CARBON DIOXIDE PIPELINES: A PRELIMINARY REVIEW OF DESIGN AND RISKS

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ABSTRACT

More carbon dioxide (CO_2) pipelines are expected to be built within the next decade to support enhanced oil recovery (EOR) projects and, possibly, geological sequestration of CO_2 where it is deemed necessary to comply with Kyoto Protocol requirements. The paper discusses the impact of carbon dioxide on equipment selection and equipment design specific to CO_2 compression and transportation.

INTRODUCTION

Carbon dioxide pipelines have been in use for many years. One of the most recent constructed was the Weyburn CO_2 pipeline from Beulah, North Dakota, USA, to the Weyburn Oil Field in Saskatchewan, Canada. Pipelines with similar, or larger, capacities will likely be designed and constructed within the next decade to enable implementation of several initiatives to capture, use, and store CO_2.

Carbon dioxide is an important gas that has been used by industry for several decades. Many of these applications are contained "Inside Battery Limits" (ISBL), and the operations of these facilities are controlled by well trained operators dedicated to the plant where this gas is produced. In many industries, CO_2 is a valuable feedstock, and it has also been used on a larger scale, in recent years, for enhanced oil recovery applications.

New CO_2 pipelines will be built in the immediate future, and some will inevitably be close to population centres. The risks associated with these CO_2 pipelines may be greater than those for hydrocarbon pipelines.

CURRENT MISCONCEPTIONS

Public perception is that there is significant experience with pipeline design and that CO_2 is relatively benign. Those in the industry know that this is not the case and that special design considerations need to be implemented when constructing facilities for processing and pipelining CO_2. Significant information has already been published detailing the hazards of CO_2 and the dangers presented by relatively low releases. The Lake Nyos incident in Cameroon, and, perhaps, ancient Pompeii, are amongst the largest known accidents involving naturally occurring CO_2. Several other isolated incidents with naturally occurring CO_2 have helped renew our interest in the public-safety aspects of handling, transporting, or storing CO_2.

Some of the risks are reviewed herein and attention is paid to material selection for equipment and valves, pipeline routing, and other issues to promote safety to humans, wildlife, and the environment in the vicinity of these facilities.

Conventional natural gas and sour gas pipelines have been designed and operated based on good industry knowledge and experience that have been acquired over the years. Despite this expertise, some incidents of small and large gas leaks are detected and dealt with by emergency response teams, confirming that even good design cannot prevent accidents. When the leaks are small, the released gas disperses easily. Major events such as pipeline

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rupture and explosions also occur and can cause gas burns and dissipations that may result in fatalities and major damage to the pipeline.

The difference with CO_2 is that neither small nor large leaks can be dispersed in the same way as for natural gas pipelines. The ability of CO_2 to collect in depressions in the land, in basements and in other low-lying areas such as valleys near the pipeline route, presents a significant hazard if leaks continue undetected. It is a "heavier than air" [1] gas similar to propane, so lending itself well to accumulation in depressions. Hydrocarbons will eventually ignite or explode in such areas if, and when, conditions are "right", but CO_2 can stay there undetected for a very long time. Current process plant practices provide for operator testing for heavy hydrocarbons and CO_2 in low-lying areas in plants before they enter these potentially dangerous areas.

DESIGN CONSIDERATIONS

Dry CO_2 is inert to commonly used industrial materials. However, CO_2 is an acid gas and will react with water to form carbonic acid. Carbonic acid corrosion is a formidable challenge and consideration for facilities that process CO_2. Carbonic acid corrosion of carbon steels has been recognized for years as a major source of damage in oil-field equipment and gas pipelines, and is commonly referred to as "sweet gas" corrosion.

Material selection in these environments is governed by the corrosion rate, which can be established by a number of predictive tools. For example, the de Waard/Milliams nomograph [2] is used to estimate corrosion rates of carbon steel under various operating temperatures and CO_2 partial pressures. For piping applications with high concentrations of carbonic acid, particularly in turbulent flow areas (such as downstream of control valves, or near pumps), corrosion-resistant stainless steels provided with erosion protection [3] may have to be used.

