Accufacts Inc.
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Accufacts' Perspectives on the State of Federal Carbon Dioxide Transmission Pipeline Safety Regulations as it Relates to Carbon Capture, Utilization, and Sequestration within the U.S.

prepared for the

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by
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This report is developed from information clearly in the public domain. The views expressed in this document represent the opinion of the author.

I. Introduction

Accufacts Inc. ("Accufacts") was asked to review and comment on various aspects related to carbon dioxide transmission pipeline safety and federal pipeline safety regulations within the U.S. In recent years there has been considerable discussion about how to address carbon dioxide emissions and global warming through carbon capture, utilization, and sequestration (aka "CCUS" or "CCS"). CCS efforts are intended to help mitigate climate change by capturing carbon dioxide emissions both before and after they are released to the atmosphere and permanently storing such material deep in underground geological structures.

The federal Pipeline Safety Act ("PSA") directs the U.S. Department of Transportation ("DOT") to issue detailed safety standards with regard to the design, construction, operation, and maintenance of CO_2 pipelines.[1, 2] In turn, the DOT has delegated its authority to the Pipeline and Hazardous Materials Safety Administration ("PHMSA"). The PSA's broad mandate is supplemented by detailed federal regulations.[3] The PSA expressly prohibits state and local regulation that interferes with or supplements federal safety standards for interstate pipelines.[4] States meeting certain conditions may supplement federal pipeline safety regulation on their intrastate pipelines as long as such state regulations are not in conflict with federal pipeline safety regulations.

The U.S. has the most mileage of CO_2 transmission pipelines in the world, consisting of approximately 5,150 miles, out of a total 229,287 miles of hazardous liquid transmission pipelines within the U.S.[5] The vast majority, if not all, of these CO_2 existing pipelines are driven by enhanced oil recovery ("EOR") efforts that increase oil production utilizing CO_2 in a supercritical state. Most of this supercritical state CO_2 comes from high pressure higher purity natural underground source domes. It is an excellent solvent for EOR efforts, but the CO_2 must be injected into oil fields as a supercritical fluid.

CCS efforts are driven by an entirely different purpose such that CO_2 used for CCS could be shipped as a gas or a non-supercritical liquid. However, current federal safety regulations regulate only pipelines that transport supercritical CO_2 containing over 90% carbon dioxide molecules, and not pipelines that ship CO_2 in these other lower concentrations or forms, leaving a large regulatory gap. Moreover, even the regulations for supercritical CO_2 pipelines are incomplete or inadequate and place the public at

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[1] 49 U.S.C. § 60101 *et seq*.
[2] 49 U.S.C. § 60102(a) and (i).
[3] 49 C.F.R. Part 195.
[4] 49 U.S.C. § 60104(c) ("A State authority may not adopt or continue in force safety standards for interstate pipeline facilities or interstate pipeline transportation.")
[5] PHMSA reporting database, "Hazardous Liquid Pipeline Miles and Tanks," as of January 31, 2022 for CO_2 commodity at: https://portal.phmsa.dot.gov/analytics/saw.dll?Portalpages&PortalPath=%2Fshared%2FPDM%20Public%20Website%2F_portal%2FPublic%20Reports&Page=Infrastructure.

great risk, especially from the tens of thousands of miles of CO_2 pipelines that may be driven by CCS efforts.[6]

A flurry of multibillion dollar CO_2 pipeline proposals have recently been announced, likely driven by enhanced tax credit incentives provided by Internal Revenue Code § 45Q.[7, 8, 9] Congress provided these enhancements in the Bipartisan Budget Act of 2018, and expanded by the Infrastructure Investment and Jobs Act of 2021 ("Acts of 2018 and 2021").[10] As intended, these laws accelerated CCS and CO_2 pipeline development efforts, because they make such credits more available and valuable to certain generators of CO_2 emissions and require projects to start construction by January 1, 2026.[11] Since most carbon dioxide emitters are likely considerable distances from suitable deep, permanent underground storage sites, it is understandable that CO_2 transmission pipelines may be needed between emitters and these storage sites. If CO_2 pipeline mileage increases as projected, the CO_2 pipeline network could soon rival the existing oil and natural gas pipeline networks in size and complexity. PHMSA would be faced with the greatest and fastest pipeline expansion in the history of the U.S. pipeline industry, and many of these pipelines could threaten the safety of countless individuals and communities.

