internal pressure,

— dynamic pressure transients, e.g. hydraulic shock, and

— fracture propagation.

7.3.3 Minimum wall thickness (t_{minDP}) depending on internal pressure

The determination of the minimum wall thickness (t_{minDP}) depending on internal pressure alone should be calculated on the basis of existing pipeline standards.

7.3.4 Minimum wall thickness (t_{minHS}) taking into account dynamic pressure alterations (hydraulic shock)

For the determination of the minimum wall thickness, the CO_2 hydraulic shocks (comparable with water hammer in liquid pipelines) shall be taken into account. Dynamic pressure alterations can be caused by, for example:

— operational procedures (closing or opening of valves during operation);

— unintentional failure of compressor or pumping stations;

— branch lines;

— pipeline shut-in and shut-down procedures.

If the potential exists for pressure surges to occur, the maximum value shall be determined using pressure surge calculations (Joukowski calculation).

The resulting pressure increase of the design pressure shall be taken into account for the calculation of the minimum wall thickness.

Additionally, measures for pressure containment should be considered if necessary, e.g. alignment of the operating envelope of the valves, the variation of the release and locking mechanisms/times and the application of flywheel masses of the pumps of the compressor stations.

7.3.5 Minimum wall thickness (t_{minDF}) against ductile fracture

Design considerations shall include pipe diameter, wall thickness, fracture toughness, yield strength, operating pressure, operating temperature, the operating regime of the sources and the decompression characteristics of the CO_2 stream.

CO_2 pipelines should be designed with adequate resistance to ductile fracture. The principal means of fracture control is by the selection of suitable materials or by the installation of suitable fracture arrestors. Requirements for preventing long running fractures are given in ISO 3183:2012, Annex G, noting that for high strength steels, the toughness requirements in ISO 3183:2012, Annex G might not be applicable; in that case, ISO 3183:2012, Annex M shall be applied.

Where the combination of pipeline materials and CO_2 stream to be transported lies outside the range of available full scale test data, a full scale test should be conducted to provide confidence that the pipeline has adequate resistance to ductile fracture.

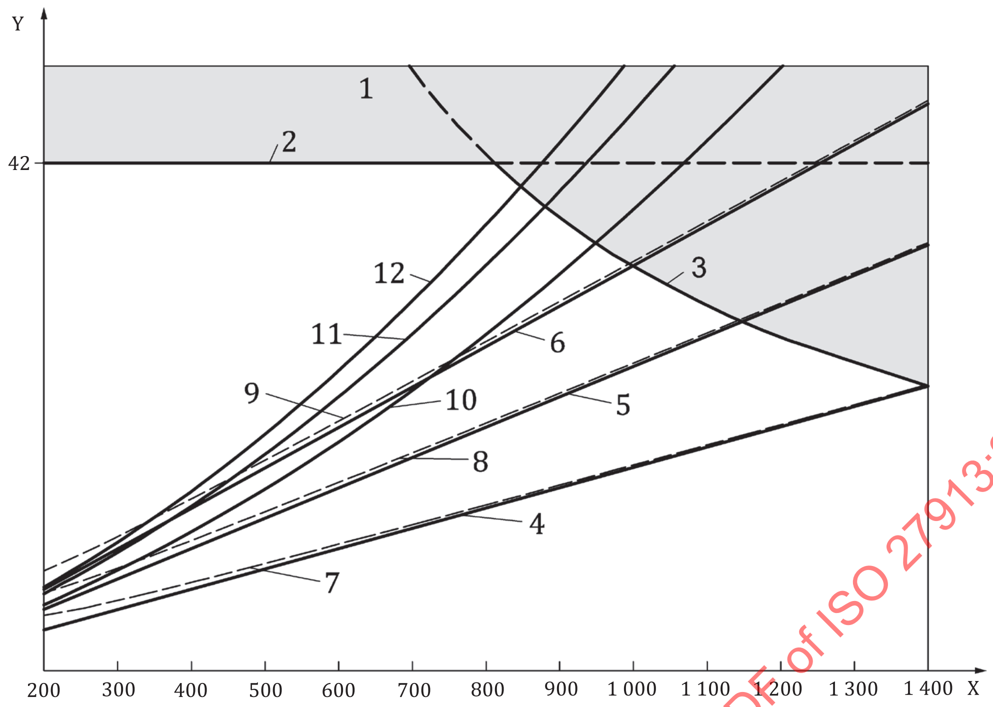
Based on knowledge at the time of publication of this document, a suggested approach is given in Annex D.

