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DNV Recommended Practice: Design and Operation of CO_2 Pipelines

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Abstract

A unified Recommended Practice (RP) for safe and reliable design, construction, operation and maintenance of steel pipelines for transportation of CO_2 has been developed through the CO2PIPETRANS Joint Industry Project (JIP). Best practice knowledge and relevant experience gathered in the JIP form the basis for the guidance given in the RP. The RP applies to pipelines for large scale transportation of CO_2, relevant for Carbon Capture and Storage (CCS), and is intended as a supplement to existing recognized standards for both onshore and submarine pipelines. This paper briefly outlines the key content of the RP.

Keywords: CO_2 transportation; Recommended Practice;

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1. Introduction

Pipelines are seen as the primary transportation means for CO_2 streams in the context of carbon capture and storage (CCS). Pipeline transmission of CO_2 over longer distances is regarded as most efficient and economical when the CO_2 is in the dense phase, i.e. in liquid or supercritical regime, due to the lower friction drop along the pipeline per unit mass of CO_2. Throughout the industry there is limited experience in pipeline transportation of dense phase CO_2 in the scale that will be required for CCS. There are a number of international recognized standards that may be used in design and operation of pipeline systems, but these are normally developed and maintained based upon transportation of hydrocarbons. Consequently, aspects related to transportation of CO_2 are normally not reflected in these standards.

Today, however, the awareness is higher both among the industry and the authorities regarding the general perception of CO_2 as a substance for transmission in large and geographically interconnected pipeline systems. Increased awareness is typically related to possible differences in system behavior influencing various failure modes as well as failure consequences. Linked with this higher awareness is the continuously increased scientific and industrial learning of the technical difference between transportation of CO_2 in large volumes in pipelines compared to transmission of hydrocarbons.

In 2008, Det Norske Veritas (DNV) launched a well supported Joint Industry Project (JIP) called CO2PIPETRANS with the objective to develop a DNV Recommended Practice (RP) for transportation of CO_2 in

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onshore and submarine pipelines. The project successfully collected and integrated current knowledge from available relevant experience, R&D and technical studies into a guideline format that has recently been converted to a DNV Recommended Practice [1]. This Recommended Practice identifies differences between pipeline transportation of CO_2 and hydrocarbons, explain the associated significance to CO_2 pipeline design and operation, and provide recommendations for design and operation of CO_2 pipelines. The RP is written to be a supplement to existing pipeline standards and is applicable to both onshore and offshore pipelines. The present paper provides an overview the content of the RP.

2. Development of the Recommended Practice

2.1. Objective

The objective of the Recommended Practise (RP) is to provide guidance on safe and reliable design, construction and operation of pipelines intended for large scale transportation of CO_2 to meet the requirements given in existing and recognized pipeline standards, and to be a supplement to existing pipeline standards such as such as ISO 13623 [2], DNV-OS-F101 [3] and ASME B31.4 [4].

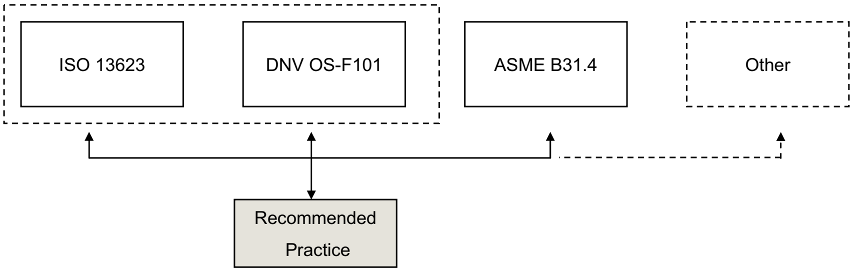

Figure 1: Referenced standards

2.2. Applicability

The recommendations given in the document applies to rigid metallic pipelines, and pipeline networks, for fluids containing overwhelmingly[1] CO_2, transported in gaseous, liquid or supercritical phases. Users of this RP are typically; CCS project developers, pipeline engineering and construction companies, pipeline operating companies, authorities or certification companies. The recommendations stated in the RP apply as a supplement to both offshore and onshore pipelines.

