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Opinions

OPINION: Carbon dioxide pipelines are under-regulated and dangerous

By Bill Caram

Updated: March 2, 2023

Published: March 2, 2023



The Alaska State Capitol building, photographed on Wednesday, Jan. 18, 2023 in Juneau. (Loren Holmes / ADN)

If you happened across the small, rural community of Satartia, Mississippi, on Feb. 22, 2020, you might have thought you'd entered the scene of the most recent zombie movie. Dozens of residents collapsed, some walking in circles and foaming at the mouth amidst a cloud of green fog. Emergency responders, donning scuba gear, heroically ran into the cloud and carried victims to safety. Vehicles' internal combustion engines were inoperable, leaving many residents stranded and sick. All told, nearly 50 people went to the hospital, and some still suffer health consequences today.

It was, of course, not a zombie movie. A carbon dioxide pipeline operated by Denbury Resources had ruptured, emptying its contents into the community. Since carbon dioxide is an asphyxiant that is heavier than air, it stayed close to the ground while the terrain and weather kept it from dispersing for hours. Satartia is incredibly lucky to have avoided fatalities. I hope this kind of danger does not come to Alaska.

Last month, Gov. Mike Dunleavy unveiled legislation that would allow state lands and waters to become an underground carbon dioxide waste receptacle. Such a plan undoubtedly would involve a system of pipelines. Given the series of tax credits in the 2022 federal Inflation Reduction Act, which incentivizes carbon capture and sequestration, ensuring carbon dioxide pipeline safety is critical. Gov. Dunleavy's proposed legislation, House Bill 50 and Senate Bill 49, do not include any measures addressing pipeline safety, leaving needed safety upgrades entirely up to the federal government.

As a pipeline safety expert, I can confidently say that we are not ready for a buildout of carbon dioxide pipelines. Federal minimum safety regulations are in desperate need of modernization. I am the executive director of the Pipeline Safety Trust, a national nonprofit pipeline watchdog formed in the aftermath of a pipeline tragedy in Bellingham, Washington, in 1999. In that completely avoidable failure, three boys died when a quarter-million gallons of gasoline emptied out of a pipeline and into the

salmon stream that runs through the middle of town and eventually ignited. The Trust works to prevent other communities from having to experience that kind of grief and loss.

Back in 1986, a large, natural release of carbon dioxide from Lake Nyos in Cameroon led to the death of every person within a 16-mile radius of the release – more than 1,700 people. In response, Congress mandated that the U.S. Department of Transportation begin to regulate carbon dioxide pipelines. Rather than develop new rules to mitigate the unique risks carbon dioxide pipelines pose, U.S. DOT simply added carbon dioxide to existing pipeline regulations designed for hydrocarbon liquids, a step that was wholly inadequate and inappropriate. For example, an impurity such as water, which is notoriously difficult to eliminate from carbon dioxide pipelines, can wreak havoc on a pipeline by producing carbonic acid which aggressively eats at steel and is not addressed in current regulations.

An important component of the safety regulations around maintaining our nation's pipelines is determining which homes, businesses, schools, hospitals and other buildings are within the area where a pipeline failure could injure or kill people. This can be a relatively simple calculation for hydrocarbon pipelines. However, for carbon dioxide pipelines, a release can travel over large distances in lethal concentrations in unknown directions for large distances. Identifying the impact area goes well beyond a simple calculation and requires sophisticated plume dispersion modeling, for which scientists and engineers have yet to develop best practices. Plume dispersion research needs to develop appropriate modeling and only then can appropriate regulations follow.

Prior to passage of legislation, Alaska legislators should read the Pipeline Safety Trust's report on carbon dioxide pipelines, prepared by an independent expert on pipeline safety engineering. It contains a list of recommended common-sense safety regulations. I call on U.S. DOT to adopt new regulations as identified in that report to keep the people of Alaska and the rest of the country safe. Additionally, I respectfully ask the leaders of your great state to not rush to pass the governor's Carbon

Capture, Utilization and Storage Act until communities are ensured of appropriate minimum safety standards for carbon dioxide pipelines.

Bill Caram is Executive Director of the nonprofit Pipeline Safety Trust in Bellingham, Washington. Previously in his career, Bill traveled around much of Alaska as a consultant for Alaska Native corporations.