7.3.6 Fracture toughness

The line pipe material should have adequate resistance to ductile fracture and, where feasible, be capable of arresting running shear fractures. Line pipe should meet the drop weight tear test and Charpy V-notch requirements specified in ISO 3183. Testing should be conducted over a range of temperatures to determine the brittle to ductile transition curve.

7.3.7 Overview

The principles and recommendations given in this subclause should be considered, because they provide relevant aspects for the pipeline design process. Figure 2 illustrates the relationship of the wall thickness as a function of the pipe diameter against different internal pressures and demonstrates their correlation.



Key

X diameter (mm)
Y wall thickness, values depending on material specification (mm)
1 not feasible area
2 limited weldability
3 limited weight
4 internal pressure (10 MPa)
5 internal pressure (15 MPa)
6 internal pressure (20 MPa)
7 internal pressure (10 MPa) + hydraulic shock
8 internal pressure (15 MPa) + hydraulic shock
9 internal pressure (20 MPa) + hydraulic shock
10 fracture arrest *Ps* = 7,2 MPag (see Annex D)
11 fracture arrest *Ps* = 8,5 MPag (see Annex D)
12 fracture arrest *Ps* = 9,2 MPag (see Annex D)

NOTE 1 The purpose of Figure 2 is to illustrate the design process for wall thickness dimension.

NOTE 2 The numbers for the wall thickness have been deliberately omitted to prevent users from inferring design information from the graph.

Figure 2 — Illustration of wall thickness as a function of pipe diameter, different internal pressures and different saturation pressures

Figure 2 illustrates the linear correlation of pipe diameter and the resulting wall thickness depending on different internal pressures (solid lines). Additionally, Figure 2 illustrates the required wall thicknesses (dashed lines) for designing a pipeline against hydraulic shocks. Moreover, Figure 2 illustrates the correlation of pipe diameter and required wall thickness against ductile fracture (curves) calculated by using the suggested approach in Annex D. That shows that this correlation is independent from the internal pressure of the steel pipeline. One example (*Ps* = 7,2 MPag) is based on the assumption that it is pure CO_2 that is being transported. For impure CO_2, the required wall thickness shall be calculated separately for each case, taking into account the specific properties of the CO_2 stream (here, for example, *Ps* = 8,5 MPag and *Ps* = 9,2 MPag).

An additional aspect which should be considered within the design and construction of a steel pipeline is a practical/technical limitation. In the example illustrated in Figure 2, areas (shaded grey) are presented, where it is difficult to construct the pipeline due to the following:

— difficulty to weld because of the large wall thicknesses (>42 mm);

— too heavy line pipe for transportation and handling during construction;

— inability to carry out field bending.

These aspects shall also be considered separately for every case.

7.4 Additional measures

7.4.1 Dynamic loads due to operation (alternating operation pressure)

Pipes which are stressed due to dynamic pressure loads should be designed in accordance with existing standards for pipelines transporting liquids.

7.4.2 Topographical profile

A dense-phase CO_2 pipeline design should consider the topographical profile due to the hydrostatic effects which could lead to higher pressures being realized downstream of a compressor or pump. The minimum and maximum values of the test pressures should take into account the local altitude along the pipeline hydraulic test section.

7.4.3 Fracture arrestors

In case neither fracture initiation control nor fracture propagation control is ensured by other means, fracture arrestors may be considered (see References [22], [45] and [60]).

The spacing and sighting of fracture arrestors should be based on a safety evaluation, and should also take into account construction and operational considerations. The prevention of external corrosion should be considered in the design and installation of fracture arrestors.

