UH ENERGY RESEARCH REPORT

Carbon Dioxide Pipelines Explained:

Critical Role in Responding to Climate Change

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UH Energy
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Scope

Efforts to reduce carbon dioxide (CO_2) in the atmosphere have led governments and industry to begin to adopt a wide range of approaches to the issue. Regardless of whether captured from industrial emissions sources or directly from the air (or the ocean), the CO_2 must be used for some productive purpose or sequestered underground. Technologies capable of capturing, and using or sequestering CO_2 exist, making the ability to transport it from the point of capture to the point of use or sequestration a critical component. There are a range of approaches to solving this transportation issue, but the use of dedicated pipelines is one of the most common.

This white paper draws upon authoritative sources, including the Pipeline and Hazardous Materials Safety Administration (PHMSA), the U.S. Department of Energy (DOE), academic research and publications, and established industry associations and aims to present:

- A factual overview of carbon dioxide (CO_2) pipelines, elucidating their purpose, types, components, and their integral role in carbon capture, utilization, and storage (CCUS).
- An exploration of safety, environmental, and health considerations in the construction and operation of CO_2 pipelines, including incident history and lessons learned.
- Potential impacts on communities that are in the path of a proposed CO_2 pipeline project.
- The regulatory landscape in place and industry best practices that pipeline operators, including CO_2 pipeline operators, use in managing the risks for safer, environmentally sound, and community friendly operations.
- The benefits and challenges inherent to CO_2 pipelines.

A growing number of CCUS projects are expected to come online over the next decade, causing a related growth in pipelines to transport the captured carbon dioxide to its final destination. This paper is intended to help people whose communities are in the path of a proposed project better understand why these pipelines are needed, what risks their construction and operation may pose, and what can be done to ensure the safety of the surrounding environment and communities.

Executive Summary

Atmospheric carbon dioxide (CO_2) levels have risen from around 280 parts per million (ppm) before the industrial revolution to about 421 ppm in 2023, driven mainly by the combustion of fossil fuels and deforestation. That has contributed significantly to atmospheric warming and a changing climate, leading to demands for an energy transition. Some aspects of the transition already are underway – sales of electric vehicles are climbing, in 2023, wind and solar power collectively contributed 31% to the total power generation[1], with wind accounting for 24% and solar for 7%. Compared to 2022, their combined contribution to the Texas grid increased by 25.9% and battery storage bolstered the Texas grid during the record-breaking heat of 2023. Industry and academic collaborations are working on clean hydrogen and other decarbonization efforts.

One key ingredient in the transition that has received less attention but nevertheless will play an outsized role: Networks of specialized pipelines engineered to safely transport carbon dioxide will have to grow dramatically if we are to take advantage of the carbon capture, utilization, and storage (CCUS) technologies that have emerged as a critical lever to mitigate climate change.

CCUS technologies involve the capture of CO_2 emissions from industrial processes, power generation, and other sources, followed by their transportation to sites where they can be stored in geologically suitable formations, used to boost oil production or converted into commercially viable products. In this context, CO_2 pipelines act as arteries across a vast network, facilitating the secure and efficient conveyance of captured CO_2 from its various sources to designated use or storage locations. Other methods are also used to move captured CO_2, including rail, trucking, and marine shipping. Pipelines, however, have emerged as the preferred choice for large-scale CCUS initiatives.

The United States has an existing CO_2 pipeline network spanning more than 5,385 miles – about half of that in the Permian Basin in Texas and New Mexico – capable of transporting 80 million tons of CO_2 a year and primarily used to move CO_2 to oil-producing fields, where it is used to boost oil recovery and then stored in the depleted reservoirs. But the current network is far too limited if we are serious about employing CCUS at scale, and by 2050, this system is projected to grow to 65,865 miles, able to transport about 930 million tons of CO_2 annually[2]. (Existing pipelines built to move natural gas and other substances can't easily be repurposed, as the construction materials and design of carbon dioxide pipelines are specifically engineered to address the properties of CO_2.)

The viability of proposed CCUS projects and, more broadly, efforts to limit warming and meet global climate goals, depends on finding a way to move captured CO_2 safely and cost-effectively to its endpoint – and if such a massive expansion is to be realized there must be a broader understanding of the advantages and risks of these pipelines. Expanding the existing network to enable additional CCUS projects will be much more time consuming and difficult, if not impossible, if the industry is unable to work effectively with stakeholders, including the communities through which the proposed pipelines will pass. Information about the realities of both CO_2 and its transport by pipeline, as well as transparency about the construction and operating phases of those pipelines, is required.