The use of CO_2 for enhanced oil recovery projects typically requires CO_2 transmission by pipeline. The properties of CO_2, corrosion rates, and gas mixture make-up, are important considerations toward establishing the material specification for a CO_2 pipeline. The gas mixture may include a mix of CO_2 and hydrocarbons, which could include liquid components, impacting overall pipeline pressures and creating design issues as the pipeline may need to be designed to operate with either gas, or liquid-phase, content. Water, hydrocarbons and CO_2, beyond forming corrosive carbonic acid, may combine to form hydrates that could plug the system. Technology for removing water from CO_2 is conventional, and is discussed extensively in the literature [4,5,6].

To be transported in a pipeline, CO_2 should be compressed to ensure that single-phase flow is achieved. The most widely used operating pressure is between 7.4 and about 21 MPa. Above 7.4 MPa, CO_2 exists as a single dense phase over a wide range of temperatures. Clearly a transmission pipeline can experience a wide range of ambient temperatures, so maintaining stability of this single phase is important in order to avoid considerations of two-phase flow that could result in pressure surges.

Statistics of pipeline incidents have been presented based on data from the Office of Pipeline Safety, US Department of Transportation [7]. Over an 11-year period (1990-2001), 10 incidents were reported for CO_2 pipelines. The sample size for CO_2 pipelines was small compared to those for natural gas and hazardous-liquids transmission, and it is reasonable to suggest that, statistically, the number of incidents involving CO_2 should be similar to those for natural gas transmission. With the knowledge that there will be incidents, pipelines must be designed, constructed, operated and maintained to mitigate these incidents. These could be the result of an outside force, corrosion, weld or pipe failure, operator error, or other influences. Although the possibility of a fire or explosion, ever-present with a natural gas or hydrocarbon liquid pipeline, is absent with a CO_2 pipeline, the safety impact of a CO_2 release is considerable. Given the density of CO_2 is high enough that the gas will collect in low-lying areas, displacing air, and given its adverse human physiological impact, a conservative approach must be used during the design and construction of a CO_2 pipeline.

On a macro scale, the design considerations for CO_2 pipeline transmission are well known. The number of CO_2 transmission projects that have been successfully operating attest to this success. However, current CO_2 transmission lines in North America predominantly run through sparsely populated areas, and the impact of an incident may be limited as the released CO_2 eventually dissipates with little chance of affecting human populations.

Nevertheless, a major CO_2 release has potentially devastating consequences, and the design of the piping system must reflect the risks involved.

Typical pipeline-engineering considerations for CO_2 include:

- operating pressure;
- operating temperature;
- gas mixture composition;
- corrosivity;
- ambient temperatures; and
- pipeline control (SCADA).

Examples of additional specific design considerations in place for CO_2 pipelines are:

- effect of cooling from pressure changes;
- requirement for dehydration of CO_2;
- routing topography;
- dispersion pattern;
- valve materials;
- compressor, seal, and auxiliary materials;
- requirement to minimize flow transients; and
- risk assessment focused on impact of rupture on human health.

RISK MITIGATION

Pipeline transmission is a mature technology. In addition to major design issues, the "small things" must also be considered in order to ensure safe operation. Given that it is reasonable to assume there will be an incident, it is necessary to plan for containment to ensure minimal impact.

A risk assessment must consider pipeline block-valve spacing philosophy. This assessment must consider code and regulatory requirements, leak detection, potential hazards (river erosion, seismic activity etc.), environmental requirements, access to valve sites, and operations and maintenance requirements. The best solution for valve spacing will balance pipeline construction, maintenance and other costs with safety considerations. It will provide the opportunity to block-in sections of the pipeline that lose pressure integrity.

The pipeline material specification must consider code and regulatory requirements. Mechanical properties are a critical component of the specification, specifically, strength and toughness. The thickness of the steel used in the pipeline relates directly to its strength, and also has considerable impact on steel cost, material availability, and weldability. From a safe-operation perspective, toughness is a critical property and is directly linked to ensuring appropriate fracture control. It is important to ensure that fractures initiate as ductile, not brittle, fractures because brittle fractures typically initiate and propagate at lower energy inputs than ductile fractures and tend to be fast-running resulting in potentially catastrophic failures. Sufficient design toughness is determined by calculating the required fracture toughness of the pipeline steel to support a critical flaw (crack) size.