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Regulatory and Knowledge Gaps in the Safe Transportation of Carbon Dioxide by Pipeline

This document is intended to provide an overview of federal regulatory and knowledge gaps related to the safe transport of carbon dioxide by pipeline. Following the CO₂ pipeline rupture in Satartia, MS in 2020 which sent 45 people to the hospital, the Pipeline Safety Trust (PST) commissioned a [report](#) to examine various aspects of carbon dioxide transmission pipeline safety and federal pipeline safety regulations related to CO₂. The report identified numerous **regulatory gaps** outlined below.

1. The current definition of “carbon dioxide” in the federal pipeline safety regulation does not apply to all CO₂ pipelines that may be developed for CCS projects.
 - a. Currently, only CO₂ that is moved in a supercritical state is regulated under the current definition.
 - b. Federal regulations need to be modified to assure that federal standards apply to all CO₂ transmission pipelines that transport CO₂ in all phases, including supercritical, gas, and liquid CO₂.
2. There is currently no defined safe distance or plume dispersion model for developing a potential impact area (PIR) along CO₂ pipelines.
 - a. CO₂ has unique physical properties which warrant the development of a unique PIR zone to be promulgated into federal pipeline regulation.
3. There is currently no requirement to add an odorant to transported CO₂.
 - a. Carbon dioxide is odorless, colorless, doesn’t burn, and is heavier than air meaning that releases are harder to observe and therefore avoid.
 - b. Adding an odorant would help alert the public of a CO₂ pipeline rupture.
4. The unique physical properties of CO₂ moved at high pressures through pipelines can cause running ductile fractures upon rupturing.
 - a. This essentially means that a pipe has a higher likelihood of opening up like a zipper when a rupture occurs, leading to more product being released over a shorter period of time and potentially violent and dangerous pipe shrapnel.
 - b. Fracture propagation protection, or fracture arresters, and steel thickness requirements should be carefully examined and incorporated into federal CO₂ pipeline design regulations.
5. Contaminants within CO₂ products being transported can jeopardize the integrity of the pipeline.
 - a. Water, when mixed with carbon dioxide, can form carbonic acid which has the ability to rapidly erode carbon steel.
 - b. Different industries can produce numerous other contaminants which can be toxic to public health and/or affect the temperature and pressure of the product, potentially impacting the safe operation of the pipeline.
 - c. Standards for maximum contaminant levels within different CO₂ producing industries should be reviewed and set by PHMSA in the federal pipeline safety regulations.
6. The risks associated with the conversion of existing transmission pipelines to CO₂ service have not been fully investigated.

- a. Given the unique properties of CO₂ mentioned previously, pipeline conversions have the potential to be at higher risk of failure from CO₂ service than conventional hydrocarbon or even new construction CO₂ pipelines.
- b. PHMSA needs to develop detailed safety standards for the conversion of existing lines to CO₂ service.

The incident in Satartia also prompted the Pipeline and Hazardous Materials Safety Administration (PHMSA) to initiate the funding of [new research and development \(R&D\) projects](#) related to the safe transportation of carbon dioxide through pipelines. These projects, titled *“Developing Design and Welding Requirements Including Material Testing and Qualification of New and Existing Pipelines for Transporting CO₂”* will attempt to address many of the elements needing more research mentioned in the above regulatory gaps. The projects are intended to cover the following **knowledge gaps**:

1. The appropriate fracture toughness and steel pipe quality is currently unknown to prevent CO₂ pipeline leak or ruptures.
 - a. R&D project findings may be used to develop pipe quality standards and strategies for the correct placement of fracture mitigation measures along these pipelines.
2. The effects of corrosion, dents, cracks, or gouges have yet to be determined on a wide range of steel grades regarding CO₂ operation.
3. Odorization strategies have yet to be identified.
 - a. Odorization of CO₂ is likely one of the simplest ways to ensure effective leak detection as well as public safety and emergency response.
4. There is currently no defined safe distance or plume dispersion model for developing a potential impact area (PIR) along CO₂ pipelines.
 - a. Without a PIR, it is impossible to establish accurate emergency response safe distances. Due to the asphyxiation potential for CO₂ pipelines, this could have deadly consequences.
 - b. Only once an appropriate PIR for CO₂ pipelines has been established can PHMSA assess the effectiveness of integrity management procedures.
5. Results from these projects will not be available for two years and the funding provided to study these complex issues is relatively small.