To address this gap in knowledge, we have conducted an intensive study, examining how the pipelines have been used in the past, their role in current and future efforts to reduce CO_2 emissions, and the advantages and risks associated with their use. As a result, we have identified a series of best practices and actions that should be taken by industry and regulators to ensure the safe and efficient operation of an expanded CO_2 pipeline network within the United States.

The stakes are high. Successfully integrating CO_2 pipelines within the proposed CCUS framework could reshape the energy landscape, allowing emission-intensive sectors to remain viable and even shifting the carbon profile of industry-heavy geographic regions. Put more starkly, we are unlikely to achieve carbon neutrality, meeting goals that have been set by governments and industry alike, without a far larger network of CO_2 pipelines. Among our findings:

- CO_2 pipelines boast a wide capacity range, from 890 tons to 103,000 tons per day, surpassing shipping (46,000 tons per vessel) and rail (80 to 83 tons per railcar)[3]. Furthermore, these pipelines ensure uninterrupted operations, running 24/7 for a consistent flow of CO_2.

- Pipelines aren't without risk, however, including challenges to pipeline integrity, such as corrosion, fractures, external damage, and pipe joint and weld failures. Additional risks can arise from soil or geological conditions, including landslides, volcanic eruptions, earthquakes, and flooding.

- Leaks and ruptures can send CO_2 into the atmosphere, contributing to greenhouse gas emissions and posing risks to the environment, including habitat loss, displacement of species, and potential imbalances in local biodiversity, among other impacts on plant and animal life, soil composition, and aquatic systems.

- CO_2 is colorless and odorless, making it more difficult to detect a leak before high concentrations displace oxygen in the air, exposing workers, nearby communities, and first responders to the associated health risks. Respiratory issues due to oxygen deprivation can have severe health consequences, including unconsciousness, respiratory distress, and even death. While a database maintained by the Pipeline and Hazardous Materials Safety Administration reported no deaths associated with a CO_2 pipeline between 2003 and 2022;

a much-publicized 2020 pipeline rupture in Mississippi sent 45 people to the hospital[4].

• Other hazards include dry ice, which can form when leaking CO_2 cools rapidly and freezes moisture in the air; noise pollution from associated compressors, pumps, and other equipment; and air pollution, primarily related to dust during the construction phase.

• Rigorous measures can offset the risks, including robust pressure monitoring and control systems to prevent pressure buildup within the pipeline, the installation of pressure relief valves and safety mechanisms that automatically activate in case of excessive pressure, and regular inspections and maintenance of pressure management equipment.

• Other measures to mitigate harm include continuous monitoring of CO_2 concentrations in and around pipeline facilities using advanced sensors, installing early warning systems to alert when concentrations exceed safe levels, and conducting regular safety drills to educate workers, nearby communities, and first responders to recognize the signs of oxygen deficiency and what to do in the event of exposure.

• Federal regulations, overseen by the Pipeline and Hazardous Materials Safety Administration (PHMSA), govern the transportation of CO_2 and other hazardous materials, from pipeline construction and operation to maintenance and emergency response measures, including requirements to develop and implement plans in response to any spill or release.

• Other regulations relate to specific operational situations, including how pipelines cross rivers, streams, lakes, wetlands, and other bodies of water, intended to safeguard water quality, aquatic ecosystems, and the surrounding environment. Operators are required to conduct more rigorous inspections and testing for pipelines located in areas near schools, residential areas, hospitals, and urban population centers.

Beyond these regulations and the use of technologies and industry-standard procedures to minimize disruptions and risks, we have identified essential steps to improve safety, limit regulatory delays, and mitigate the impact on the environment and surrounding community. These practices are routinely utilized by reputable pipeline operators and by PHMSA. However, communities may wish to enquire about their specific use in their locale. Our recommendations include:

• Regular and rigorous inspections by both operators and regulators to ensure pipelines adhere to established standards throughout their life cycle. This includes monitoring construction, operation, maintenance, and decommissioning phases. Frequent inspections can help identify issues before they escalate into major incidents.

• Trace amounts of odorants (like the industry practice of adding traces of mercaptan to natural gas) should be added to CO_2 to ensure that any leak can easily be detected.

• PHMSA should update dispersion modelling standards to reflect the latest scientific research and technology, improving understanding of how leaks or ruptures might affect nearby communities.

• PHMSA should regularly review and assess the integrity management programs implemented by pipeline owners, including preventive and mitigative measures, emergency response plans, and incident reporting procedures. It should identify areas for improvement and ensure compliance.

• PHMSA should consider categorizing projects based on their potential impact. This could lead to establishing specific timelines and regulatory requirements tailored to the sensitivity of the project. Project segments in high consequence areas rightfully need additional scrutiny.