2.3. Structure of RP

The RP is structured as a typical pipeline development project, from the concept and design phase, through construction to commissioning and operation. The RP also contains a separate chapter on general guidance on how existing pipelines used for other purposes than transporting CO_2 can be re-qualified.

3. Specific properties of CO_2 relevant for pipeline design and operation

3.1. Specific properties

CO_2 has a molecular weight approximately 50% higher than air, i.e. at ambient condition the density of (gaseous) CO_2 will be higher than air, which has implications on how CO_2 disperses when released to the ambient.

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[1] In the RP, the term 'overwhelmingly CO_2' refers to definitions given in the London Convention, the OSPAR convention and the EU CCS Directive. The actual percentage of CO_2 and other components present in the CO_2 stream shall be determined based upon technological and economical evaluations, and appropriate regulations governing the capture, transport and storage elements of a CCS project.

Dense phase occurs in the phase diagram, ref. Figure 2, for pressure and temperature combinations above the vapour (gas)-liquid line and under the solid-liquid line. When the temperature is below the critical temperature it is common to say that the CO_2 is in the liquid dense phase and above in the supercritical phase.

Physical properties of a CO_2 stream defined by its individual chemical compounds may vary from the physical properties of pure CO_2 in terms of but not limited to:

- Toxicity
- Critical pressure and temperature
- Triple point
- Phase diagram
- Density
- Viscosity
- Water solubility.

The acceptable amount of other chemical components relates optimization considering both technical and economical aspects not limited to the pipeline but including the facilities at the pipeline upstream and downstream battery limits

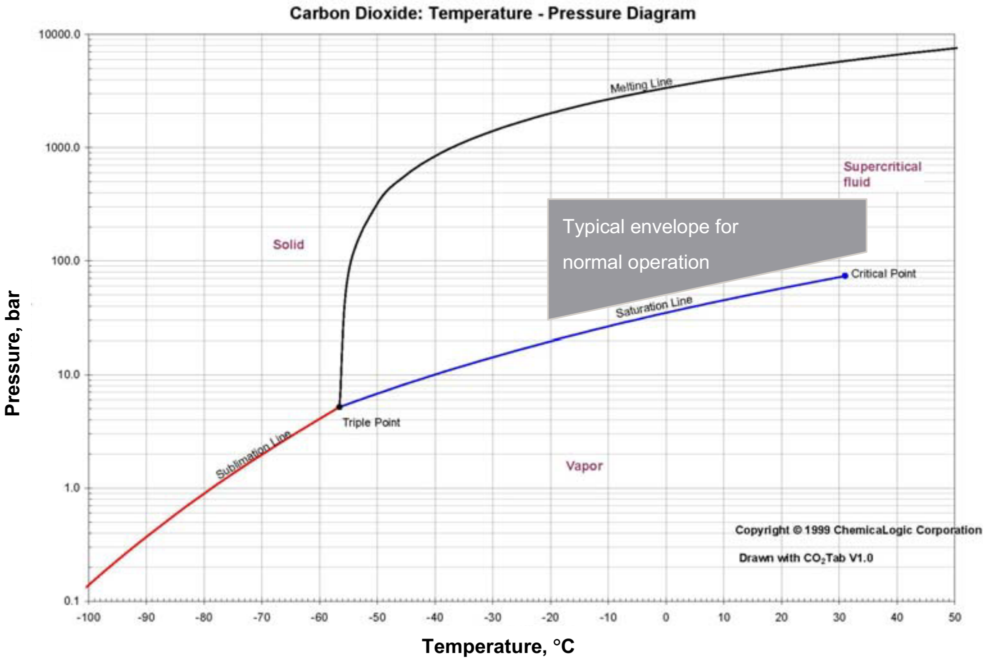

Figure 2: Phase diagram of pure CO_2 [5]

3.2. Water solubility

In the vapour state the ability of CO_2 to dissolve water increase with increased temperature and reduced pressure as for natural gas. With transition from vapour to liquid state there is a step change in solubility and the solubility increase with increasing pressure which is the opposite effect of what occurs in the vapour state, ref. Figure 3. The ability of the CO_2 stream to dissolve water may be significantly affected by the fraction of different chemical components, hence this needs consideration.