In addition to these issues, PHMSA has directed the researchers of this project to “identify safety gaps and requirements to support best practices for both gaseous and supercritical liquid systems, beyond the requirements of 49 CFR Part 195 for CO₂ pipeline transportation.”

Considering the scope of this project, and the directive to look at CO₂ as both a gas and a liquid, it is clear that PHMSA is concerned not only with the under-regulation of CO₂ pipelines, but also with the current lack of technical knowledge which is needed to create appropriate minimum safety standards.

With a focus on reducing the impacts of climate change, the expansion of the 45Q tax credits, and now with the Inflation Reduction Act being signed into law, there has been a massive push for Carbon Capture Sequestration and Storage projects across the country. However, the regulatory and knowledge gaps outlined above make clear the need for caution moving forward.

CO₂ PIPELINES MATERIAL AND SAFETY CONSIDERATIONS

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This paper presents an overview of some of the most important factors and areas of uncertainty affecting integrity and accurate hazard assessment of CO₂ pipelines employed as part of the Carbon Capture and Sequestration (CCS) chain. These include corrosion, hydrate formation, hydrogen embrittlement and propensity to fast running ductile and brittle fractures. Special consideration is given to the impact of impurities within the CO₂ feed from the various capture technologies on these possible hazards. Knowledge gaps in the modelling of outflow and subsequent dispersion of CO₂ following the accidental rupture of pressurised CO₂ pipelines, central to their safety assessment, are also presented.

INTRODUCTION

Pressurised pipelines are widely considered to be the most practical, and in the case of fossil fuel power generation plant, the only option for transporting captured CO₂ for subsequent sequestration. Typically, such pipelines may be several hundred kilometres long, transporting enormous amounts of CO₂ under supercritical conditions.

CO₂ is hazardous as defined by the UK Health & Safety Executive (<http://www.hse.gov.uk/hid/haztox.htm>). At concentrations greater than 7% v/v the gas is likely to be instantly fatal (Kruse and Tekiela, 1996). Given this and the large quantities of CO₂ involved (typical several thousand tonnes), understanding of the factors that may undermine the mechanical integrity of such pipelines is central to the successful risk management of CCS and its implementation as an effective means for combating the effects of global warming.

It is widely acknowledged (see for example CRS Report, 2007) that existing experience with the use of pressurised CO₂ pipelines is simply too limited to draw any meaningful conclusions. Additionally, the widely different hazard profile of CO₂ as compared to hydrocarbons means that there is some lack of confidence that the existing experience with operating hydrocarbon pipelines can be wholly extended to CO₂ pipelines. Furthermore, this may result in a significant under estimation of the hazards and risks from such pipelines and such may be dangerously misplaced (Mahgerefteh et al., 2008).

This paper presents an overview of some of the most important areas of uncertainty affecting CO₂ pipeline safe operation and integrity that require further investigation. These include consideration from the molecular level, such as the impact of impurities on thermodynamics and phase behaviour of CO₂, corrosion resistance and hydrate formation to macroscopic considerations such as fast running ductile or brittle fracture propagation.

It is important to note that although many tools currently available in support of design and safety assessment can and are being applied to assess the pipeline transportation hazards, there is in general no firm scientific basis for such

application in the case of CO₂ pipelines. Basic research and development work is now required in order to provide the underpinning knowledge that will form the basis of the design tools needed to ensure the success of CCS.

RESULTS AND DISCUSSION

CO₂ IMPURITIES

CO₂ transported through pipelines will contain impurities. The type and the concentration of these impurities will depend on the power production method, capture technologies employed and possible purification of the feed stream.

Table 1 shows typical data for the three main methods of power production including post-combustion (CO₂ captured from flue gas), pre-combustion (CO₂ captured before combustion) and oxyfuel combustion (almost pure O₂ used in combustion). It should be noted that these data are based on the assumption of prior drying of the CO₂ stream at the inlet. In practice, water concentrations may reach as much as 5% v/v giving rise to significant design and operational difficulties. These issues will be dealt with separately below. For now, returning to Table 1, it is clear that post-combustion capture, being the most popular of the three carbon capture technologies, presents the biggest challenge due to the largest number of impurities present in the CO₂ stream.