7.4.4 Offshore pipelines

For offshore pipelines, the difference in dispersion following a release between that from a CO_2 pipeline and a hydrocarbon pipeline should be taken into consideration in the design safety assessment.

8 Construction

8.1 General

Due to CO_2 pipelines possibly having higher wall thickness than natural gas pipelines, as part of the construction process, consideration shall be given to the specific challenges relating to thicker wall pipelines, such as welding, field bending, radius of curvature, hydraulic testing and larger handling equipment being utilized.

The standards referred in this document should give the necessary guidance in combination with the specific design considerations as provided by the previous clauses.

8.2 Pipeline pre-commissioning

8.2.1 Overview

Pipeline pre-commissioning shall be carried out in accordance with the procedure described in standards for natural gas or oil pipelines.

The standards referred to in this document contain guidance on the issue of pipeline pre-commissioning activities and the relevant considerations. In the following subclauses, some specific requirements and recommendations for the pipeline pre-commissioning activities are given.

8.2.2 Pipeline dewatering and drying

Due to the particular corrosion issues associated with CO_2 and water, the pipeline shall be dried to a sufficient dew point before filling with the CO_2 stream (see References [50] and [64]).

8.2.3 Preservation before pipeline commissioning

The need for preserving the pipeline between pipeline pre-commissioning and pipeline commissioning phases shall be assessed. Gases such as nitrogen or dry air can be used for preservation of the pipeline, but the requirement of the gas quality needs to be assessed.

The means of preservation shall be selected with proper consideration toward the pipeline commissioning requirements. This can include requirements for internal pressure.

9 Operation

9.1 General

The purpose of this clause is to provide minimum requirements for the safe and reliable operation of pipeline systems for the whole service life.

Integrity management for CO_2 pipelines shall take into account the specific operating challenges, threats and consequences associated with such pipelines, which are different from those associated with hydrocarbon pipelines. The following subclauses cover those aspects of commissioning and integrity management that require additional consideration for CO_2 pipelines relative to other pipelines.

9.2 Pipeline commissioning

9.2.1 First/initial/baseline inspection

It is recommended to perform a baseline intelligent pigging run before the pipeline is put into operation. This inspection can determine the condition of the pipeline and can be used as a reference for later in line inspections. In addition, the results can be used as input to the first inspection plans (see Annex E).

The baseline intelligent pigging run may be performed in the construction phase.

9.2.2 Initial filling and pressurization with product

After completion of the construction activities, hydraulic testing, draining and drying, the pipeline is considered to be in a condition ready for pipeline commissioning.

Pressurization of a CO_2 pipeline requires special design consideration. The CO_2 stream should be injected into the pipeline in such a manner to avoid the formation of solids or temperatures to fall below design values. A number of different techniques may be used to achieve this, including

— controlled filling with CO_2,

— use of an intermediate gas, such as nitrogen, and

— hydrate inhibitors (e.g. glycol, methanol).

9.2.3 Onshore vent facilities

The temperature inside the pipeline should be always above a design temperature dependent on steel and liner quality to protect external coatings and other non-metallic materials and to prevent the potential for solid CO_2 formation within the pipeline during venting. The pressure shall be maintained above the triple point of the inventory (i.e. 0,52 MPag for pure CO_2).

However, the routine venting of CO_2 pipelines should be avoided if possible because

— it would discharge the large inventory of CO_2 into the atmosphere (with associated costs, environmental impact and possible regulatory impacts),

— it would increase the potential for solid formation within the pipeline, and

— it could allow some areas of pipeline material to experience low temperatures as a result of Joule-Thomson cooling or evaporation of the escaping material.

9.2.4 Pipeline shut-in

A pipeline shut-in procedure should be established.

Pipeline shut-in should be performed carefully and in a controlled manner. The shut-in procedure can depend strongly on the pipeline layout and utility system, hence, should be established for each specific pipeline.

During a planned shut-in, the pressure in the pipeline should be kept sufficiently high to prevent

— vapour forming for dense-phase pipelines (unless designed to do so), and

— risk of forming a free water phase.