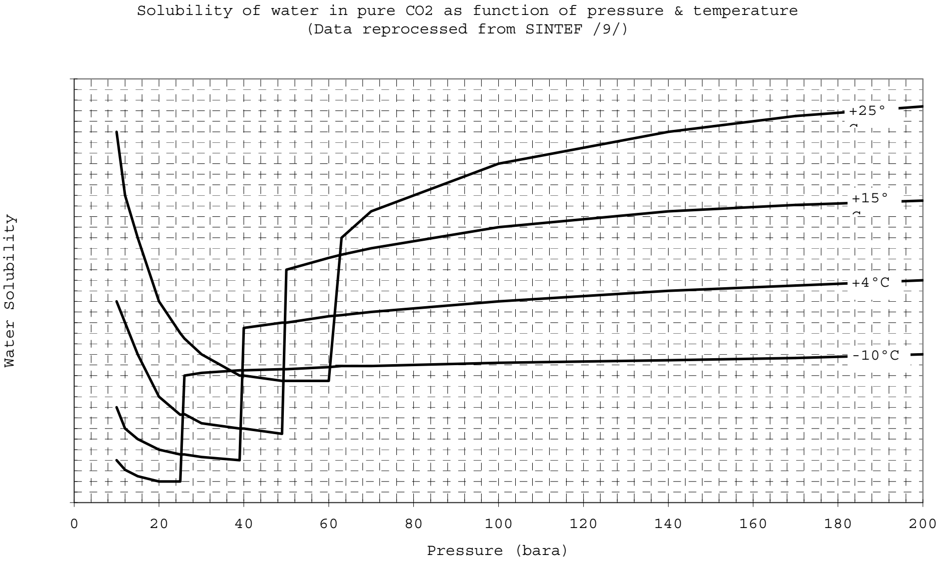

Figure 3: Solubility of water in pure CO_2; only for illustration [6]

4. Safety philosophy

4.1. Safety evaluations

It should be recognized that CO_2 pipelines at the scale that will be associated with CCS projects are novel to many countries and this should be reflected in the risk management strategy adopted. The risks to people in the vicinity of the pipeline shall be robustly assessed and effectively managed down to an acceptable level. To achieve this, CO_2 hazard management processes, techniques and tools require critical examination and validation. The safety risk related to transport of CO_2 should include but not be limited to controlled and uncontrolled release of CO_2.

For CCS, with few companies or people with hands on experience and few relevant hazard identification studies, great care should be taken during hazard identification exercises since hazards may be missed, or hazards that are identified may be deemed non-credible due to lack of relevant knowledge. Until experience and knowledge is built up and communicated within the CCS industry, greater focus should be applied to hazard identification (and risk assessment) to compensate for the lack of experience. Major Accident Hazard (MAH) risk assessment should be performed to provide estimates of the extent (i.e. hazard ranges and widths) and severity (i.e. how many people are affected, including the potential numbers of fatalities) and likelihood of the consequences of each identified major accident hazard. MAH risk assessment could be used as input to design requirements, operational requirements and planning of emergency preparedness.