By far the most important effect of impurities on CO₂ pipeline transportation is the modification of the CO₂ thermo-physical and phase equilibrium behaviour. Such data for pure CO₂ spanning the triple point to supercritical conditions are extensively available and dedicated equations of state have been developed (see, for example, Span and Wagner, 1996). However, in the case of mixtures, all of the reported studies are either confined to cases in which CO₂ is present as an impurity (Weber, 1995) or for binary CO₂ mixtures (Perakis et al., 2006). There is no validated equation of state for CO₂ in the presence of multi-component impurities that would be typically encountered during CO₂ pipeline transportation. The same applies to the pertinent thermo-physical properties such as thermal

Table 1. CO₂ composition for different CCS technologies (Oosterkamp and Ramsen, 2008)

	Post-combustion	Pre-combustion	Oxyfuel
CO ₂	>99 vol%	>95.6 vol%	>90 vol%
CH ₄	<100 ppmv	<350 ppmv	
N ₂	<0.17 vol%	<0.6 vol%	<7 vol%
H ₂ S	Trace	3.4 vol%	Trace
C ₂ +	<100 ppmv	<0.01 vol%	–
CO	<10 ppmv	<0.4 vol%	Trace
O ₂	<0.01 vol%	Trace	<3 vol%
NO _x	<50 ppmv	–	<0.25 vol%
SO _x	<10 ppmv	–	<2.5 vol%
Ar	Trace	<0.05 vol%	<5 vol%

diffusivity, viscosity and flow and phase dependent frictional properties. Knowledge of such data will have a direct impact on the following CO₂ pipeline operational and design requirements.

COMPRESSOR REQUIREMENTS

Impurities may result in two-phase flow at the compressor inlet giving rise to significant operational difficulties such as cavitation. The limited experience available for binary CO₂ mixtures such as CO₂/H₂S reveals an increase in the dew point temperature (Stouffer et al., 2001). This means that a higher degree of cooling will be required at the compressor inlet to ensure liquid compression for the CO₂/impurities mixtures as compared to pure CO₂. Additionally, the increase in the dew point temperature will require higher operating pressures within the pipeline in order to maintain the liquid phase during pipeline transportation. This will mean thicker pipe walls or the use of more exotic materials to ensure pipeline integrity and hence increased costs.

A change in the bulk fluid density or viscosity on the other hand will impact the compressor power requirement with the former affecting the overall effective capacity of the pipeline in transporting CO₂.

Investigations using the REFPROP program from NIST (Heggum, 2005) for a number of relevant CO₂ binary mixtures including CO₂/C₄, CO₂/N₂ and CO₂/O₂ generally reveal a reduction in the CO₂ viscosity as compared to that for pure CO₂. Clearly, the higher molecular weight impurities will increase the bulk density.

PIPELINE INTEGRITY

Impurities may also affect pipeline integrity through hydrogen embrittlement, corrosion damage, and fast running brittle or ductile fracture mechanics. These issues are considered further below.

HYDROGEN EMBRITTLEMENT

Molecular hydrogen in the pipeline may diffuse into the pipeline material resulting in a local internal pressure

which in turn reduces its ductility and tensile strength thus promoting brittle fractures. This topic has been extensively studied for hydrocarbon conveying pipelines (Irzhov et al., 1982). Hydrogen embrittlement can be overcome to a large extent through appropriate pipeline material selection such as low sulphur content steels, but at increased cost. Mikhailovski (2000) has developed a sensor technology for monitoring hydrogen embrittlement in carbon steel hydrocarbon conveying pipelines.

If hydrogen is present as an impurity in CO₂ then the hydrogen may add to the problem of brittle fracture as it exhibits a different failure mechanism associated with lattice penetration (considered later).

CORROSION

As mentioned above, the presence of water in the CO₂ pipeline will be inevitable. The post-combustion capture technology presents the biggest challenge due to the largest potential concentration of water in the inlet stream as compared to the oxyfuel or pre-combustion routes.

The solubility of water in CO₂ is a function of temperature and pressure. The problem occurs when the solubility of water in CO₂ is exceeded and free water is formed. This can then give rise to corrosion and/or hydrate formation issues.

Corrosion can occur when free water directly attacks the pipeline material by acting as an electrolyte. Alternatively, free water can react with CO₂ resulting in carbonic acid corrosion. Both types of corrosion mechanisms have been extensively studied and corrosion rate data are readily available. For carbon steel pipeline, corrosion is a serious issue and numerous studies involving hydrocarbons with relatively small amounts of CO₂ have been reported (see, for example, Kermani, and Morshed, 2003).

