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Development of a Guideline for Safe, Reliable and Cost Efficient Transmission of CO_2 in Pipelines

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Abstract

During the last decades significant effort has been put into research on the social, economical, political and technical issues related to large scale deployment of Carbon Capture and Storage (CCS). A complete CCS cycle requires safe, reliable and cost efficient solutions for transmission of CO_2 from the capturing facility to the location of permanent storage. The current initiative originates from DNV's long engagement in developing standards and guidelines for offshore pipelines and an identified need to specifically address the technical challenges related to transmission of CO_2 with associated contaminants. The guideline will be based on a comprehensive literature review and gathering of experience from existing (both onshore and offshore) CO_2 pipeline operators. Available pipeline codes, standards, guidelines and regulations combined with the latest available research and technical developments is set as the point of departure for this guideline development. Issues related to pipeline design, commissioning and operation as well as re-qualification/conversion of existing pipelines for transmission of CO_2 will be addressed. The guideline is being developed as a joint industry project and is scheduled for delivery by end of July 2009. After completion of the JIP, the guideline will be converted into a public available Recommended Practice (RP) by Det Norske Veritas (DNV). The guideline will give "how to?" answers for safe, reliable and cost-effective transmission of CO_2 in pipelines. This paper addresses main technical issues one need to manage .

Keywords: CO_2 in supercritical phase; Transmission of CO_2; CCS; Offshore pipelines; Safety.

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1. Introduction

There is a growing world-wide recognition that global warming is a likely result of excessive anthropogenic greenhouse gas emissions into the atmosphere. The need for a reduction in greenhouse gas emissions is driving the efforts of several industry leaders and research institutes in the direction of developing a wider portfolio of cleaner energy solutions. Acknowledging the fact that fossil fuels is likely to remain one of the primary sources of energy for several decades, solutions for carbon capture and storage (CCS) is becoming ever more relevant.

A complete CCS cycle requires safe, reliable and cost efficient solutions for transmission of the CO_2 from the capturing facility to the location of permanent storage. For transmission of large quantities of CO_2 over moderate distances, pipelines are considered the most cost-efficient solution. Onshore pipelines for transmission of CO_2 have existed (e.g. in North America) for several decades, primarily for the purpose of Enhanced Oil Recovery (EOR). Operational experience with offshore CO_2 transmission pipelines is, however, limited both in terms of time in operation and extent. Even though significant effort has been put into research on the social, economical, political and technical issues related to large scale deployment of CCS, several issues still remain uncertain or unsolved.

The current initiative originates from DNV's long engagement in developing standards and guidelines for offshore pipelines and the identified need to develop more specific guidance for safe, reliable and cost efficient design and operation of CO_2 pipelines [2]. There are various codes and standards available today that are applicable to pipeline design and operation including, the US Federal Code of Regulations, ASME Standards B31.4 and B31.8 (B31.8s), IP6, BS EN 14161, BS PD 8010, ISO13623, API RP1111and DNV OS-F101. The current guideline is intended as a supplement to the existing codes and standards, providing "how to" answers specifically related to transmission of CO_2. Through a comprehensive literature review and gathering of experience from existing CO_2 pipeline operators, the latest available knowledge is applied as point of departure for the guideline development.

The guideline is developed as a joint industry project, sponsored by a number of companies, including Gassco, StatoilHydro, Shell, BP, Vattenfall, ArcelorMittal, ILF and Dong Energy with 50% financing through the Norwegian state enterprise for carbon capture and storage, Gassnova. The guideline is scheduled for delivery by end of July 2009. After completion of the JIP, the guideline will be converted into a public available Recommended Practice (RP) by Det Norske Veritas (DNV).

The current paper addresses main issues identified at the current stage of the project; implications of CO_2 composition and operational conditions, safety issues, fatigue, fast propagating running ductile fractures, material compatibility, internal corrosion, reliability, availability, maintainability and operation aspects.

2. Supercritical CO_2 – the most efficient condition for transmission in pipelines

Pipeline transmission of CO_2 over longer distances is most efficient when the CO_2 is in the dense phase, ref. Figure 1 (left), i.e. in liquid or supercritical regimes. This is due to the lower friction drop along the pipeline per unit mass of CO_2 compared to transmitting the CO_2 as a gas or as a two-phase combination of both liquid and gas.