4.2. Risk basis for design

The pipeline shall be designed with acceptable risk. The risk considers the likelihood of failure and the consequence of failure. The consequence of failure is directly linked to the content of the pipeline and the level of human activity around the pipeline. Hence, both the content (CO_2) of the pipeline and the human activity around the pipeline need to be categorized, and will provide basis for safety level implied in the pipeline design criteria. CO_2 pipelines will have MAH potential due primarily to a combination of vast pipeline inventories and the consequences if CO_2 is inhaled at concentrations above threshold level. A precautionary approach to risk management is therefore recommended, and it is recommended that, until sufficient knowledge and experience is gained with CCS pipeline design and operation, a more stringent fluid categorization, than one would normally apply for CO_2 according to e.g. ISO 13623 [2], should be applied in populated areas.

5. Concept development and design premises

The RP contains a separate section related to design issues that are specific to CO_2 and that are normally considered as part of the pipeline concept phase. Some of these issues are briefly presented below.

5.1. Pipeline routing

The general recommendation with respect to CO_2 pipeline routing is that a standard approach as for route selection for hydrocarbon pipelines should be applied. The standards referred to, in combination with the specific CO_2 safety aspects and the pipeline design considerations provided elsewhere in the RP, should give the necessary guidance on CO_2 pipeline routing issues.

For onshore pipelines the population density should be determined according to ISO 13623. The distances used to determine the population densities should, until CO_2-specific distances are defined and stakeholder-accepted, be determined using dispersion modeling. Due cognizance should be taken of the heavier than air characteristic of CO_2 and ground topography when determining the zone width along the pipeline.

5.2. CO_2 stream composition evaluations

It is recommended that the CO_2 stream composition specification shall be determined based upon technological and economical evaluations, and compliance with appropriate regulations governing the capture, transport and storage elements of a CCS project.

5.2.1. CO_2 composition in integrated pipeline networks

In case of mixing of different CO_2 streams in a pipeline network, it must be assured that the mixture of the individual compounds from the different CO_2 streams do not cause:

- Risk of water dropout due to reduced solubility in the comingled stream
- Undesired cross chemical reactions /effects.

5.2.2. Water content

Maximum water content in the CO_2 stream at the upstream battery limit shall be controlled to ensure that no free water may occur at any location in the pipeline within the operational and potential upset envelopes and modes, unless corrosion damage is avoided through material selection. For normal operation a minimum safety factor of two (2) between the specified maximum allowable water content and the calculated minimum water content that may cause water drop within the operational envelope should be specified.

6. Materials and pipeline design

6.1. Internal corrosion

The primary strategy for corrosion control should be sufficient dewatering of the CO_2 at the inlet of the pipeline. For a carbon steel pipeline, internal corrosion is a significant risk to the pipeline integrity in case of insufficient dewatering of the CO_2 composition. Free water combined with the high CO_2 partial pressure may give rise to extreme corrosion rates, primarily due to the formation of carbonic acid. The most likely cause of off-spec water content is considered to be carry-over of water/glycol from the intermediate compressor stages during compression of the CO_2 to the export pressure.

There are currently no reliable models available for prediction of corrosion rates with sufficient precision for the high partial pressure of CO_2 combined with free water. Presence of other chemical components such as H_2S, NO_x or SO_x will also form acids which in combination with free water will have a significant effect on the corrosion rate.

6.2. Materials

The selection of materials should be compatible with all states of the CO_2 stream.

6.2.1. Linepipe materials

Candidate materials need to be qualified for the potential low temperature conditions that may occur during a pipeline depressurization situation. Carbon-Manganese steel linepipe is considered feasible for pipelines where the water content of the CO_2 stream is controlled to avoid formation of free water in the pipeline. Application of homogenous corrosion resistant alloy (CRA) or CRA clad/lined linepipe may be an option, but normally only for shorter pipelines.

6.2.2. Non-Linepipe materials

Dense phase CO_2 behaves as an efficient solvent to certain materials, such as non-metallic seals. With respect to elastomers, both swelling and explosive decompression damage shall be considered.

6.2.3. Internal coating

Internal coating for either flow improvement or corrosion protection is generally not recommended due to the risk of detachment from the base pipe material in a potential low temperature condition associated with a too rapid pipeline depressurization.