In case there is a risk of the temperature decreasing during shut-in, i.e. due to lower ambient temperature (e.g. in offshore conditions), the potential decrease in temperature shall be considered with reference to the avoidance of two-phase flow phenomena to protect the system.

In case there is a risk of the temperature increasing during shut-in, i.e. due to higher ambient temperature, the potential increase in pressure shall be considered with reference to the overpressure protection system and the design parameters of the pipeline system.

9.2.5 Pipeline depressurization

A procedure for planned depressurization should be established. The procedure should consider the pipeline layout in terms of segmentation, as well as location, capacity and function of vent facilities. For additional information, see 9.2.3.

Based on operational experience with existing CO_2 pipelines, it should be considered that the main concerns related to pipeline depressurization are the potential risks associated with low temperature effects and formation of solid CO_2 at low points in the pipeline. The temperature reduction inside the pipeline relates to the pipeline design, operating conditions, ambient conditions and depressurization rate. For further information, see Annex B.

9.3 Inspection, monitoring and testing

9.3.1 General

Types of data which may be required in an integrity management plan to manage CO_2 specific threats and consequences are shown in Annex E.

9.3.2 In line inspection procedure

Detailed procedures for launching and receiving an in line inspection tool in a CO_2 pipeline shall be developed, in order to ensure that the compression/venting processes does not result in situations damaging to the inspection equipment or harmful to nearby personnel.

9.3.3 Monitoring of water content

Water content shall be measured using a moisture analyser. The precision of the instrumentation shall be considered with respect to the specified margins on water content.

10 Re-qualification of existing pipelines for CO_2 service

Existing pipelines may only be converted to CO_2 service, provided that they are re-qualified for such service in accordance with the requirements described in this document.

Annex A
(informative)

Composition of CO_2 streams

This annex provides essential information on the composition of CO_2 streams which is relevant for the definition of the operational envelope during the design phase. The exact composition of the CO_2 stream will depend on the CO_2 source and the installed capture technology.

Impurities in a CO_2 stream can include the following:

— oxygen (O_2);

— water (H_2O);

— nitrogen (N_2);

— hydrogen (H_2);

— sulfur oxides (SO_x);

— nitrogen oxides (NO_x);

— hydrogen sulfide (H_2S);

— hydrogen cyanide (HCN);

— carbonyl sulfide (COS);

— ammonia (NH_3);

— amines;

— aldehydes;

— particulate matter (PM).

In addition, further impurities can occur. Example CO_2 stream compositions, particularly from the power plant sector, can be found in literature[25], but the data should be handled with care as the technology is still in development.

Impurities have impacts on the thermodynamic properties of a CO_2 stream which cannot be predicted out of the properties of pure CO_2. Furthermore, impurities can effect corrosion or generate chemical reactions. Also, properties of a CO_2 stream, like viscosity, can change.

Research to identify those impurities that can have a critical impact on the thermodynamic, chemical and other properties of the CO_2 is still taking place. Indicative levels discussed in literature are presented in summary in Table A.1.

Table A.1 — Indicative levels of main CO_2 impurities and factors driving these levels