Including too many valves from the compressor to the injection or storage point can also be a problem. Although more legs can be isolated and vented, extra valves produce additional leakage paths at the flange connections and past the stem packing. All pipelines have both operating and emergency pressure-relief systems. With CO_2 pipelines, however, care must be taken to ensure that extreme cooling does not take place during pressure relief as this will be detrimental to the valves.

Attention to the "small things" is especially important in CO_2 pipeline design.

MERCAPTANS

Many people recognize the unpleasant smell of domestic natural gas due to the addition of odourizers to the gas. The odour is an early warning indication of a leak. CO_2 is odourless, so, given its dangerous qualities, there may be advantages to using a similar odour-additive strategy for CO_2 transmission and leak detection, particularly if the CO_2 pipeline is routed near human population centres.

THERMAL IMAGING

Aerial pipeline surveys are a common approach to checking pipelines. A release of pressurized CO_2 is accompanied by a temperature transient, typically a drop in temperature. This property presents an opportunity to inspect for CO_2 releases or leaks using thermal imaging. A low-level aerial survey would allow high-resolution thermal images to be obtained that could help detect releases on an above-ground pipeline and possibly from buried pipelines depending on the magnitude of the CO_2 release.

INTERNAL-CORROSION CONTROL PROGRAM

An internal-corrosion control program is an important element for the safe operation of the pipeline. It is closely linked to the pipeline design specification, requiring that thorough baseline knowledge of the pipeline be established. The program should encompass the broad spectrum from prediction of corrosion rates, in-service inspection, maintenance, and engineering assessments.

EQUIPMENT

Careful selection of the compressor and other major equipment is required. Materials of construction casings, internals, valves and gaskets, are critical. Pressure, temperature and flow excursions and transients needs to be evaluated by a risk review team to ensure that all components have the ability to handle these transient conditions without damage.

A suction scrubber is needed upstream of the CO_2 compressor unit to ensure that liquids do not enter the machine and thereby cause significant damage to internal parts of the compressor. This unit is a critical component, and it is essential that the selected manufacturer can demonstrate sufficient experience with this application.

Another aspect of the design is to ensure that miscellaneous smaller items, such as valves, are appropriate for operation at very low temperatures, and are suitable for this service. The very cold temperature caused by leaks can cause embrittlement of the valve components, leading to breakage and additional unwanted events. Minor materials occasionally overlooked when considering CO_2 leaks include gaskets and O-rings in a valve that may not be suitable for CO_2 or low-temperature service.

CONTAMINATION

Contamination of CO_2 can have potentially catastrophic consequences as it can cause major excursions in the property behaviour of the gas in the pipeline. It is therefore important that a thorough study be done at the CO_2 source, and at any branch connections, to ensure that contaminants cannot enter the pipeline gas. An example of a possible contaminant is methane, and CO_2 with small amounts of methane alters the properties of pure CO_2 significantly. Because methane might be "taken for granted" in pipeline design as its properties are so well known and most pipeline systems carry methane, its potential for harm might be easily overlooked in pipeline design.

If the pipeline, or upstream equipment in the source plant, has been used to transport or process other fluids or gases, contamination is certain unless adequate cleaning and inspection are performed prior to placing the unit into service.

LINEPACK

Natural gas pipelines are designed to occasionally tolerate "linepack". This occurs when the upstream compressor continues to operate even though a valve several kilometres downstream may have been inadvertently closed. If adequate control has not been designed, the compressor can operate for as long as a few hours before increasing discharge pressure or temperature shut down the machine. The storage of natural gas in the pipe can be tolerated when the pipeline has been designed for this. However, it is undesirable to have CO_2 compressors continue to operate when downstream valves are closed, since considerable inventory could accumulate that cannot be vented or disposed off without some risk to personnel, equipment, or nearby populations. A fully functional pipeline control system for monitoring CO_2 accumulation at strategic points in the pipeline is essential.