This report is intended to increase regulator and public awareness of the regulatory challenges posed by this proposed massive expansion in CO_2 pipeline mileage and the unique safety risks of transporting CO_2, especially in its supercritical state. It focuses on a higher-level review of the more technical pipeline safety matters, based on decades of pipeline safety experience including pipeline failure investigations, process engineering and process safety management practice, as well as years of experience in processing and handling many tons of liquid CO_2. This report also makes specific recommendations for improvements in federal pipeline safety regulations needed to fill regulatory gaps and ensure public safety. The proposed CO_2 pipeline boom presents

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[6] For one perspective see what I would call a planning study from Princeton University, "Net-Zero America - Potential Pathways, Infrastructure, and Impacts," Final Report, October 29, 2021, pp. 212 – 219 of 348, indicating a possible need of over 60,000 new miles of CO_2 pipelines by 2050.

[7] Des Moines Register, "What we know about two carbon capture pipelines proposed in Iowa," https://www.desmoinesregister.com/story/money/business/2021/11/28/what-is-carbon-capture-pipeline-proposals-iowa-ag-ethanol-emissions/8717904002/, Nov. 28, 2021.

[8] Agweek, "World's largest carbon capture pipeline aims to connect 31 ethanol plants, cut across Upper Midwest," https://www.agweek.com/business/worlds-largest-carbon-capture-pipeline-aims-to-connect-31-ethanol-plants-cut-across-upper-midwest 12/6/2021.

[9] S&P Global Platts, "Oil producer Denbury plans CO_2 storage hub in southern Alabama." https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/020822-oil-producer-denbury-plans-co2-storage-hub-in-southern-alabama, 2/8/2022.

[10] 26 U.S.C. § 45Q.

[11] I.R.C. § 45Q.

PHMSA with an unprecedented challenge; hopefully, this report will help PHMSA rise to this challenge.

II. A brief history of U.S. federal CO_2 pipeline safety regulation

PHMSA and its predecessor agencies, such as the Office of Pipeline Safety, have historically relied on more prescriptive minimum safety approaches. In the past several decades federal minimum pipeline safety regulations have, by the industry's lobbying, shifted to more "performance-based" approaches that rely heavily on certain industry standards or recommended practices, some of which are incorporated by reference into federal pipeline safety regulation.[12] This industry driven shift can result in changes in pipeline safety regulations without proper public input. A prime example may be in the development of CO_2 transmission pipeline safety regulations that historically have been a very small percentage of overall transmission pipeline mileage in the U.S. This country may be facing a significant increase in CO_2 transmission pipeline mileage without appropriate pipeline safety regulatory development or enactment, leaving the country and the public ill prepared for a tsunami of CO_2 pipeline construction.

Congress, in Section 211 of the Pipeline Safety Reauthorization Act of 1988, required that the DOT regulate carbon dioxide transported by pipeline facilities. Part of this concern was driven by a 1986 natural carbon dioxide release event in Lake Nyos, Cameroon spanning many miles with over 1,700 fatalities, underscoring the dangers and possible consequences of CO_2 releases.[13] On July 12, 1991, federal regulators issued a minimalist final rule that mainly added the words "and carbon dioxide" to existing federal minimum pipeline safety regulations developed for hazardous liquid petroleum pipelines (49CFR§195). It opted to not issue standards specifically applicable to supercritical CO_2 pipelines due to the small number of already existing and anticipated CO_2 pipelines. Even though the situation is about to change dramatically, PHMSA has not proposed to review and overhaul its CO_2 pipeline standards, such that these limited regulations are still in effect today.[14] As a result, many of PHMSA's regulations no longer are adequate to protect public safety.

For example, under federal regulations "carbon dioxide" is defined as follows:

> "Carbon Dioxide means a fluid consisting of more than 90 percent carbon dioxide molecules compressed to a supercritical state."[15]

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[12] 49CFR§195.3 What documents are incorporated by reference partly or wholly in this part?
[13] Federal Register / Vol. 56, No. 113 / Wednesday, June 12, 1991/Rules and Regulations, Research and Special Programs Administration (RSPA), DOT, Docket No. PS-112, Amendment 195-45, RIN 2137-AB72, 49CFR Part 195, "Transportation of Carbon Dioxide by Pipeline," final rule.
[14] *Ibid*, p. 26924.
[15] 49CFR§195.2 Definitions.

The above definition is clearly not appropriate to deal with CCS CO_2 pipelines, nor is that its intent as demonstrated further in this report.

Existing U.S. CO_2 transmission pipelines are primarily located in sparsely developed or more rural locations and, as mentioned previously, involve approximately 5,150 miles moving CO_2 mostly from natural underground sources/domes to EOR projects. The current definition of "carbon dioxide" does not include pipelines that transport supercritical carbon dioxide streams in which CO_2 makes up less than 90 percent of the stream. It also excludes pipelines that transport CO_2 as a non-supercritical liquid or gas. In 1991, there were only a very limited number of pipelines transporting CO_2 in these other forms that apparently didn't justify the need for federal regulation, which is not the case now.

