State-of-the-Art in Transporting CO_2 in Pipelines

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Abstract

Pipelines are expected to play a central role achieving net-zero greenhouse gas emissions by transporting CO_2 from large industrial sources to end users or storage operations. Some CO_2 pipelines currently operate around the world, but the planned expansion of carbon capture, utilization and storage will require many new CO_2 pipelines operating in and around urban areas and could include repurposing some natural gas pipelines to transport CO_2. The most efficient way to transport CO_2 is in a supercritical state (also referred to as "dense phase"). This introduces special pipeline design considerations in terms of higher pipeline operating pressures, requirements for greater fracture toughness of the pipeline steel and complex behaviour of large accidental releases. The key areas of work required to ensure the safe and reliable operation of CO_2 pipelines are identified as:

- Dispersion modeling in populated areas and areas where the topography will have a significant impact on the dispersion pattern;
- Effects of impurities from carbon capture processes on the transport and decompression behaviour of CO_2;
- Fracture toughness requirements of new and converted CO_2 pipelines to ensure safety and reliability levels are comparable to natural gas pipelines.

1. Purpose of This Paper

This paper has been published as part of a series of papers on work completed on various aspects of CCUS with recommendations regarding how to advance carbon capture in the future. This paper shares the lessons learned from a portfolio of projects including projects funded by Alberta Innovates and ERA and projects executed by C-FER and InnoTech related specifically to CCUS completed over the past two decades. These organizations work very closely to ensure the most efficient development and deployment of promising solutions occurs within Alberta. This paper serves to summarize the body of knowledge developed and supported by these organizations, and to identify the remaining gaps that need to be addressed with recommendations regarding how to help enable widespread use of CCUS both in Alberta and around the world. This paper is not intended to be a policy position paper, but it may be used to inform policy decisions as required. It is primarily focused on technology and knowledge development, identifying technology gaps, insights and priority focus areas for further investment to de-risk CCUS technologies for widespread deployment to support emissions reductions targets.

2. Introduction to CO_2 Transportation

Carbon capture operations are rarely co-located with use or storage facilities, so the captured CO_2 requires some mode of transportation for delivery to its destination.

For most CCUS operations, pipelines will be the most economical and the safest way to transport CO_2 from the capture location to the storage location (Doctor, et al., 2005). Rail and road tankers can transport small quantities of liquefied CO_2 over short distances, but they are generally not suitable for large-scale storage projects. Marine transport of liquefied CO_2 could be used to transport large quantities over long-distances. This would require storage and loading facilities like those for liquefied natural gas shipping, making it impractical for most projects that do not require intercontinental transport. Offshore storage facilities could use a combination of ships and pipelines to transport CO_2, in some cases by repurposing existing oil and gas pipeline infrastructure to reduce the cost of developing these projects (Neele, ten Veen, Wilschut, & Hofstee, 2012).

This report focuses on pipeline transportation of CO_2 as it will be the primary means to connect CO_2 capture facilities to end users and storage facilities.

3. Brief History of CO_2 Pipelines

A review of CO_2 pipelines by the International Energy Agency in 2014 identified 29 CO_2 pipelines worldwide (International Energy Agency Environmental Projects Ltd., 2013). The review noted that the majority of CO_2 pipeline experience is in the US. Pipelines carrying naturally occurring CO_2 for enhanced oil recovery in Texas have been in operation since 1972 (Mohitpour, Seevam, Botros, Rothwell, & Ennis, 2012). Note that naturally occurring sources produce pure CO_2, unlike CO_2 captured from industrial sources that typically contain impurities such as nitrogen, oxygen, argon, carbon monoxide, hydrogen and methane.

Pipeline transportation of CO_2 in CCUS operations is much more recent and of a more limited extent than the enhanced oil recovery operations in the US. The Weyburn-Midale CO_2 Monitoring and Storage Project in southern Saskatchewan was one of the first, in 2000, transporting CO_2 by pipeline 320 km from the Great Plains synfuel plant in Buelah, Montana, to oil fields in Weyburn, Saskatchewan (International Energy Agency Greenhouse Gas Research & Development Programme, 2004). In 2016, the SaskPower Boundary Dam Carbon Capture Project began to supply CO_2 from a coal-fired power plant to the Weyburn CO_2 Enhanced Oil Recovery Project through a 66 km long pipeline (Craig & Butler, 2017).