However, no comparative investigations involving CO₂ in the presence of impurities are available. O₂, H₂S, SO₂ and NO_x are all expected to increase corrosion rates. In addition, even for CO₂-water corrosion, no data in the supercritical region are available. The fact that supercritical CO₂ is an extremely efficient solvent (IPCC, 2004) poses serious uncertainties in extrapolating the current understanding of CO₂-water corrosion behaviour to pipelines transporting supercritical CO₂.

Apart from direct and costly mitigation steps such as the use of corrosion inhibitors, pre-drying or improved pipeline material selection, the ultimate aim should be determining the conditions for which the formation of free water will be unlikely. This will require a fundamental approach involving the understanding of the thermodynamics of the CO₂/impurities corrosion mechanism in conjunction with careful experimentation.

HYDRATE FORMATION

Gas hydrates are another potential hazard associated with CO₂ pipelines. Gas hydrates are formed as a result of the combination of water and gas molecules at suitable

temperature and pressure conditions. Many gases, including methane and CO₂, can form gas hydrates. Probably the first evidence for the existence of CO₂ hydrates dates back to the year 1882, when Wróblewski (Wroblewski, 1882) reported clathrate formation while studying carbonic acid. He noted that the gas hydrate was a white material resembling snow and could be formed by raising the pressure above certain limits in his H₂O-CO₂ system. Hydrates can cause the blockage of the pipeline thus giving rise to serious operational and safety issues.

Figure 1 shows CO₂/water phase diagram. The dark grey region (V-I-H) represents the conditions at which CO₂ hydrate is stable together with gaseous CO₂ and water ice (below 273.15 K). Based on the diagram, it is clear that CO₂ hydrates may be formed at temperatures below 280 K, typical for many offshore pipelines.

Even for pipelines operating above this temperature, hydrate formation can still be a serious issue during emergency blowdown due to significant localised temperature drops associated with rapid depressurisation. Once again, no comparative studies investigating the impact of typical CCS impurities on CO₂ hydrate formation have been reported.

FRACTURE PROPAGATION

Pipeline failure due to fracture propagation is a serious issue in the hydrocarbon industry (see, for example, Picard and Bishnoi, 1988). Mitigation has involved measures such as the use of fracture arrestors placed at regular intervals along the pipeline length, the selection of appropriate pipeline materials, or operating conditions which are less likely to give rise to such types of failure. The correct choice of all of these approaches requires a fundamental understanding of the fracture failure mechanism and the consequences

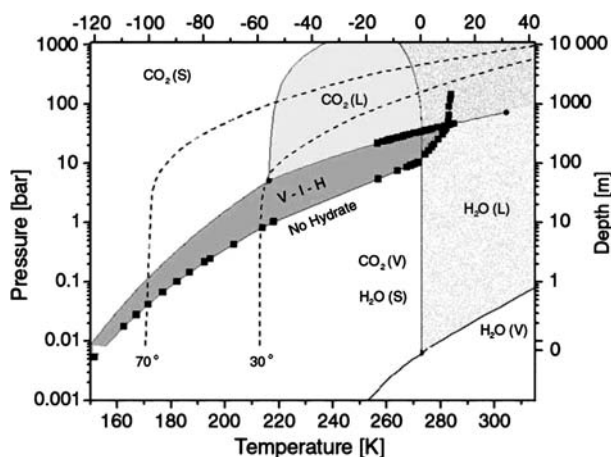


Figure 1. CO₂ hydrate phase diagram. The black squares show experimental data (Sloan, 1998). The lines of the CO₂ phase boundaries are calculated according to the Intern. Thermodyn. Tables (1976). The abbreviations are as follows: L – liquid, V – vapour, S – solid, I – water ice, H – hydrate

of such failures on hazard source term and likelihood estimation to enable the establishment of appropriate material and operational standards.

Little is known about the spontaneity of CO₂ pipelines to such types of failure. As will be shown later, this is important since the thermodynamic properties of the pressurised inventory play a central role in governing fracture propagation.

Pipelines can fail through either ductile and/or brittle fractures. Figure 2 shows a schematic representation of both failure modes.

Ductile fractures involve significant pipeline deformation. The more insidious brittle fractures on the other hand involve little deformation during fracture growth and hence may be left unnoticed until they become unstable by which time catastrophic pipeline failure has occurred. The study of pipeline ductile fractures has received a great deal of attention (see, for example, Takeuchi et al., 2006).