In 2011, Congress, in the Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011, Section 15, mandated that the Secretary of Transportation "prescribe minimum safety standards for the transportation of carbon dioxide by pipeline in a gaseous state." As a result, PHMSA issued a report in early 2015 entitled "Background for Regulating the Transportation of Carbon Dioxide in a Gaseous State."[16] Unfortunately, PHMSA never issued new regulations for transportation of CO_2 as a gas.

Thus, PHMSA currently has no regulations applicable to pipelines transporting CO_2 as a gas, liquid, or in a supercritical state at concentrations of CO_2 less than 90 percent. This regulatory gap means that current federal pipeline safety regulations are clearly inadequate because CO_2 pipeline companies could develop CO_2 gas and liquid pipelines that fall outside of this narrow federal rule. The definition of "carbon dioxide" should be modified so that <u>all</u> CO_2 transmission pipelines are regulated by federal law and held to appropriate minimum safety standards. Otherwise, CO_2 pipelines could be designed, constructed, operated, and maintained with no federal or state oversight.

III. CO_2 transmission pipelines can take on three basic forms

CO_2 transmission pipelines can be designed to transport carbon dioxide either as a supercritical state fluid, a liquid (aka in a subcritical or chilled state), or as a gas. Within the industry the term "dense phase" is often used to label CO_2 pipelines operating in either a supercritical state fluid or in a liquid phase as explained below. It is odd that the proposed new CO_2 transmission pipeline applications recently reviewed have not clearly stated in what phase they are designed to operate, their temperature ranges, nor their quality requirements.[17] The key characteristics of supercritical, liquid, and gaseous CO_2 transmission pipelines are summarized below.

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[16] PHMSA report dated February 2015, posted to the 2016 docket under PHMSA-2016-0049-001 at www.regulations.gov.

[17] For example, see Summit Carbon Solutions, "Application to the South Dakota Public Utilities Commission for a Permit for the SCS Carbon Transport LLC (SCS) Pipeline Under the Energy Conversion and Transmission Facility Act – Document Number: SCS-0700-ENV-05-PE-009-A," dated February 7, 2022.

i. **Supercritical state CO_2 transmission pipelines**

Pure CO_2 has a critical temperature of about 88 ºF (33 ºC) and a critical pressure of approximately 1070 psia, or pounds force per square inch absolute (73 atm). At temperatures and pressures above these critical values, CO_2 is not technically a liquid and instead is in a supercritical state as a dense phase "fluid" or vapor with properties between that of a liquid and a gas. This supercritical fluid will not condense to liquid within the pipeline, as long as the temperature remains above the critical temperature, no matter how high the pressure is increased above the critical pressure. If the temperature along a supercritical state pipeline drops below the critical temperature, part of the fluid will condense to liquid with a higher density than the fluid. If the pressure along a supercritical state pipeline drops below 1070 psia, part of the CO_2 will convert to a gas/liquid mixture depending on the temperature.

The primary reason that the existing 5,000 or so miles of CO_2 pipelines transport CO_2 in a supercritical state is because CO_2 in this state is an excellent solvent having no liquid surface tension. It readily dissolves oil trapped in porous rock. In contrast, CO_2 destined for sequestration could be transported as a gas or liquid, because sequestration does not, as a practical matter, need the CO_2 to be in a supercritical state, and federal law does not require transportation in a supercritical state. In fact, a clever pipeline operator could employ loopholes to avoid federal pipeline safety oversight by PHMSA. Clearly the sources and needs of CO_2 for EOR are not the same as those for the CCS objective, which is to remove CO_2 from the atmosphere.

CO_2 supercritical fluid transmission pipeline operating pressures usually range from 1,200 to 2,200 pounds force per square inch gauge, or psig. The higher pressure is set based on the maximum operating pressure ("MOP") usually related to a pipe specification limit.[18] There are a minor number of CO_2 supercritical state pipelines that have been designed to operate at much higher MOPs (*e.g.*, 3200 psig). Moving CO_2 as a dense phase supercritical state fluid permits the use of pumps along a pipeline instead of compressors that would be needed to move the material if it were a gas. For pipelines, the use of pumps to move higher density fluids requires smaller, less complex, equipment that is more efficient in moving mass along a pipeline than compressors (*i.e.*, pumps are cheaper to build, install, maintain, and operate than compressors). In addition, the higher MOPs of supercritical state CO_2 pipelines permit them to utilize smaller diameter pipe, albeit much stronger pipe, to move the same tonnage of CO_2 as compared to shipment as a gas. In contrast, gas pipelines require larger diameter pipe to move the same tonnage, because they must usually operate at pressures lower than the supercritical pressure (1070 psig), otherwise some of the CO_2 could convert to a liquid

[18] MOP stands for maximum operating pressure for liquid pipelines and is defined in federal minimum pipeline safety regulations that provide conditions for "normal" operation of pipelines. Pipelines are permitted to exceed MOP within certain limits, under certain situations.