In 2015, the Shell Quest project in Fort Saskatchewan, Alberta, began transporting CO_2 in an 80 km pipeline from a bitumen upgrader to geological storage wells (Alberta Department of Energy, 2019). Project funding for Shell Quest was provided by Alberta Innovates, the Province of Alberta and Natural Resources Canada.

The most recent CO_2 pipeline development in Canada is the Alberta Carbon Trunk Line (ACTL) operated by Wolf Midstream that was in full operation in 2020 (Enhance Energy, 2019). The ACTL runs 200 km from Fort Saskatchewan, Alberta, to an enhanced oil recovery operation in Clive, Alberta (Wolf Midstream, n.d.). Project funding for the ACTL was provided by the Province of Alberta and Natural Resources Canada.

A new proposal to develop the Alberta Carbon Grid (ACG) was announced in August 2021 by Pembina Pipelines Corporation and TC Energy (Pembina Pipeline Corporation, n.d.). The ACG will consist of an approximately 650 km long CO_2 pipeline network running from multiple industrial CO_2 sources in oil sands operations in Fort McMurry, Alberta, and refining and petrochemical operations in Fort Saskatchewan, Alberta, to sequestration reservoirs in west central Alberta around Drayton Valley.

The total industry experience with operating pipelines carrying CO_2 from industrial sources is only about 7,000 km-years. This pales in comparison to just the Canadian experience gained from operating 117,000 km of oil and gas transmission pipelines for decades (Natural Resources Canada, 2020). The challenges of long-term operation, inspection, maintenance and repair of these new pipelines are, therefore, still unknown. These challenges could also change as new industrial sources and different carbon capture technologies come online that could change the makeup of the impurities in the CO_2 stream.

Release incidents on CO_2 pipelines are reported in a similar way to how they are reported for oil and gas pipelines. Compared to oil and gas pipelines, the incident history for CO_2 pipelines is limited due to the relatively short length of pipelines in service and the short duration of their operation. Consequently, reviews of CO_2 pipeline safety have been unable to conclude whether existing CO_2 pipelines have safety records similar to that of oil and gas pipelines (International Energy Agency Environmental Projects Ltd., 2013).

4. State of the Art in CO_2 Pipelines

CO_2 pipeline technology is generally considered to be mature, based largely on systems operating for many years in enhanced oil operations in the US. Design requirements for pipelines in Canada are contained in CSA Z662 *Oil and gas pipeline systems* (CSA Group, 2019). Note, however, that the Alberta Energy Regulator emphasizes the following five requirements for CO_2 pipelines in Directive 56 (Alberta Energy Regulator, 2021):

a. Specific operating pressure ranges and pressure drops to avoid unnecessary phase changes

CO_2 is typically transported as a dense-phase gas that has a density similar to that of hydrocarbon liquids, but it has a low viscosity similar to that of a gas, making it easy to pump large volumes through pipelines. If the pressure of the CO_2 drops below the pressure required to maintain the dense-phase state, a separate, low-density gas phase would develop in the pipeline that could cause flow instabilities in the pipeline and adversely affect gas compression and metering equipment.

b. Corrosion mitigation and monitoring issues due to water content and other impurities

Capturing CO_2 from industrial sources (anthropogenic CO_2) generally contains a variety of impurities such as nitrogen, oxygen, argon, carbon monoxide, hydrogen and methane (Petroleum Technology Alliance Canada, 2014). This project, which was partially funded by Alberta Innovates – Energy and Environmental Solutions (now Alberta Innovates), showed that the types and concentrations of these impurities vary depending on the specific capture technology used. Upsets in the capture process can also cause the concentrations of these impurities to change during operations. In addition, water content must be tightly controlled to avoid the formation of highly corrosive acids in the pipeline system as water combines with CO_2 and other impurities. Excess water in the gas can also form solid, ice-like deposits called hydrates under some pressure and temperature conditions and they can impede flow and damage equipment in the pipeline. The potential for hydrate formation might require a lower allowable water content in cold regions where the CO_2 is chilled by the surrounding cold ground.