Ductile fractures may start due to an external force such as loss of material (corrosion or external third party action), ground movement or impact damage and grow when the pressure stresses within the pipeline exceed the pipeline mechanical properties such as yield stress or fracture toughness.

As failure will involve a continuous drop in the line pressure due to loss of fluid, the fracture will come to rest when the corresponding fluid decompression velocity within the pipeline exceeds the fracture propagation speed or the crack is arrested. Such fractures are modelled using the rather simplistic Batelle Two Curve Methodology (Makino et al., 2001) which expresses this balance in terms of the fracture velocity and decompression velocity curve. Figure 3 shows a typical diagram for a gas decompression curve.

Much the same as ductile failures, brittle fractures are also initiated as a result of a through wall defect. However, the failure mechanism is more complex with both pressure and thermal stresses playing a major role. A comprehensive analysis of the important processes leading to catastrophic brittle failure is presented in a publication by Mahgerefteh and Olufemi (2006).

In essence, the rapid depressurisation of the inventory at the point of failure following pipeline puncture may result in a large drop in its temperature and that of the pipe wall in contact with it. If the pipe wall temperature falls to below its ductile/brittle transition temperature (DBTT), a significant drop in its fracture toughness (ca. 100% for carbon steel) will occur. Figure 4 shows a schematic representation of this phenomenon. Catastrophic failure is characterised by a fast running fracture and massive escape of inventory will occur if the transient localised pressure and thermal stresses at the defect plane exceed the *critical* pipeline fracture toughness.

The critical fracture toughness at which a crack length becomes unstable is given by (Irwin, 1957)

$$K_C = Y\sigma\sqrt{\pi a}$$

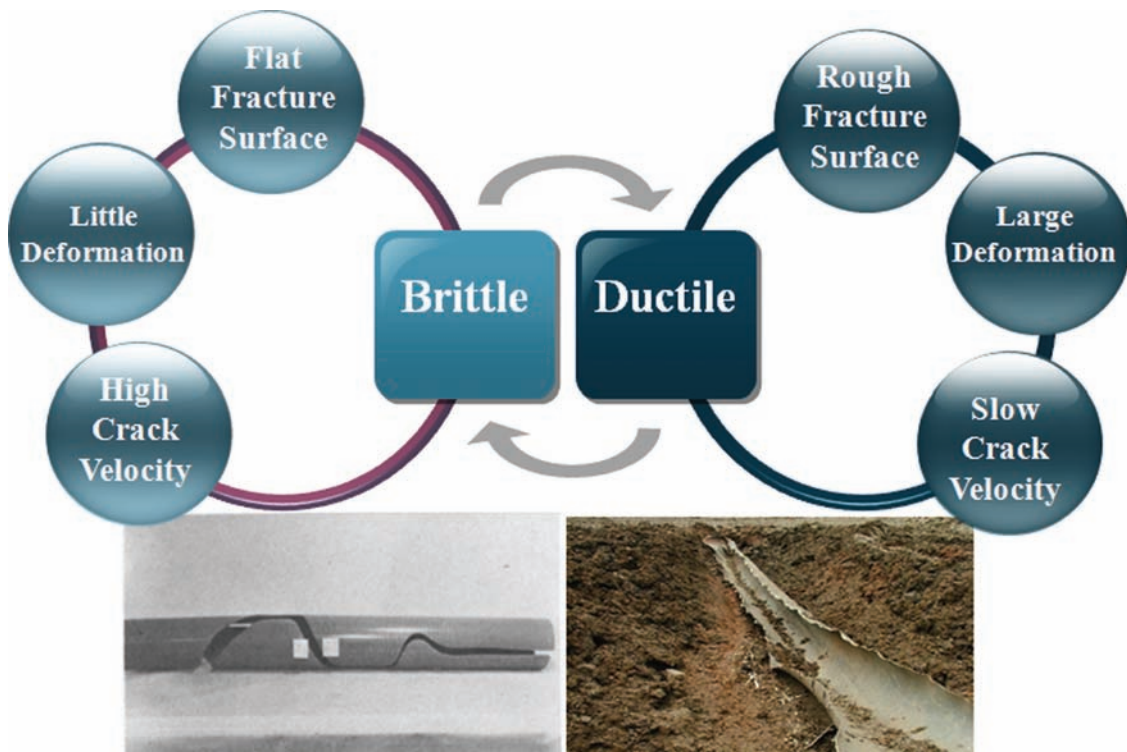


Figure 2. Schematic representations of pipeline failure through brittle and ductile fractures

where Y and a , are, respectively, the crack geometry shape factor and half length. σ , is the sum of the transient thermal and pressure stresses in the defect plane.