The dense phase occurs in the phase diagram 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 we say that the CO_2 is in the liquid dense phase and above in the supercritical phase. For temperatures below the critical temperature, crossing the vapour-liquid line by reducing the pressure, results in a phase transition from liquid to gas with an accompanying step change in enthalpy. For the CO_2 to transform from liquid to gas, heat must be added in the same way as heat must be added to convert liquid water into steam. For a pipeline, the heat ingress from the ambient is determined by the difference between the ambient temperature and the temperature of the CO_2 inside the pipeline, combined with the insulation properties of the pipeline. Above the critical temperature there is no noticeable phase change, hence when the pressure is reduced from above to below the critical pressure, a smooth enthalpy change occurs from super critical fluid to gas. Pure CO_2 has a triple point at -56.6 ºC and 5.18 Bara, which determines the point where CO_2 may co-exist in gas, liquid and solid state. At the right combination of pressure and temperature CO_2 may turn into the solid state commonly known as dry ice, ref Figure 1 (right).

Figure 1 (right) show a schematic pressure and temperature profile (green line) for a CO_2 pipeline operated in dense phase with no intermediate compression or large terrain variations. Along the pipeline the pressure is reduced due to friction and the temperature is reduced due to heat exchange with the ambient. The CO_2 gradually transitions from supercritical fluid to liquid dense phase, however, still remains as a single phase. If the pipeline is depressurised either due to a controlled operation or due to a pipeline failure, the pressure will drop until the liquid-vapour line is reached and CO_2 vapour starts to form (blue line). For the pressure to continue to drop, heat must either be gained from the ambient or extracted from the CO_2 or pipe wall. In case of a rapid depressurisation the heat gained from the ambient will be low, hence the heat must be extracted from the CO_2 itself. The mixture of gas and liquid CO_2 will follow the gas-liquid line, meaning that the temperature will drop along with the reduction in pressure. A too rapid depressurisation may cause the CO_2 to drop down to the triple point at which solid state CO_2 will form (dry ice). Formation of dry ice may have critical implications both for the feasibility of and the risk associated with resuming operation.

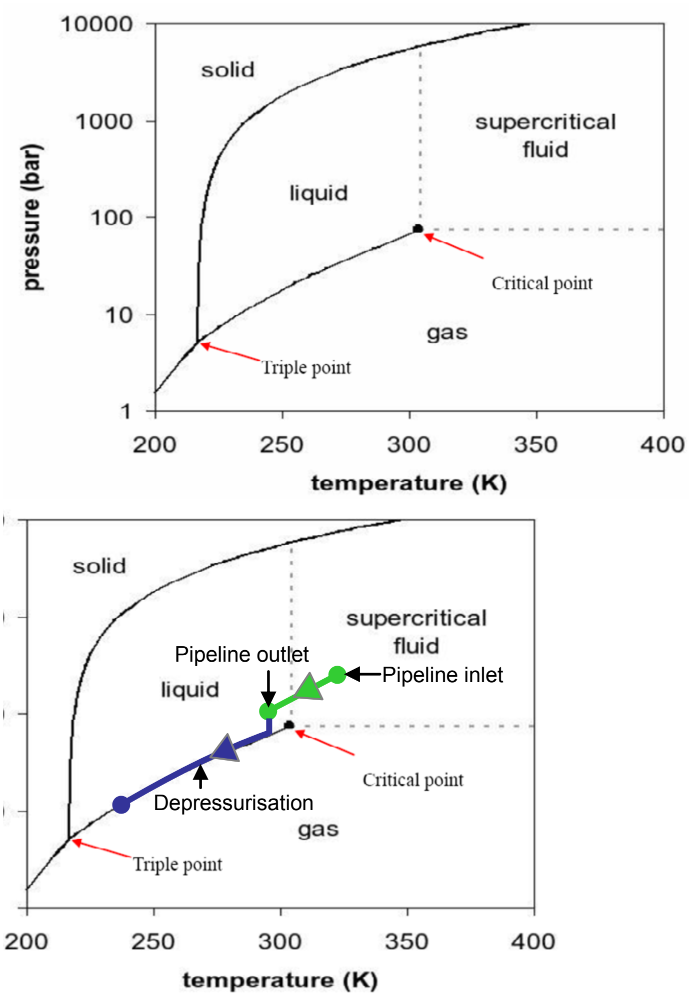

Figure 1: Phase diagram for pure CO_2 [4].