(depending on the temperature along the pipeline) and such liquid slugs would severely damage/destroy the compressors used in gas pipelines.

While there are many cost/efficiency advantages to moving CO_2 in a supercritical state, there is one well known threat associated with supercritical state operation. A CO_2 pipeline operating in a supercritical state can be more prone to pipe running ductile fractures than hazardous liquids or natural gas pipelines. Running ductile fractures are unusual and particularly dangerous fractures that can "unzip" a CO_2 transmission pipeline for extended distances exposing great lengths of the buried pipeline. These extreme rupture forces throw tons of pipe, pipe shrapnel, and ground covering, generating large craters along the failed pipeline. It is well known that CO_2 pipelines operating in dense phase, either supercritical or as a liquid, are particularly susceptible to such running ductile fractures. Although current federal regulations recognize this risk, they do not contain any detailed requirements that specifically identify how to address fracture propagation threats. Though there are various approaches well known in the industry (*i.e.*, pipe steel fracture toughness parameters, usually for new pipe, and/or mechanical arrestors such as valves, thicker/tougher pipe transitions) such approaches should be specifically mentioned in safety regulation.[19] To address this risk, PHMSA should revise federal regulations, especially for supercritical CO_2 pipelines, to specifically mitigate the effects of these fracture propagation forces. The current regulations do not adequately address these CO_2 fracture risks.

ii. Liquid CO_2 transmission pipelines

Subcooled or subcritical state means to transport CO_2 as a liquid that usually requires chilling and/or cooling of the stream slightly below ambient temperatures to assure the pipeline is operated in one phase, that of a liquid. For new pipelines this also may require the use of pipeline insulation, though not always, to reduce temperature increase of the CO_2 along the pipeline, assuring it stays as a liquid. It is important that cooling stay well above the pipe carbon steel brittle transition temperature of approximately - 20 ºF to avoid the threat of catastrophic pipeline rupture. Despite these obstacles, transporting CO_2 as a liquid, basically at its highest density, which is typically about double the density of CO_2 fluid in its supercritical state, allows the pipeline transportation of more tonnage of carbon dioxide with even smaller diameter pipe than a supercritical state operation, as well as lower MOPs. Because the liquid phase operation also has a lower viscosity, a liquid CO_2 pipeline system for a given length can utilize a fewer number of pump stations that can have major advantages over supercritical state or gas pipeline approaches needed to move similar tonnage of CO_2. For CCS objectives, liquid phase CO_2 transmission pipelines additional efficiency over their supercritical state or gas counterparts may justify the additional cooling infrastructure along such

[19] 49 CFR§195.111 Fracture propagation. The regulation states in full: "A carbon dioxide pipeline system must be designed to mitigate the effects of fracture propagation." Thus, pipeline safety law contains no detailed standards to prevent running ductile fractures leaving much room for misinterpretation.

pipelines. It is worth emphasizing that PHMSA chose to not issue regulations for CO_2 pipelines designed to operate as a liquid, so such pipelines are currently unregulated.

iii. CO_2 gas transmission pipelines

New pipelines designed to move CO_2 as a gas in a transmission pipeline is not likely, given that the system must be operated at lower pressures. For a CO_2 gas pipeline, the MAOP must not exceed approximately 1,000 psig at normal operating temperatures, so that the CO_2 is maintained as a gas and does not convert to a liquid as this could be disastrous for the pipeline's compressors.[20] For an equivalent daily CO_2 tonnage pipeline capacity, the requirement to keep design pressure lower drives such new gas pipeline approaches to much higher pipe diameters than their liquid or supercritical state pipeline alternatives. However, specific situations may exist where existing liquid or larger diameter natural gas pipelines could be "repurposed" into primarily CO_2 gas service.[21] Such change in service, will most likely be highly limited in its pipeline mileage and, in my opinion, should exceed the requirements identified in ADB-2014-04, addressing repurposing of natural gas pipelines or liquid pipelines. For example, an Advisory Bulletin, or ADB, does not carry the force of promulgated pipeline safety regulation but is issued to more quickly alert pipeline operators of PHMSA concerns on certain issues. ADB-2014-04 does not address, nor was it intended to address, the specific additional challenges associated with unique fracture propagation risks associated with CO_2 transmission pipelines as previous discussed. While there are unique situations where nonoperating or underutilized pipelines exist, there are several factors that can make repurposing of such pipelines to CO_2 gas service economically attractive, given the billions of dollars in tax credit incentives associated with CCS under the Acts of 2018 and 2021, and the associated start construction deadline. The critical deadlines to meet tax credit triggers could make timing of such conversions more favorable than routing and construction of new CO_2 pipelines for CCS. Such pipeline conversions would be at much greater risk of failure from CO_2 service than conventional hydrocarbon or new construction CO_2 pipelines, given the unique and increased potential for CO_2 pipeline ruptures from various risks associated with CO_2 operation. Only time will tell, given the economic temptations and timing thresholds, whether such repurposing of an existing transmission pipeline to CO_2 service will prove practical for CCS utilization.