c. Specific material considerations to minimize the risk of fracture propagation

If a crack in a pipeline carrying dense-phase CO_2 penetrates the pipe wall, the through-wall crack can continue to extend lengthwise if the pipeline operating pressure is sufficient to promote crack extension. The decompression characteristics of dense-phase CO_2 are such that the internal pressure available to drive crack extension, once crack extension begins, is much higher than for oil and gas products. Unless the line pipe material has adequate strength and toughness to resist crack extension, the resulting rapid, fracture-driven crack propagation can extend long distances before the driving pressure falls to the point where fracture arrest occurs, resulting in extensive damage to the pipeline and its surroundings. Proper material property and wall thickness selection can minimize the potential for fracture propagation and, where it is deemed uneconomical to design the pipeline to ensure adequate prevention of fracture propagation in the event of crack-induced pipeline failure, reinforced or thicker sections of pipe (i.e. crack arrestors) can also be added at intervals along the pipeline length to limit the extent of fracture propagation.

d. Emergency Response Planning and dispersion modelling considerations

Unlike oil and gas products, CO_2 is not combustible, so the consequences of releases from the pipeline are different. A CO_2 release can form a vapour cloud that is denser than the surrounding air, causing it to stay close to the ground. The CO_2 tends to collect in low-lying areas, displacing the air and creating an asphyxiation hazard to people and animals in the impacted area. Product release and dispersion modelling are required to determine where the CO_2 will travel and in what concentrations it will accumulate. Specific emergency response plans and procedures need to be developed by operating companies and first responders to recognize this hazard and to minimize the potential impact of major CO_2 releases.

e. Safety precautions that will be taken during pipeline operation and repair.

The hazards of CO_2 to workers in and around pipelines are different from oil and gas products. Different sensors to detect leaks might be required. Releases of CO_2 will tend to accumulate in excavations and sumps, creating low oxygen environments that could be harmful to workers. This includes intentional releases or “blow downs” of the pipeline to allow inspection and maintenance of the pipeline. Rapid depressurization of the pipeline during a blow down will cause significant cooling of the pipeline as the gas expands and cools. The resulting low temperatures could reduce the available fracture toughness of the pipeline and exposed equipment, thereby increasing their susceptibility to damage or failure while under pressure.

The Alberta CO_2 Purity Project (Petroleum Technology Alliance Canada, 2014), which was partially funded by Alberta Innovates – Energy and Environmental Solutions, set out to determine the impact of impurities such as nitrogen, oxygen, argon, carbon monoxide, hydrogen and methane on the flow characteristics of captured CO_2 streams from industrial sources. A series of flow tests with different impurity levels at TC Energy’s Gas Dynamics Test Facility in Didsbury, Alberta, showed that the flow capacity of a pipeline carrying CO_2 is reduced in proportion to the change in the mixture density caused by the impurities. For instance, if the CO_2 stream density is reduced by 6 per cent by the impurities, the flow capacity would be reduced by approximately half that amount, or 3 per cent. Low density impurities including hydrogen and methane would have the largest impact in reducing the mixture density. Therefore, impurities left in the CO_2 from the capture process will have an impact on the operating cost and deliverability of the pipeline system.

The Alberta CO_2 Purity Project also included work by Dr. Weixing Chen at the University of Alberta to assess how impurities affect the corrosivity of CO_2 in pipelines. The work concluded that impure CO_2 would not cause corrosion if the pipeline is operated such that the pressure and temperature prevents creation of a separate water phase in the pipeline. Other work in the project by Dr. David Sinton at the University of Toronto showed that the pipeline operating pressure might have to be increased for some mixtures of impurities to avoid formation of the separate water phase that could lead to corrosion.

Recent work by C-FER, a subsidiary of Alberta Innovates, has been investigating how releases of different gases and liquids disperse when they are released from a pipeline. This analysis includes products such as crude oils and refined liquid products, sweet and sour natural gas, carbon dioxide and natural gas liquids including ethane and propane. The analysis assesses the overall size and downwind extent of the safety-related hazard zones associated with these products as a function of key pipeline and weather conditions and the life safety and environmental impact considering the flammability and toxicity of the product. The results of this work will inform planned updates to the Canadian pipeline design standard CSA Z662 that are intended to ensure that the safety-related hazards posed by liquid and gas releases (including CO_2) are adequately and consistently addressed during both the pipeline design phase and the operational phase, when safety assessments are required to address, for example, class location changes.