<table>
<tr><th>Species</th><th colspan="3">Indicative levels (volumetric composition in ppmv, unless stated as mol%)</th></tr>
<tr><td>CO_2</td><td colspan="3">>95 mol%[a]</td></tr>
<tr><td>H_2O</td><td colspan="2">Corrosion, 20 to 630[b], Hydrate, <200[c,d]</td><td rowspan="11">Avoiding the formation of corrosive phases and solids in the pipeline is essential for safe operation of the CO_2 pipeline system. There are a number of possible cross-chemical reactions that have the potential to form sulfuric/sulfurous acid, nitric acid and elemental sulfur when water and SO_2, NO, NO_2, O_2 and H_2S are present[33], also N_2O, N_2O_4[40]. Presently, there is no publically available model that can predict which of the reactions are thermodynamically and kinetically possible and favourable when the impurities are mixed. Since the maximum concentration of a single impurity will depend on the concentration of the other impurities, it is not possible due to lack of data and current understanding to state a fixed maximum concentration of a single impurity when other impurities are, or may be, present.</td></tr>
<tr><td>H_2</td><td><0,75 mol%[e,f]</td><td rowspan="7"><4 % total for all non-condensable gasses, but individual contributions may also be significant</td></tr>
<tr><td>N_2</td><td><2 mol%[f,g]</td></tr>
<tr><td>Ar</td><td>[f]</td></tr>
<tr><td>CH_4</td><td>[f,g]</td></tr>
<tr><td>CO</td><td><0,2 mol%[j,k]</td></tr>
<tr><td>O_2</td><td>[f,h]NB. Downstream limitations</td></tr>
<tr><td>H_2S</td><td><200[g,i,k]</td><td rowspan="3">Individual values, each below STEL,[m] but see Footnote n.</td></tr>
<tr><td>SO_2</td><td>Health and Safety < 100[k,l]</td></tr>
<tr><td>NO_2</td><td>Corrosion < 50[n]</td></tr>
<tr><td>Amine</td><td></td><td colspan="2" rowspan="4">The presence of amines, MeOH, EtOH, glycols and other water soluble components (e.g. HCl, NaOH, other salts) will facilitate the formation of an aqueous phase (free water) and reduce the concentration of water in the CO_2 at which a separate aqueous phase is formed. The maximum concentrations that are acceptable will depend on the concentration of the other impurities (see above note).</td></tr>
<tr><td>Methanol</td><td></td></tr>
<tr><td>Ethanol</td><td></td></tr>
<tr><td>Glycol</td><td></td></tr>
<tr><td>C2+</td><td colspan="3"><2,5 mol%[o]</td></tr>
</table>

[a] Industry accepted interpretation of “overwhelmingly CO_2” required by the London Convention and Protocol which came into force in February 2007.

[b] The Cortez and Central Basin pipelines in the USA have 630 ppmv H_2O, but it is noted that they also have <26 ppmv of H_2S, <14 ppmv of O_2 and no SO_x or NO_x (see References [61] and [55]).

[c] A figure of 250 ppm is recommended in Reference [62], which states “In case of a system shut-in or start-up, the risk of hydrates is low if the water content of the CO_2 stream is below 250 ppm. In situations of rapid depressurization, even a low water content level might not be sufficient to avoid hydrates.” An additional margin has been applied to recognize this. The maximum acceptable concentration will depend on the pressure/temperature operation window. It is recognized that a number of pipelines have been operated for a long time with a target water concentration of 630 ppmv without reported hydrate incidences. See also Footnote b.

[d] For measures to avoid hydrate formation, see C.2.

[e] See C.2 for criteria on which the hydrogen content should be decided.

[f] The presence of “non-condensables”, particularly, H_2, H_2S and N_2, but also O_2, Ar, CH_4 and CO affects the decompression behaviour of the CO_2 stream[23] and this should be taken into consideration when considering methods to avoid running shear fracture[30].

[g] The presence of “non-condensables” CH_4, N_2 and H_2S can affect the solubility of water in the CO_2 stream.

[h] O_2 content to be such that it does not promote acids formation, solids formation and corrosion that adversely affect the operational integrity of the pipeline over the design lifetime, noting that a much lower level of O_2 can be required to avoid unwanted downstream impacts.

[i] The Weyburn pipeline has 9 000 ppmv of H_2S[58], noting that the CO_2 is dry (<20 ppm)[55], and that the oilfield into which the CO_2 is being injected is already sour.

[j] The level of impurity required to cause CO_2-CO cracking under pipeline operating conditions is not yet known. However, it has been confirmed that in order for cracking to occur, water needs to be present and that the presence of O_2 enhances the susceptibility to cracking.

[k] Health and safety impacts of individual impurities within the CO_2 stream are only relevant if their concentration is such that the combined toxic harmful effect of the impurities is greater than the CO_2 itself. The limitations on harmful toxic substances in the CO_2 composition should be specified such that the harm criteria are determined by exposure limits for CO_2 rather than the other harmful toxic compounds, i.e. the permissible level of an impurity can be arranged such that, in the event of a severe uncontrolled discharge, the harmful toxic effect of CO_2 dominates that of the impurity; hence, the former is not relevant, as the recipient would already be affected by the CO_2. It should be documented that the combined hazardous effects have been properly taken into account including the partitioning of impurities between the gaseous and dense phases, noting that toxic components do not necessarily act separately or independently. For examples, see References [61] and [63].