EMERGENCY-RESPONSE PLANNING

Knowing that most CO_2 pipelines may have a number of incidents per year, designers must ensure that adequate procedures are in place to handle leaks and that there is a review process with an emergency-response (ERP) team during the risk-review study. Odourization of CO_2 in pipelines appears to be a necessity to ensure that there is early detection of leaks. The disadvantage with this detection approach is that there may not be an increase in the odour level to indicate when lethal limits are being approached. Special precautions and design elements need to be investigated and incorporated as necessary. It is critical that a thorough study be made of the routing, terrain, and seasonal effects, to ensure that a good dispersion study is performed to assist the ERP team to immediately identify evacuation needs.

SAFETY REVIEWS

An experienced risk-review team should be formed to carefully assess the design of the system and to ensure that operating parameters will not lead to risky operational excursions. Should such an excursion happen, adequate mitigation measures must be in place.

All equipment, pipe, compressors, control valves, and valves purchased in bulk, must be carefully selected, with sufficient quality checks, balances and traceability to ensure that one inadequate "minor" valve does not lead to a major catastrophe.

The pipeline needs to be considered as a complete system inclusive of pipe, compressors, valves, and upstream processes. The system needs to be looked at as it would be under a HAZOP (Hazard & Operability) study with careful review of what can go wrong in the system. A HAZOP study team, typically made up of technical people who have significant experience in design, operation, control, and safety of particular processes, jointly reviews the design and attempts to find areas where safety and operability issues may have been compromised or inadequately addressed. As an example, in a typical HAZOP study, the "system" or "subsystems" are assumed to be operating within design parameters of pressure, temperature, flow, and fluid composition. Excursions from these conditions are intentionally considered to see a) the effect of changes to design parameters and b) if these changes cause safety or operability risks. If it is found that, say, the design flow can increase due to overspeeding of the compressors, and if these are driven by gas or steam turbines, the system components need to be reviewed to ensure that adequate protection is in place to prevent or mitigate these excursions. In this example, had this been a natural gas pipeline, the increased flow may have caused the relief valve to operate. However, inadvertent operation of a relief valve in a CO_2 pipeline would cause freeze up of the valve due to formation of dry ice with the sudden expansion of the supercritical fluid. Designers therefore need to review each of the parameters to ensure that flow, pressure, and temperature excursions can be safely handled with this supercritical fluid.

OWNER/CONTRACTOR/SUPPLIER EXPERIENCE

Owners must ensure that all operations personnel are provided with the necessary training, as they are for sour-gas processes. Contractors must be selected who have sound experience in the design of these pipeline systems. The experience of the manufacturers of all components needs to be verified, and audits should be performed by experienced owner/contractor personnel. A minimum of three years' operating experience is suggested for all equipment in this type of service to ensure that all components have had the necessary exposure to $CO_{2,}$ and its contaminants, without detrimental effects.

PIPELINE CONTROL

A control system must be reliable and responsive in adequate time to ensure that leaks do not propagate. Real-time monitoring of key parameters, including pressure, temperature and flow rate, is required to ensure that, if large swings in values occur, timely intervention is made to prevent unwanted changes. Dynamic static and strain measurement, leak detection, fatigue-life-prediction, and other key indicators should be part of the control system design.

CONCLUSION

CO_2 pipelines can be safely constructed by ensuring that adequate risk assessment is done and that conventional wisdom is used in both design and operation. Industry experience has to date generally been good with the storage and handling of CO_2. However, if the potential for developing new, longer CO_2 pipelines which have branch lines close to populated areas is realized, there will be increased risk to the public. It is therefore imperative that extra vigilance be used when designing these pipelines, and it is recommended that there be experienced management of the project from start to finish. In addition, regular safety reviews must be performed of the operating pipeline, any recorded incidents should be studied carefully, and corrective procedures be established to prevent recurrence. The initial design should also include appropriate procedures for eventual abandonment of the pipeline and prevention of use if damaged equipment and material are not replaced.

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