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[20] MAOP stands for maximum allowable operating pressure, which is the standard for gas pipelines and is defined in federal minimum pipeline safety regulations that provide conditions for "normal" operation of pipelines. Pipelines are permitted to exceed MAOP within certain limits, under certain situations.

[21] See DOT PHMSA, Advisory Bulletin, ADB-2014—04, "Pipeline Safety: Guidance for Pipeline Flow Reversals, Product Changes and Conversion to Service," Docket No. PHMSA–2014–0040, Sept 12, 2014.

IV. CO_2 transmission pipelines pose different risks than traditional hydrocarbon transmission pipelines

Carbon dioxide gas is odorless, colorless, doesn't burn, is heavier than air, and is an asphyxiant and intoxicant, making CO_2 pipeline releases harder to observe and avoid especially as a released plume spreads and migrates well off the pipeline right-of-way. CO_2 properties differ from those for materials moved in hazardous hydrocarbon liquid or natural gas transmission pipelines. CO_2 pipeline releases significantly increase the possible "affected" or "potential impact" area identified in federal regulations addressing hydrocarbon transmission pipelines upon pipeline rupture release, and CO_2 pipeline ruptures have a greater potential to endanger the public. Current federal pipeline safety regulations do not incorporate these important CO_2 differences to assure safety to the public. Federal pipeline safety regulatory changes are warranted if CO_2 pipeline mileage is to be increased dramatically in the U.S., especially under CCS. CO_2 transmission pipelines have many unique failure dynamics such that a rupture may impact significantly greater geographic areas than hydrocarbon pipelines. In particular, a combination of CO_2 phase/temperature changes may result in explosive pipe release forces as the CO_2 converts to gas. Moreover, CO_2's lack of odor and invisibility means that it may not be possible for citizens and first responders to determine if they are in a hazard area before they are harmed, unless they have access to a CO_2 detection meter. It is important that anyone using such CO_2 detection meters assure that such equipment has been properly calibrated/maintained and users properly trained in their use and limitations. Once a CO_2 pipeline release has been warmed by the surrounding environment, it travels unseen influenced by gravity, terrain, and the wind, preferentially settling in low spots, displacing air and providing no warning to persons and animals caught in the invisible release plume. Hydrocarbon pipeline releases that haven't ignited, can usually be detected by unusual smell or sight, which makes CO_2 pipeline releases different and harder to detect by emergency responders or the public.

During a CO_2 pipeline rupture release, multiple phase changes can result not only in the significant lowering of temperature near the pipe failure site, but also the likelihood of solid CO_2 formation (i.e., dry ice). Dry ice particles within the fluid can contribute to fogging in the air and ground around the pipeline release, as well as the formation of dry ice within the pipeline upstream/downstream of the pipe failure site that can impact the rate of release out of a pipe failure. Such dry ice blockage can result in temporary restriction/blockage within the pipe, affecting release rate, especially for smaller diameter transmission pipelines experiencing rupture fracture.