[l] The presence of H_2S in the CO_2 stream can promote corrosion at lower water levels than in pure CO_2[51].

[m] STEL: Short-term Exposure Limit, the acceptable average exposure over a short period of time, usually 15 minutes as long as the Time Weighted Average is not exceeded.

[n] There is experimental evidence that even at levels of <50 ppmv of NO_x and SO_x nitric and sulfuric acid can be formed[44].

[o] Hydrocarbon content should have a dew point such that condensation does not occur within the operational envelope (combined pressure and temperature) of the pipeline.

In ANSI/NACE MR0175/ISO 15156-1, the onset of Sulfur-Induced Stress Corrosion Cracking (SICC) is related to the presence of water, H_2S and the pH of the fluid being transported. If the pipeline dehydration of CO_2 stream is such that corrosion is not anticipated or no free water is formed, (thus no pH is measurable), it would then not be necessary to assess the pipeline for SICC. If the water content is such that it is likely that a water phase will be present, then an assessment using the criteria of ISO 15156 should be carried out and an appropriate grade of steel selected.

Annex B
(informative)

CO_2 characteristics

B.1 Accidental release of CO_2

Accidental release of CO_2 (controlled pipeline depressurization is described in 9.2.5) from an initial dense phase to ambient conditions involves decompression and expansion of the released medium with a corresponding drop in temperature of the released medium and remaining inventory.

CO_2 differs from the decompression of hydrocarbons because the release can appear as a combination of gaseous and solid state CO_2[35].

Any solid components in the CO_2 inventory can potentially impart erosive properties to the release stream. Direct impingement of this stream has the potential to affect critical equipment. Safety assessments should consider this possibility as a part of the design process.

The Joule-Thomson temperature reduction through the fracture/opening at the leak point may not be significantly more pronounced than for volatile hydrocarbons. Measures to predict and, if necessary, mitigate against running ductile fracture should be considered in the design. Mitigation measures could include fitting fracture arrestors or increasing the wall thickness of the pipeline (see 7.3.5).

Even though CO_2 is a colourless gas, a release from a CO_2 inventory will most likely cause condensation of the water saturated in the ambient air, resulting in a fog type cloud visible to the human eye (until the release cloud warms to above the air's dew point temperature). This can be a good indicator of the extent of a plume of CO_2, but instruments should be installed at facilities or carried by operational personnel to detect the presence and concentration of CO_2 in a release situation and not rely upon visual indicators. A release of CO_2 above the ambient air dew point temperature will be invisible to the naked eye since there will be no condensing water or solid CO_2 particles. In this situation, harmful levels of CO_2 can arise without any visible indication and this factor should be considered. Releases of CO_2 from offshore pipelines are unlikely to be detected by the appearance of bubbles reaching the surface unless the leak is significant, in which case, calm weather fly-overs or boat patrols along the length of the pipeline can be able to detect them. These visual methods of inspection for leaks can be triggered by leak detection methods (see 6.9.9), or third-party observations, such as fishing vessels.

B.2 Release rates

Accidental release rates from a CO_2 pipeline primarily differ from a hydrocarbon pipeline because of the potential for phase changes within the flow expansion region.

To enable modelling of accidental release rates, the transient thermo-hydraulic behaviour of the pipeline should be considered.

Calculation of the transient release profile should include, but not be limited to

— hole size and geometry,

— variations in the mass flow rate of the CO_2 stream over time,

— pipeline diameter, length and topography,

— initiation time and capacity of pipeline depressurization system,

— temperature, pressure and chemical composition of the CO_2 stream,

— heat transfer between pipeline and the surrounding environment, and

— closing time of any inventory segregation valves (e.g. block or check valves).