Figure 5 shows a schematic representation of the pertinent fluid/structure interactions leading to brittle fracture propagation in a pressurised pipeline.

As shown above, the pressurised fluid decompression velocity (manifested in the localised transient pressures stresses) and heat transfer characteristics (manifested in the localised thermal stresses) play important roles in

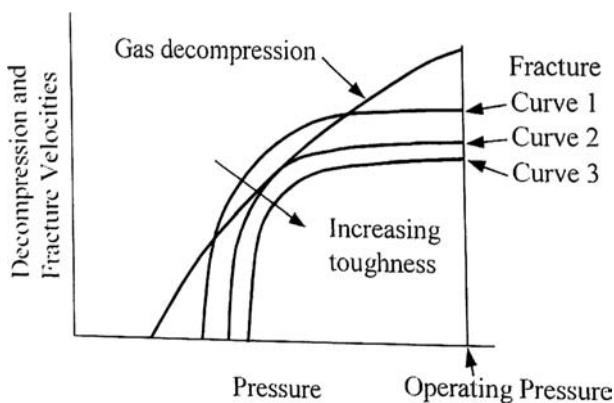


Figure 3. Schematic – Gas decompression curve and fracture velocity curve; Curves 1,2,3 correspond to different pipe toughness values (Rothwell, 2000)

governing fracture propagation. Table 2 gives a representation of the main features of brittle and ductile fast running fractures.

CO₂ pipelines are more susceptible to fast running fractures as compared to hydrocarbon pipelines for the following reasons:

- i) CO₂ exhibits a prolonged phase transition during depressurisation. This means that the pressurise stresses driving the fracture remain relatively unchanged during failure despite loss of material from the pipeline;
- ii) CO₂ undergoes marked Joule-Thomson expansion cooling during rapid depressurisation with temperatures reaching as low as 203 K. The inevitable drop

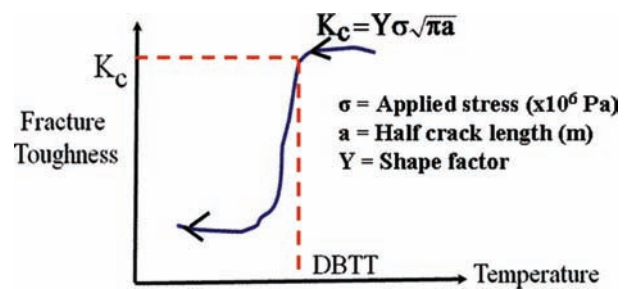


Figure 4. Schematic representation of fracture toughness as a function of temperature

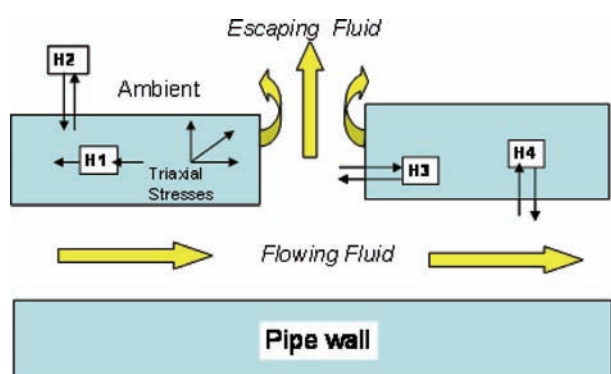


Figure 5. Schematic representation of the pertinent fluid/structure interactions leading to brittle fracture; H1: heat transfer within the pipe wall (conduction); H2: heat transfer between ambient and the pipe wall (natural convection); H3: heat transfer between the escaping fluid and defect neck (forced and natural convection); H4: heat transfer between flowing fluid and inner pipe wall (forced convection)

in the pipe wall temperature in contact with the escaping CO₂ and the corresponding likely significant drop in fracture toughness will lead to significant localised thermal stresses in the defect plane thus promoting fracture propagation.