3. Effects of associated impurities

In the context of CCS, the CO_2 is most likely to come from large scale sources of combustion of fossil fuels, typically gas, oil or coal fired power plants. The different techniques for capturing the CO_2 are commonly characterized as pre-combustion, post-combustion or oxy-fuel processes. Combined with the type of fossil fuel, each of these processes may generate different types and amounts of contaminants or impurities such as H_2O, H_2S, SOx, NOx, N2, O_2, Glycol and other impurities.

The implications of the type and amounts of contaminants are not only limited to the individual effects but also how the different contaminants react with each other [3]. Combined with free water, H_2S, NO_x and SO_x will form acids which may significantly increase corrosion rates. At the right combination of pressure and temperature and presence of free water, hydrates may form in a similar way as for natural gas. The guideline will provide recommendations on how to handle the effects of contaminants both addressing design and operational issues.

The importance of sufficient dewatering of the CO_2 composition at the inlet of the pipeline is evident for a number of reasons described in further detail in the following sections. It is important to note, however, that the water content for CO_2 at the inlet to the pipeline must be specified in a different way compared to what is standard procedure for natural gas pipelines. For natural gas pipelines the water content is normally specified by a maximum water dew point temperature at the maximum operating pressure (or pipeline design pressure). As long as the pressure at any location in the pipeline does not exceed the maximum operating pressure and/or the temperature does not drop below the dew point temperature, free water can not appear. For dense phase CO_2 the ability to contain water is reduced with reduced pressure, i.e. the dew point temperature increase with decreasing pressure. At the same time other contaminants present in the CO_2 composition may have significant effects on the water solubility. Appropriate Equations of State (EOS) needs to be applied when designing the CO_2 dewatering system. As part of the guideline development a detailed review of existing Equations of State is being performed along with an assessment of the capabilities of available commercial pipeline simulation tools to account for water solubility with sufficient precision.

4. Pipeline safety issues

The guideline will give provisions for safe design and operation of a CO_2 pipeline. The guideline will address both design and operational aspects to reduce the probability as well as the consequences related to CO_2 pipelines. Both in-field CO_2 distribution lines in an enhanced oil recovery (EOR) project and long distance transmission pipelines will be included in the guideline. Operational experience of today and the available statistics do not give a clear empirical picture of the probability of incidents per unit length of a CO_2 pipeline compared to natural gas pipelines. However, the operational experience of today is based upon much longer length of natural gas pipelines compared to CO_2 pipelines.

Current CO_2 pipelines run mainly through sparsely populated areas. In the context of industrial scale CCS, the total length of CO_2 pipelines will increase and it is likely that the pipelines will expose more densely populated areas. The latter primarily relates to onshore CO_2 pipelines, but the potential risks associated with an uncontrolled release from a subsea CO_2 pipeline can not be disregarded, particularly in the near shore areas or near offshore facilities.

The guideline will give recommendation on the hazard classification of CO_2, also considering the effects of other contaminants in the CO_2 composition that may potentially pose a safety or environmental risk. In addition, recommendations related to technical design and operational philosophy will be given, and also recommendations on safety zones depending on the potential consequences of a CO_2 release. Typically for offshore oil & gas pipelines a higher pipeline wall thickness (fortified zones) is selected for safety critical sections of the pipeline.

Considering that CO_2 is a non-flammable gas, the consequences of an incidental release of CO_2 are different compared to a natural gas. The implications of exposure to elevated concentrations to humans are relatively well known. Depending on the CO_2 concentration inhaled and exposure duration, toxicological symptoms in humans range from headaches, increased respiratory and heart rate, dizziness, muscle twitching, confusion, unconsciousness, coma and death.