B.3 Dispersion modelling

Empirical models for estimating the dispersion of released gases in air and liquids are readily available; however, they may need further validation for CO_2 in CCS-scale applications. Accidental release of CO_2 differs from other typical fluids in terms of formation of a solid state (see 6.9.2).

Effects that should be considered within the modelling, include

— release quantity, rate and pressure,

— ambient temperature and weather conditions,

— leak profile,

— jet direction (consider both impinging and free jets),

— release gas density,

— wind speed and direction,

— atmospheric stability class,

— air humidity,

— surface roughness, and

— impurities and their partitioning between gaseous and dense phases.

It is expected that the effect is larger for large leaks and full bore ruptures than for small releases. When the cold stream of CO_2 hits the ground, a small release will be heated by the surface; however, if the leak is large and/or long lasting, less of the CO_2 stream will be heated by the surface and the effect of sublimed CO_2 is expected to be larger.

In addition to being influenced by the wind, the heavier than air CO_2 stream will spread out sideways, with off-axis ground level concentrations being higher than for a neutrally buoyant or buoyant gas release. Ground topography (e.g. slopes, hollows, valleys, cliffs, streams, ditches, road/rail cuttings and embankments) and physical objects (e.g. buildings), as well as wind direction, may have a significant influence on the spread and movement of a CO_2 cloud. Particular care should be taken in identifying topographical features and assessing how this may impact the consequences of a CO_2 release.

Modelling releases from underground pipelines should receive careful consideration since the crater formation and subsequent release flow could significantly reduce the momentum and therefore air mixing of the release, thereby decreasing the dispersion.

Submerged releases of CO_2 may be modelled in a similar way as for hydrocarbon gas having similar molecular weight (i.e. propane). Dispersion models are available, but the designer should ensure that they have been validated for CO_2 in CCS-scale applications or make suitable adjustments.

Annex C
(informative)

Internal corrosion and erosion

C.1 Measures to minimize internal corrosion

Field experience and experimental work show that CO_2 without other impurities than water well below the saturation limit is non-corrosive to carbon steel at transportation pipeline operation conditions.

For a carbon steel pipeline, internal corrosion is a significant risk to the pipeline integrity in case of insufficient pipeline dehydration of the CO_2 stream. Free water combined with the high CO_2 partial pressure may give rise to high corrosion rates, primarily due to the formation of carbonic acid.

There are currently no reliable models available for the prediction of corrosion rates with sufficient precision for the high partial pressure of CO_2 and free water, although there is ongoing research in this area.

C.2 Impact of impurities on internal corrosion

The presence of free water with H_2S can induce severe H_2S-induced corrosion phenomena.

The presence of other chemical components such as NO_x or SO_x can lead to a free water phase containing strong acids, significantly increasing the corrosion rate.

Based on the present understanding of CO_2 corrosion mechanisms at high partial pressure, there exists significant uncertainty, particularly considering the effects of other components in the CO_2 stream. The most up to date research should be consulted during pipeline design.

The water content should be such that, under all operational conditions, hydrate formation in the low temperature regions of the pipeline is avoided and internal corrosion of the pipeline is within an acceptable design range.

C.3 Internal corrosion control

The primary strategy for internal corrosion protection should be sufficient pipeline dehydration of the CO_2 stream.

Generally, it is recommended to operate the system such that internal corrosion is avoided through operational control. Off-specification operations may occur and the likelihood of such events should be evaluated as part of the system design.

A corrosion allowance may be applied to the wall thickness for the complete pipeline or for shorter stretches. Tolerance to off-specification water content over shorter time periods should also be considered.

C.4 Measures to minimize erosion

The particulate content within the CO_2 should be such that it is within the limits that will allow it to be compressed without causing damage to the impellors of the compressor or pump. This will be specific to the composition of the particulate. A guideline of <1 mg/Nm^3 with a maximum particle size of <10 µm may be used.

The bubble point for hydrogen within the CO_2 stream should be determined for the lowest pressure and highest temperature in the pipeline. A design margin should be introduced such that the normal operating temperature is 10 % less than this, or the normal operating pressure is 5 % higher than this.