• PHMSA and pipeline operators should establish robust mechanisms for involving all relevant stakeholders throughout the pipeline life cycle. This includes pipeline owners, local communities, landowners, environmental groups, industry experts, and state regulatory agencies. Operators should proactively address concerns, provide information, and involve stakeholders in decision-making.

• Operators and contractors should establish and maintain rigorous quality assurance programs for construction and operation. All personnel should receive adequate training and certifications to perform their roles effectively and safely.

• Operators and regulators should embrace advances in pipeline technology, such as corrosion-resistant coatings, monitoring sensors, and automated inspection tools. A culture of continuous improvement to enhance safety and environmental performance should be established.

Managing carbon emissions will remain a critical effort as the world transitions to cleaner sources of energy, and CO_2 pipelines play a critical role. These pipelines offer strategic advantages over other forms of transportation for CO_2, but the health and safety risks are real, as is the potential for backlash from landowners and other stakeholders that can contribute to delays and cost overruns for pipeline projects. Neither the benefits nor the challenges should be ignored.

Existing regulations address many of the risks, and robust enforcement can go a long way toward lessening those risks and alleviating stakeholder concerns. However, additional measures will be needed if the pipeline buildout envisioned by proponents of CCUS systems is to be achieved.

1. Introduction

In an era marked by remarkable technological advancements, our world is undergoing a profound energy transition as we shift toward sustainable electrical energy and adopt the use of cleaner fuels such as hydrogen. Even so, carbon dioxide (CO_2) levels in the atmosphere continue to rise. There are numerous sources of these emissions, and many segments of the global economy are taking action to address them. Scientists have linked CO_2 emissions with more frequent extreme weather events, rising sea levels, and other impacts, a reminder that the clock is ticking if we are to address these additional carbon dioxide emissions.

The solutions are complex, and low-carbon sources of energy, including wind, solar, and geothermal power, are essential. But the world will continue to depend on fossil fuels for at least the next few decades, both to satisfy growing global demands for energy and to produce the plastics, chemicals, pharmaceuticals, and other necessities of daily life we have come to depend upon. Hydrocarbons are a key building block for these products, and at least for now, there is no reliable, affordable substitute. Allowing the resulting levels of carbon dioxide to continue to rise unabated risks serious impacts on people, the environment, and the economy.

The International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) have identified carbon capture, utilization, and storage (CCUS) technologies as necessary to reduce the impact of carbon dioxide emissions. CCUS, along with other decarbonization strategies including fuel switching and nature-based solutions, are part of an umbrella of strategies needed to address the energy transition. The IEA identifies four reasons to deploy CCUS:

(a) tackling emissions from existing energy assets.

(b) as a solution for sectors where emissions are hard to abate.

(c) as a platform for clean and affordable hydrogen production.

(d) removing carbon from the atmosphere to balance emissions that cannot be directly abated or avoided.

One approach has been to capture CO_2 emissions from fossil energy combustion, such as coal-fired power plants, the manufacturing of cement and steel, or directly from the air or the ocean and either safely sequester the emissions or use the CO_2 for the manufacture of materials. A network of CO_2 pipelines, capable of safely and efficiently moving the captured emissions to places they can be stored or used, is a key component of the effort, and their significance cannot be overstated. The captured CO_2, once transported, can be safely stored in geological formations deep underground, harnessed to enhance oil production, or transformed into commercially viable products. Such a network of CO_2 pipelines would allow us to translate the potential of CCUS technologies into tangible, impactful solutions for mitigating the effects of increased CO_2 emissions on the climate. However, there are risks associated with the construction and operation of these pipelines. The best practices and guardrails that ensure continued safety and protection of the environment and communities during the construction and operation of pipelines continue to evolve. This paper endeavors to explain the role these pipelines play in CCUS, the best practices for their construction and operation, and their contribution to a broader journey toward a sustainable world, connecting various industries and safely moving the captured CO_2 to its secure end destination.

2. Stages in Carbon Management - Capture, Transportation, Utilization, and Storage

The term "CCUS" encompasses four stages[5] **(Figure 1).** The steps are:

• **Carbon Capture:** The capture step represents the initial phase of CCUS, where CO_2 emissions are intercepted and isolated from industrial processes or power generation before they are released into the atmosphere. They also can be removed directly from the ambient air or from ocean water. For more details on Capture see Appendix I.

• **Transport:** The transportation step represents a crucial link between capturing the emissions and their ultimate destination for storage or utilization. This is commonly achieved through pipelines, but ships, rail, or trucks can also be used, especially when the storage site is inaccessible by pipeline.

• **Storage (or Sequestration):** This involves storing the captured CO_2. The most common approach is geological storage, where CO_2 is injected deep underground into rock formations, often formations that once contained oil or gas and/or saline aquifers. Another method is mineral storage, wherein CO_2 reacts with certain minerals to form solid carbonates.