As such the study of CO₂ pipeline ductile and brittle fractures must entail detailed consideration of fluid/structure interactions involving a robust equation of state capable of correctly predicting the depressurisation thermodynamic trajectory of CO₂, especially in the presence of impurities.

OUTFLOW AND DISPERSION MODELLING

The accurate prediction of the fluid phase, discharge rate and subsequent atmospheric dispersion during accidental releases from pressurised CO₂ are pivotal to quantifying all the hazard consequences associated with CO₂ pipeline failure. Such data form the basis for emergency response

planning and determining minimum safe distances to populated areas. So far, all the discharge modelling work has been either based on very simplistic and wholly unrealistic assumptions treating the ruptured pipeline as a vessel discharging through an orifice (see for example, Cruse and Tekiela, 1996), or the much more advanced CFD numerical simulations based on the homogeneous equilibrium model (HEM) in which the constituent phases are assumed to be at thermal equilibrium, travelling at the same velocity (Mahgerefteh et al., 2008). HEM has been shown (see, for example, Chen et al., 1993; Mahgerefteh et al., 2006; Mahgerefteh and Oke, 2006) to produce reasonably good, conservative predictions of discharge and decompression rates following pipeline rupture when compared to actual data. However, given that the constituent phases are assumed to be fully dispersed, HEM is incapable of correctly predicting the discharge fluid physical state in the presence of phase slip. This may be especially the case for CO₂ given the very different densities of solid, liquid and vapour.

CO₂ has very different hazard profiles in the gas or solid states directly influencing many of its features including dispersion behaviour, solubility or erosion impact of the high velocity escaping fluid.

Likewise, the near-field behaviour of releases of supercritical CO₂ is not understood. Depending on the precise time during any release, supercritical CO₂, a gas-liquid droplet mixture or gas alone will be released to atmosphere and disperse over large distances. This may also be followed by gas-solid discharge during the latter stages of depressurisation due to the cooling taking place. The detailed modelling of the near-field characteristics of these complex releases is required since predictions of major hazards used in safety and risk assessments are generally (Connolly and Cusco, 2008) based on the use of near-field source terms to provide input to far-field dispersion models.

Addressing the above limitations through the developments of robust mathematical models backed by small and large scale validations is the subject of a major multinational study by the present authors (MF and HM).

Table 2. A representation of the main features of brittle and ductile fast running fractures

Main features	Fracture mode	
	Brittle	Ductile
Driving mechanism	Heat transfer Fracture toughness	Fracture toughness
Crack propagation	Slow, followed by catastrophe	Rapid
Crack arrest length	Unlimited	Limited
Energy dissipation	Instantaneous	Slow
Fracture shape		

CONCLUSIONS

1. Presently there is insufficient knowledge to enable the correct predictions for the depressurisation thermodynamic trajectory of supercritical or dense phase CO₂ in the presence of impurities particularly those likely to be present from carbon capture resulting from power generation using fossil fuels. Our preliminary investigations show significant changes in the presence of N₂ at concentrations greater than 1%. This is followed by hydrogen and methane.
2. The study of CO₂ pipeline ductile and brittle failures must entail the development and application of appropriate equations of state and the detailed consideration of the interactions between the transported fluid and the materials of containment.
3. Development of a means for accurate thermodynamic depressurisation trajectory and multiphase outflow modelling are necessary to enable adequate determination of the mass, momentum, energy and state of CO₂ released as a result of a pipeline failure.
4. Utilising the factors determined in 3 above should enable hazard source term definition sufficiently to select and apply the appropriate transmission (dispersion) models used to estimate distance to a specified level of harm for a receiving target.
5. Establishment of the conditions for, and consequences of, ductile or brittle failure is also necessary to define the physical attributes of a release source and subsequent hazard analysis.
6. Comparison of the factors resulting in CO₂ pipeline brittle or ductile failures against established models used for such predictions of other hazardous fluids (particularly natural gas) will enable confidence in the application of available pipeline damage and failure data for the estimation of supercritical or dense phase CO₂ pipeline failure probability.
7. Satisfaction of points 1–6 coupled with appropriate vulnerability criteria should enable adequate and appropriate estimation of the risks associated with CO₂ pipelines.
8. Satisfaction of all of the above should enable the development of appropriate standards for relevant matters of material selection and maintenance activities associated with the purification and transportation of supercritical and dense phase CO₂.

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