In CO_2 pipelines experiencing smaller, slower rate releases, often called leaks, such as through minor holes or cracks, the resulting lower rate CO_2 rich clouds may disperse/dissipate after a short time. In much larger rate releases, such as pipeline rupture fractures caused from various anomalies or pipeline threats, the resulting release of cold gas and dry ice solid mixtures can be quite dangerous (see video of

DNV rupture failure test of an CO_2 8-inch diameter pipeline).[22] The CO_2 released from a pipeline will be heavier than air, and the high-rate release from a pipe rupture will form cold dense gas fog clouds comprised of dry ice particles and visible water vapor as the humidity in the air condenses from the extreme cooling. Such high-rate releases can produce areas of low visibility from "fog," both from dry ice particles and water condensation. The CO_2 pipeline rupture fog becomes transparent when eventually warmed by the surrounding environment. Upon warming, the CO_2 plume can flow considerable distances from the pipeline unobserved, traveling over terrain, displacing oxygen while settling or filling in low spots. Oxygen displacement can starve gasoline or diesel powered equipment, such as first responder and private vehicles, causing such equipment to malfunction or even shut off, and cause pilot lights on furnaces, stoves, and natural gas fireplaces to go out. Oxygen displacement by CO_2 gas can cause asphyxiation of humans and animals, that can lead to death. Further, CO_2 gas can cause disorientation, confusion, and unconsciousness, which can be dangerous for persons caught in the plume, especially those who are driving, using power equipment, or exposed to cold weather. Cooling of a CO_2 release can also impact the rate of release and exacerbate pipe fracture propagation during rupture. Clearly, dispersion modeling for analyzing potential impact areas for CO_2 pipeline failures and their related released gas plumes, must consider the propensity of heavier than air CO_2 gas to displace oxygen and to follow the terrain as terrain factors can play a critical role in evaluating a potential area and receptors that could be affected by a CO_2 pipeline release. It is vitally important to not underestimate the potential distance that a CO_2 pipeline rupture plume can reach and affect, especially in nonlevel terrain. Additional safety margins should be employed in populated areas when using dispersion modeling results for CO_2 pipeline releases.

Before the U.S. is blanketed with a major increase in CO_2 transmission pipeline mileage driven by CCS efforts, substantial changes need to be implemented in federal pipeline safety regulations specifically addressing the unique dangers of CO_2 in transmission pipelines in any phase. CO_2 is not flammable. It doesn't burn or explode/detonate from ignition, so heat radiation is not an issue of concern as in conventional hydrocarbon pipelines. CO_2 can, however, generate similar overpressure "blast" forces upon pipeline rupture (from the high-rate releases associated with pipeline fracture failure, see previous referenced 8-inch CO_2 pipeline rupture test). CO_2 pipeline rupture and resulting rapid "blast like" expansion forces dissipate quickly with distance from the pipeline but can easily extend well beyond the pipeline right of way. The areas potentially impacted by ruptures of oil and gas transmission pipelines are well defined in current federal regulations, which estimate how far liquid hydrocarbon will spread and the blast or burn radius resulting from a natural gas pipeline rupture. The danger zone for human life for hazardous hydrocarbon liquid and natural gas pipeline releases is generally measured in feet, albeit many thousands of feet for larger diameter higher pressure pipelines.

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[22] Video of 2013 DNV Spadeadam Research and Testing test experiment of dense phase CO_2 8-inch buried pipeline rupture, https://www.dnv.com/oilgas/laboratories-test-sites/dense-phase-spadeadam-video.html.

In contrast, a CO_2 pipeline's impact area may be measured in miles, not feet. This is likely because:

- CO_2 pipeline ruptures can release many tons of CO_2,
- the compressed CO_2 will expand into gas phase upon pipeline rupture and fill a much larger volume that it did inside the pipe, and
- the CO_2 may not disperse quickly because it is heavier than air, meaning that it will tend to flow toward and settle in low lying areas including ravines, valleys, and basements.

Current federal pipeline safety regulations do not provide any methodology for assessing the hazard zone for CO_2 pipelines or require that pipeline operators adequately address this risk.

V. Impact of impurities on CO_2 pipelines

The amounts and types of impurities in a CO_2 stream can have an impact on pipeline design and approaches. Current CO_2 pipeline regulations, which only address CO_2 pipelines greater than 90% CO_2 concentration compressed to a supercritical state, make no mention as to the level of non-CO_2 impurities such as H_2S, which can be lethal even in very low parts per million concentrations. Also, impurities can affect the range of safe operating pressures. Most of the natural sources of CO_2 for existing pipelines contain CO_2 well above 90%, but this may not be the case for all CO_2 streams captured from industrial facilities. Federal regulation should be modified to adequately regulate CO_2 pipelines used for CCS, and subsequent transportation by transmission pipeline, especially because CCS pipelines may operate differently from those used for EOR. Such federal regulatory improvements should focus on public safety for all forms/phases of CO_2 transmission pipelines. There are some very pure sources of CO_2 emitters, such as ethanol plants and some hydrogen reformers, that emit very high concentrations of CO_2 to the atmosphere that require very little, if any, impurity treatment to prepare for pipeline transportation for CCS.[23] Unlike most of the currently existing CO_2 pipelines whose sources are underground natural gas domes or reservoirs, CSS pipelines may be supplied from various sources where the concentration of CO_2 is quite low and needing concentration, processing, and treatment for contaminant removal before it may be safely transported by pipeline.