C-FER is also assisting pipeline operators in assessing the feasibility of converting existing pipelines to carry CO_2. The first step of a conversion assessment is usually to determine if the pressure rating of the pipe is sufficient to accommodate the pressure required to maintain the CO_2 in the optimal dense-phase. If the pipeline does not have sufficient pressure capacity for dense-phase operation, lower pressure operation can be considered, but this significantly reduces the transportation capacity of the pipeline. The second step of the assessment is usually to determine if the existing pipeline material has the fracture toughness properties required to prevent uncontrolled fracture propagation in the event of crack-induced pipeline failure. The decompression behaviour of CO_2 with impurities, and the specific toughness requirements necessary to ensure fracture arrest of pipelines transporting these CO_2 mixtures, is an area of active research (Wei, et al., 2021). While various gas decompression models and fracture toughness assessment models are available, additional work is required to provide clear and specific guidance in the Canadian standards (and Provincial guidance documents) that are applicable to the design and assessment of pipelines transporting CO_2.

5. Remaining Gaps - Transportation

Some of the unique challenges that are expected when establishing and operating a pipeline network to transport CO_2 from capture facilities to end users or storage sites are described in the following subsections.

5.1. Brownfield Development

Most CO_2 pipelines will be connecting operating industrial sites to storage operations in areas with mature oil and gas fields. As such, numerous crossings (roads, railways, watercourses, pipelines and utilities) will be encountered when constructing new pipelines, which will add to the complexity and cost of construction. These crossings will also be susceptible to long-term damage due to activities or events on those crossings, such as:

- vehicle traffic and construction equipment on roads and railways;
- failure of other pipelines and utilities; and
- erosion and flood events on watercourses.

The industrial sites where carbon capture facilities will be established are also likely to be adjacent to urban developments where the life safety impact of releases from the facilities and pipelines must be carefully considered.

5.2. Conversion of Legacy Pipelines to CO_2 Service

Some operators are considering converting under-utilized legacy oil and natural gas pipelines to transport CO_2. Operating pressures for CO_2 transport must stay above about 7.0 MPa at typical pipeline operating temperatures to maintain the dense-phase condition to minimize transportation costs. Most oil pipelines are designed to operate between 4.1 and 6.9 MPa (Natural Resources Canada, n.d.), so they are not likely to be suitable for transporting CO_2 in the dense phase state. Natural gas transmission pipelines are generally designed to operate at higher pressures, with some as high as 12.4 MPa, potentially making them suitable for conversion to dense-phase CO_2 transport. However, the fracture toughness required to prevent fracture propagation for these existing natural gas pipelines is typically lower than would be required to ensure fracture arrest in CO_2 service, requiring verification of the fracture toughness of the as-built pipeline and determination of the maximum operating pressure at which the existing line would be able to ensure adequate fracture propagation control. Where the inherent fracture arrest capability of the line pipe is found to be insufficient for CO_2 service, consideration must be given to the use of external crack arrestors at a prescribed spacing to ensure fracture propagation control. The cost-effective design of such external crack arrestors usually involves the use of non-metallic, composite material wraps, the performance of which is the subject of ongoing research.

Pipelines could also be converted to transport CO_2 at lower pressures, but this would significantly reduce the throughput on the line. Studies have shown that the cost of low-pressure CO_2 transport is up to 20 per cent higher than with a dense-phase system (Doctor, et al., 2005). In addition, Doctor, et al. (2005) note that the dense-phase system has the added advantage of delivering the CO_2 at high pressure, which is required for injection into storage reservoirs or for enhanced oil recovery operations.

Another key aspect of CO_2 pipeline design is ensuring that the pipe material has sufficient fracture toughness to arrest fracture propagation. The fracture toughness requirements for CO_2 pipelines can be significantly higher than required for natural gas and oil pipelines because the dense-phase CO_2 maintains the pressure longer as it decompresses during a release than other products. Various organizations have worked with shock tube tests, including NOVA Chemicals in Didsbury, Alberta, to develop models to simulate the decompression behaviour of CO_2 in a pipeline to understand how fractures propagate (Botros, Hippert, & Craidy, 2013).

Large-scale testing work to determine fracture toughness requirements for a planned CO_2 pipeline in the UK showed that it is difficult to predict the fracture toughness requirements (Cooper & Barnet, 2016). More recent tests were conducted in support of development of a CO_2 pipeline in China (Wei, et al., 2021). Large-scale fracture propagation tests, as shown in Figure 1, are helpful in verifying the ability to arrest fractures, but the cost and complexity of the tests prompted the authors to recommend developing simpler test procedures to verify pipe performance.