6.3. Running ductile fracture control

The pipeline shall have adequate resistance to propagating fracture. The fracture arrest properties of a pipeline intended for transportation of a CO_2 composition at a given pressure and temperature depends on the wall thickness of the pipe, material properties, in particular the fracture toughness, and the physical properties of the CO_2 composition in terms of saturation pressure and decompression speed. The pipeline should be designed such that the rupture is arrested within a small number of pipe joints. The fracture control design philosophy may be based on ensuring sufficient arrest properties of the linepipe base material to avoid ductile running fractures or installation of fracture arrestors at appropriate intervals.

To prevent ductile running fractures, the decompression speed of the fluid needs to be higher than the fracture propagation speed of the pipe wall, i.e. if the decompression speed outruns the fracture propagation speed, the fracture will arrest. The particular issue related to CO_2 is the step change in rapid decompression speed as the pressure drops down to the liquid-vapour line (saturation pressure). Compared to natural gas, the decompression speed of liquid CO_2 may be significantly higher. However, as vapour starts to form, the decompression speed of the CO_2 stream drops significantly. To that extent running ductile fractures is a higher concern for CO_2 pipeline compared to, for example, natural gas pipelines, this needs to be related to the design pressure of the pipeline. For low design pressure (typically less than 150 bar), CO_2 pipelines may come out worse compared to natural gas pipeline. This may, however, not be the case for higher design pressure.

A fracture control plan should be established.

A coarse assessment of fracture arrest may be performed through the following steps:

Step 1: Determine Fracture Arrest pressure (P_A) based on proposed pipeline design in terms of pipeline diameter (D), wall thickness (t) and material specifications.
Step 2: Determine the critical pressure (P_C) based on CO_2 stream composition
Step 3: If $P_A > P_C \rightarrow$ Fracture Arrest

It should be noted that for a CO_2 stream containing a significant fraction of non-condensable gases, such as H_2, the above approach may be non-conservative.

As a consequence of the above approach, low (design) pressure pipeline (thin-walled) will have a lower margin between arrest pressure (P_A) and saturation pressure (P_C), hence be more susceptible to running ductile fractures. If the coarse assessment described above does not demonstrate sufficient margin between P_A and P_C, the Battelle two-curve model may alternatively be applied.

In case neither fracture initiation control nor fracture propagation control is ensured by other means, fracture arrestors should be installed. The feasibility and type of fracture arrestors should be documented. Spacing of fracture arrestors should be determined based on safety evaluations and cost of pipeline repair.

7. Operation

7.1. Pipeline depressurization

Depressurization of a long pipeline section may take considerable amount of time (e.g. days), and will have impact on the availability of the pipeline. This concern applies both to planned and unplanned depressurization events. Temperature measurement and control should be used for controlling the depressurization rate. If solid CO_2 is formed, a considerable amount of time may be required for the CO_2 to sublimate to vapour. The sublimation time will depend on the ambient temperature and the pipeline insulation properties.

Solid CO_2 deposits will be at pipeline low points which may plug the pipeline. Re-introduction of dense phase CO_2 into a pipeline which has (or could have) significant solid CO_2 deposits must be avoided. The consequence of the very rapid sublimation of solid CO_2 to vapour, with the corresponding 750 times increase in volume could lead to over pressurization of the containment envelope.

8. Remaining knowledge gaps

During the development of the Recommended Practice it became evident that sufficient guidance could not be given on all aspects of design and operation described in the RP, due to the lack of knowledge. Hence, a set of knowledge gaps was identified, which will be closed in the second phase of CO2PIPETRANS. In this next phase, a set of R&D activities will be preformed and an updated version of the DNV Recommended Practice will be issued in early 2012.

9. Acknowledgement

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State Supervision of Mines in the Netherlands, and the Petroleum Safety Authority in Norway who where observers in the consortium.

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