There appears to be no transmission pipeline in the U.S. that transports pure CO_2, although there are pipelines that move very high concentrations of CO_2, well above 90%, containing only small levels, of impurities, especially those from natural sources of CO_2. Such CO_2 rich sources can still contain impurities, such as hydrogen sulfide, methane, carbon monoxide, oxygen, nitrogen oxide, sulphur oxide, hydrogen, or

[23] My experience is that purity from such CO_2 specialized emitters can exceed 99.9 % with trace impurities.

water.[24] The types and amounts of impurities in a CO_2 rich pipeline is largely driven by the source of CO_2, and proper operation of associated upstream treatment equipment to assure the material meets pipeline quality specifications, which is not always assured. At relatively low levels of impurities, such as at trace or levels in the lower parts per million, the specific effects of the impurities on the overall stream critical thermodynamic properties (such as enthalpy, entropy, density, and viscosity), are not significantly impacted. However, higher impurity concentrations, such as impurities measured in percentage concentrations should not be ignored as they can impact the critical pressure, but more importantly the critical temperature, such that even a percent or two change in impurity levels can result in unexpected phase change from dense phase fluid to other phases. Such phase changes may impact the system hydraulics, and to some extent the rupture release dynamics should the pipeline fail.

Two impurities that might be possible in CO_2 pipelines merit mention given their unique dangers to pipelines and the public: water and H_2S. CO_2 pipelines are usually made from carbon steel and require special maximum water quality specifications typically measured in the part per million, or its equivalent, that prevents the possibility of free water forming anywhere in the pipeline system. The presence of free water in a CO_2 stream permits the formation of carbonic acid in the pipeline, an acid that has a ferocious appetite for carbon steel. Given the rapidity and unpredictability at which carbonic acid can attack pipelines, prudent CO_2 pipeline operators have voluntarily established maximum water quality limitations for their input streams. Given the risks associated with carbonic acid attack, PHMSA should not leave this critical factor to company discretion, but instead should adopt federal regulations that specify a maximum water quality limitation for CO_2 pipelines.

Hydrogen sulfide, or H_2S, is mentioned here because of a curious item identified in an article related to a supercritical state CO_2 pipeline rupture failure in Mississippi in early 2020.[25] The observations noted in the article by responders of a "green cloud" from the pipeline release, is a possible indication of high levels of H_2S. Further investigation indicates that the source of the CO_2 (Jackson Dome) has levels of H_2S at 5 percent, or 50,000 ppm. In contrast, the Centers for Disease Control and Prevention states that a level of 300 parts per million is "immediately dangerous to life or health."[26] While the H_2S level that transitions into "sour" gas is not defined in federal

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[24] For example, see Suoton P. Peletire, Nejat Rahmanian, Iqbal M. Mujtaba, "Effects of Impurities on CO_2 Pipeline Performance, Chemical Engineering Transactions," Vol. 57, 2017.

[25] Dan Zegart Huffpost article, "The Gassing of Satartia," August 26, 2021 at https://www.huffpost.com/entry/gassing-satartia-mississippi-co2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f,

[26] https://www.cdc.gov/niosh/idlh/7783064.html. It is my understanding that while a few states have attempted to impose H_2S limits on intrastate pipelines, there is no such federal pipeline safety regulation limiting H_2S on transmission pipelines, even though there are OSHA H_2S limits on workplace workers, much lower than 300 ppm.

pipeline safety regulations, serious questions need to be raised about this specific CO_2 pipeline operation.

For CCS generated CO_2, from fuel combustion emission, an expected source for CCS, H_2S is not a likely contaminant of the stream with trace levels of H_2S in the less than 1 ppm to be expected. Treatment for the removal of water and water quality enforcement control limitations, however, are critical for CCS pipelines transporting CO_2 from combustion sources. Yet, current federal pipeline safety regulations also do not require that this risk be addressed.

VI. Areas needing additional federal pipeline safety focus for CO_2 pipelines

Based on my experiences, the following are my preliminary observations on specific areas where CO_2 pipeline safety regulation improvement efforts should focus.

1. **PHMSA should update the definition of carbon dioxide in current regulation.**
   The current "carbon dioxide" definition incorporated into pipeline safety regulation is driven by EOR and does not or may not apply to all CO_2 pipelines that may be developed for CCS projects. Federal regulations need to be modified to assure that federal standards apply to all CO_2 transmission pipelines that transport CO_2 for CCS projects, including all supercritical, gas, and liquid CO_2 transmission pipelines.