As part of any safety risk assessment, the consequence zone for both controlled and uncontrolled release of CO_2 needs to be established. Compared to natural gas, CO_2 has a significantly higher molecular weight, i.e. the density of the CO_2 gas at ambient conditions will be heavier than air. A release of natural gas may also appear as a heavy gas due to reduced temperature at the leak point. However, as the temperature of the gas cloud increase, the gas plume is expected to rise. Dispersion of CO_2 is comparable to dispersion of e.g. propane which has a similar molecular weight and for which modelling techniques are currently available. The main concern relates to elevated concentrations of CO_2 at topographically low points.

It is essential that the risks to people and the environment in the vicinity of a CO_2 pipeline are 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 issues related to transport of CO_2 includes both controlled and uncontrolled release of CO_2.

5. Internal corrosion

The guideline will clearly emphasize the criticality of dewatering of the CO_2 composition, also addressing the potential issues related to other contaminants.

The guideline will also address possible methods for quantifying the risk of internal corrosion resulting from temporarily off-spec water content. From an operational point of view, however, free water in the pipeline is not an option.

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 will give rise to extreme corrosion rates, primarily due to the formation of carbonic acid. Presence of other contaminants/impurities 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.

Internal corrosion may lead to a pin-hole leak that can be detected by a leak detection system. The time it takes to depressurise the pipeline may, however, be significant depending on the size and length of the pipeline and/or the distance between block valves. In worst case internal corrosion may cause pipeline rupture with a subsequent large instantaneous release of CO_2.

From the long operational experience with onshore CO_2 pipelines in North America, internal corrosion is not experienced as a significant pipeline failure mode. According to U.S. Department of Transportation's Office of Pipeline Safety there are no reported pipeline damages caused by internal corrosion. Based on discussions with the pipeline operators, this is mainly a result of the high focus on the measured water content in the CO_2 before entered into the pipeline, and the strict procedures for shutting down the line in case the dewatering system can not meet the specifications. 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. Concern has been raised with respect to the future increase in number of CO_2 pipelines and the additional effects of impurities such as H_2S.

Current available models for calculation of the corrosion rate are not considered applicable for a carbon steel CO_2 pipelines operated with presence of free water.

Application of corrosion resistant steels for longer pipeline sections is generally not considered feasible from a cost perspective. However, it may be an option for shorter pipeline sections considered particularly critical.

6. Ductile running fracture

A ductile running fracture may potentially run for several pipeline joints and cause.an instantaneous release of the contained medium. This must be avoided. The guideline will develop design requirements in order to ensure that the pipeline has sufficient fracture arrest capacity. The fracture arrest properties of a pipeline intended for transportation of CO_2 at a given pressure and temperature depends on the wall thickness of the pipe, the type of material and its properties, in particular the fracture arrest toughness, and the type of backfill.

A ductile running fracture starts with the initiation of a fracture. Typically the cause of this is not directly related to the progression of the possible ductile fracture, and the damage mechanism is not the same. Experience has shown that initial fracture is often caused by an "outside force"; i.e. damage caused by excavating, trawling, and even pipe laying. Typically the initiation takes place along a longitudinal weld, whereas the running fracture travels through the base material of the subsequent pipes.

The first barrier to fracture of a pipeline is a sound design and material selection, which together provide a low probability of fracture initiation. However, in case a fracture should initiate the probability of a ductile running fracture should be minimized.

.DNV has carried out extensive calculations of full scale tests and of pipelines carrying natural gas with the Battelle TCM in order to set necessary requirements to steel impact toughness to avoid ductile running fractures. The Battelle TCM is in principle applicable also to CO_2 pipelines as it includes the effect of the decompression of CO_2 from the actual conditions of gas transportation. However, it is a semi-empirical method, and there is a lack of available full scale test results where CO_2 has been used as media for verification of the method. Full scale burst testing will be planned for in phase 2 of the project.