Figure 1: Result of a Full-Scale Test to Verify Fracture Propagation Arrest Capabilities for a Dense-Phase CO2 Pipeline

Source: **(Cooper & Barnet, 2016)**

5.3. Vapour Cloud Dispersion Modelling

For CO_2 pipelines, the primary threat is a release that forms a cloud of CO_2 vapour that is denser than the surrounding atmosphere, causing it to stay close to the ground so that it follows the local topography and accumulates in low-lying areas. These accumulations could pose an asphyxiation hazard to people and animals. Previous releases from CO_2 pipelines have not resulted in any human fatalities; however, note that the majority of current CO_2 pipelines are in rural areas, away from a significant number of people (International Energy Agency Environmental Projects Ltd., 2013). Detailed modelling of dispersion behaviour of CO_2 releases will be required as CCUS operations in industrial areas and adjacent to urban developments become more common (Vitali, et al., 2021). These analyses apply to constructing new CO_2 pipelines, as well as repurposing legacy oil and natural gas pipelines for CO_2 transport. The review of dispersion models indicates that simplified commercial models can generally match vapour cloud behaviour when local topography such as hills and depressions or buildings in urban developments do not significantly influence the vapour cloud behaviour. For these more complex dispersion scenarios, computational fluid dynamics (CFD) modelling shows promise. However, CFD modelling of CO_2 vapour cloud dispersion is relatively new and requires further benchmarking to ensure reliable results.

5.4. Impact of Impurities

Establishing a CO_2 transportation network with multiple CO_2 capture sources could introduce a complex and variable mixture of impurities in the pipeline system. Past work funded by Alberta Innovates – Energy and Environmental Solutions (Petroleum Technology Alliance Canada, 2014) and elsewhere has shown that impurities can affect both the flow capacity of the pipeline system and the potential for corrosion. Impurities can also impact the decompression behaviour during a release, which drives the fracture toughness requirements for the pipeline material.

Monitoring these impurities will be critical to the safe and efficient operation of a CO_2 pipeline network. This will become more important as multiple CO_2 sources come online to supply into the pipeline system, with each new process potentially adding different impurities. It will be important for the CO_2 generators to treat the CO_2 as a product, with tight specifications, rather than treating it as a waste stream for disposal.

The previous work also recommended learning more about the impact of impurities on the flow behaviour of captured CO_2 by conducting more tests with specific impurity mixtures and at conditions representative of dense-phase CO_2 transportation that could not be reproduced in the test flow loop at the time of the initial study (Petroleum Technology Alliance Canada, 2014).

5.5. System Reliability

Initially, the pipeline carrying CO_2 will be a critical component of ensuring the reliability of a CCUS network. If the network has multiple sources of CO_2, the supply will likely be relatively stable and relatively insensitive to upsets or planned/unplanned shutdowns of the CO_2 generation or capture processes. Likewise, a network with multiple CO_2 injection wells, possibly at multiple field locations, will ensure that the capacity to store CO_2 will be relatively constant and insensitive to well shut-ins or workovers. The pipeline, however, will be the single conduit for transporting the CO_2 from capture facilities to disposal. Interruptions in pipeline operation for planned activities like inspection and maintenance, and unplanned events such as third-party damage or leaks could temporarily halt CO_2 transmission. Temporary interruptions to storage and enhanced oil operations may not pose a significant problem; however, capture operations would immediately need to shutdown or vent CO_2 if the pipeline is not operating or throughput is temporarily reduced. If uninterrupted CO_2 capture is required, local temporary storage at the capture site would need to be added to the CCUS system to allow the capture operation to continue, even if the pipeline is not available or capacity is reduced. In Alberta, salt caverns at the capture facilities would likely be the most economical option for providing temporary surge storage for the pipeline system (Dusseault, Rothenburg, & Bachu, 2002). The utility of temporary CO_2 storage can be studied through an engineering design study to determine the functionality of equipment during intermittent versus continuous operation.

6. Recommendations for CO_2 - Transportation

Based on the work done through Alberta Innovates and C-FER, as well as work done by industry, academia and others, the key gap areas that require further research and development include:

- Conducting further testing of the impacts of impurities on dense-phase transportation of CO_2;
- Validating models for atmospheric dispersion of CO_2 vapour clouds that are used to determine hazard zone extent; and
- Evaluating available fracture arrest assessment methods and models and the toughness requirements they establish for pipeline materials to ensure that they provide levels of fracture propagation control comparable to that achieved for natural gas pipelines.

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