2. **PHMSA needs to identify in regulation the potential impact areas for CO_2 pipeline ruptures.**
   The unique, and potentially very large impact areas for CO_2 pipeline ruptures need to be developed, defined, and promulgated into pipeline regulations. As mentioned previously, these areas are most likely to be measured in miles, not feet.

3. **Specific CO_2 pipeline federal regulations should not be based solely on industry Recommended Practices.**
   Changes in the CO_2 pipeline safety regulation are needed and should be prescribed to avoid misinterpretation or misuse. Recent efforts by many in the industry to rely on more performance-based standards, even those incorporated by reference, have proven ineffective and disastrous. Such industry efforts also remove an important party to pipeline safety regulatory development, the public. Ironically, it is the public that has the most to lose from inadequate pipeline safety regulation if such referenced citations are not clear, relevant, effective, and cannot be enforced in assuring pipeline safety.

4. **PHMSA should specifically identify how to incorporate fracture propagation protection on CO_2 transmission pipelines.**
   Given the differential propensity for CO_2 pipelines to propagate fractures along the pipeline upon rupture, regulations should specifically list pipeline design methods to arrest CO_2 fracture propagation.

5. **PHMSA should mandate the use of odorant injection into CO_2 transmission pipelines.**
   Given the inability to detect or observe a CO_2 pipeline release, it is time to require the use of odorant injection in such pipelines, especially those pipelines that are not in unpopulated areas, to assist the public in identifying dangerous releases.

6. **PHMSA should require CO_2 pipeline operators to update their required procedural manuals related to coordination with local emergency response agencies for CO_2 pipeline ruptures.**
   The major differences and uniqueness of CO_2 pipeline releases compared to hydrocarbon pipelines require that pipeline operators improve the sections of their federally mandated operation, maintenance, and emergencies procedural manuals for emergency response to CO_2 pipeline ruptures.[27] In particular, operators must be required to periodically and fully inform, train, and equip key local officials and emergency responders with regard to special response actions unique to CO_2 pipeline releases. Moreover, upon a rupture, pipeline operators must inform state and local emergency personnel so that they can quickly and adequately protect impacted citizens and themselves.

7. **PHMSA should establish regulations setting specific maximum contaminant impurities for CO_2 pipelines.**
   Given the various sources and the unique risk associated with the introduction of water into a CO_2 pipeline, PHMSA should prescribe the maximum concentration of water allowed in them. This requirement goes well beyond a quality specification given the ability of water to rapidly cause CO_2 pipeline failures in unpredictable ways. Given the wide range of impurity sources for CO_2 streams for CCS, PHMSA should review a full range of limits for all common impurities and consider establishing maximum levels for all impurities that pose a safety risk in federal pipeline safety regulations.

8. **PHMSA should strengthen federal regulations for conversion of existing pipelines to CO_2 pipeline service.**
   It is not clear whether the public interest is best served by CO_2 shipment in existing transmission pipelines converted to CO_2 service. Further, the general conditions of PHMSA's advisory bulletin are not adequate for conversion to CO_2 pipelines. PHMSA should fully investigate the risks of such conversions and issue regulations appropriate to the serious risks that could result from repurposing a pipeline for CO_2 service.

VII. Conclusions

Current federal minimum pipeline safety regulations focus on higher concentration CO_2 pipelines transporting CO_2 in a supercritical state for use in oil production. Such

[27] 49CFR§195.402 and 49CFR§192.605 Procedural manual for operations, maintenance, and emergencies.

regulations are incomplete or in conflict with the intent of CCS, to reduce CO_2 content in the atmosphere to address global warming. Federal pipeline safety regulation concerning CO_2 pipelines need specific changes to address the likely expansion of CO_2 transmission pipeline mileage expected by CCS efforts enhanced by the Acts of 2018 and 2021.

Certain manufacturing processes, such as ethanol and some hydrogen reforming refinery units, produce CO_2 emission that are very pure CO_2, with only trace amounts of contaminants, that are higher priority choices for CCS and associated pipelines, most likely new liquid transmission pipelines, especially under the immense tax credits associated with the Acts of 2018 and 2021. Current federal pipeline safety regulations, however, are not adequate to deal with the additional pipeline risks associated with the expected significant increase in associated CO_2 transmission pipelines under CCS.

The country is ill prepared for the increase of CO_2 pipeline mileage being driven by federal CCS policy. Federal pipeline safety regulations need to be quickly changed to rise to this new challenge, and to assure that the public has confidence in the federal pipeline safety regulations.[28]

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