7. Material compatibility

The choices of materials have to be compatible with all states of CO_2. Dense CO_2 behaves as solvent to certain materials and diffuses for instance into polymers. With respect to elastomers, both swelling and explosive decompression can occur. Swelling of the elastomer is attributed to the solubility/diffusion of the CO_2 into the bulk material. Explosive decompression occurs when system pressure is rapidly decreased and the gases that have permeated or dissolved into the elastomer expand. In a mild case, the elastomer will only show blistering, due to expansion of the diffused CO_2. Potentially the seal can rupture [4].

Assessment on behavior of polymeric materials used in seals, liners, and flexible pipes will be carried out. The most relevant materials to consider include HDPE, PA11, PVDF, PEX elastomers and epoxy coatings. Issues related to rapid decompression, diffusion and material degradation will be addressed. The guideline will give provisions for a proper approach to material selection.

8. Pipeline layout

The pipeline layout comprises the pressure safety, control and check valves as well as intermediate compressor and/or pump stations and instrumentation. The pipeline layout is a critical part of not only the pressure safety functions but also determines the accessibility for maintenance and repair. For existing onshore pipelines, intermediate block valves are normally installed to reduce the total volume to be relieved in case of a planned or unplanned depressurisation. To prevent down time, two valves are often installed in parallel, such that the repair can be performed under flowing condition in the bypass valve. Intermediate block valves are not considered a feasible solution for offshore CO_2 pipelines. The guideline will, however, address the critical pipeline layout issues to ensure optimum availability and minimum impact of maintenance and repair.

9. Pipeline operation

Optimum pipeline availability can only be achieved on basis of a sound pipeline design in combination with operational procedures that reduces the possibility of unplanned events causing pipeline shut-down and/or repair.

As previously addressed, the importance of continuous monitoring of the water content in the CO_2 stream at the inlet to the pipeline is essential to prevent several of the most likely failure modes. Existing CO_2 pipelines in operation applies automatic shut-down if the dewatering system does not meet the water content specification, which has proven to efficient in preventing both internal corrosion and hydrate formation. Another concern is to control and monitor additional impurities from a mixture of several CO_2 streams, such as methane (CH_4), hydrogen (H_2), nitrogen (N_2), sulphur oxides (SOx), nitrogen oxides (NOx), which may affect the CO_2 with respect to flow, pressure, water drop out and hydrate formation [3]. The effects of contaminants may also have implications on the pipeline response during shut-in and/or depressurisation.

Based on operational experience with existing CO_2 pipelines, one of the main concerns related to pipeline depressurisation is the potential risk for formation of solid state CO_2. If solid CO_2 is formed, a considerable amount of time may be required for the CO_2 to sublimate. The sublimation time will depend on the ambient temperature and the pipeline insulation properties. A too rapid depressurisation will also cause a rapid cool down of the pipeline, potentially causing detachment of external coating when the pipe diameter contracts. Formation of solid state CO_2 may be prevented by appropriate setting of the depressurisation rate. Hence, depressurisation of a longer section of a CO_2 pipeline may take considerable amount of time, hence will potentially have significant impact on the availability of the pipeline. This concern applies both to planned and unplanned depressurisation events. The guideline will address and provide recommendations on how to perform controlled pipeline depressurisation without causing risk of freeze out of solid CO_2 in the pipeline.

10. Conclusion

The guideline issued by the end of July 2009 will be a fully applicable guideline based on current knowledge. The next phase of the project will be to close identified knowledge gaps with extensive R&D activities. By issuing a guideline based on current knowledge, we ensure implementation of existing knowledge and experience. Also, we make existing knowledge available to the industry and regulatory bodies. Uncertainties related to R&D activities will be reduced by time as these activities are completed and the guideline is revised.

11. Acknowledgements

The development of the guideline is carried out as a joint industry project. The industry partners are StatoilHydro, BP, Shell, Vattenfall, Dong Energy, Petrobras, BG International, ArcelorMittal, Gassco, Gassnova SF – the Norwegian state enterprise for carbon capture and storage, and ILF Consulting Engineers. Governmental representatives from the Netherlands, Norway, and the UK are involved as observers. Sintef, Institute for Energy Technology (IFE) and Polytec will assist on the technical content. DNV gratefully acknowledges the support by the project partners.

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