• **Utilization:** Refers to repurposing captured CO_2 emissions for economically beneficial applications. In addition to its use for enhanced oil recovery, CO_2 can serve as a feedstock for products including chemicals, plastics, and building materials.

CCUS not only helps mitigate the environmental impact of carbon emissions but can also transform them into valuable resources that can contribute to economic growth and sustainable development.

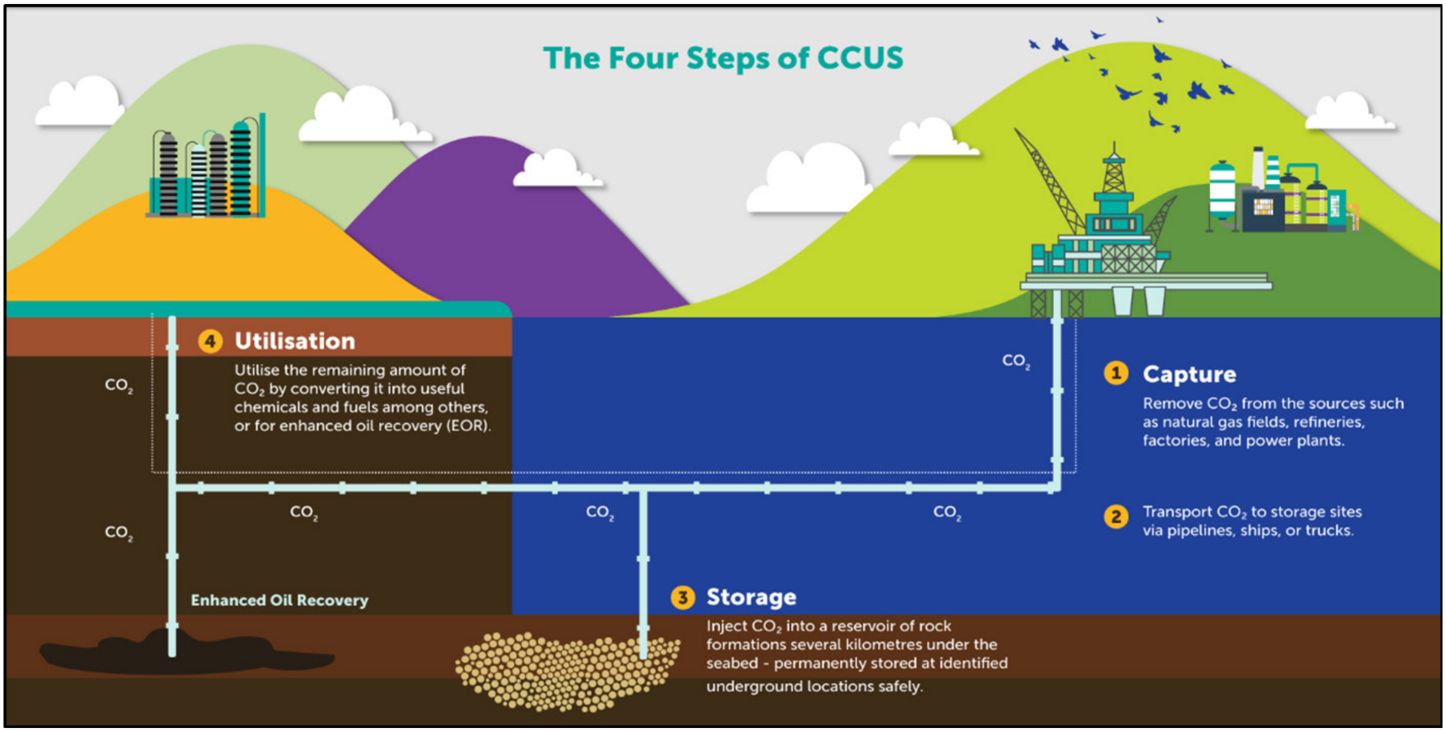

Figure 1. Stages of CCUS[1]

For more details on Storage/Sequestration and Utilization see **Appendix II** and **Appendix III**, respectively.

[1] PETRONAS. (2021, November 17). Getting to know CCUS at PETRONAS. Retrieved from https://www.petronas.com/flow/technology/getting-know-ccus-petronas

3. CO_2 Transportation: A Vital Link in Carbon Management

3.1 Different Ways of Transporting CO_2

While the capture and use/storage of CO_2 often dominates discussions of CCUS, transportation bridges these two stages. Efficiently and safely moving captured CO_2 from source to storage is crucial to the success of any CCUS project. Different transportation methods can be used depending on the source of the captured CO_2, the proximity to storage sites, and the volume to be transported. Here are the primary types of CO_2 transportation:

- **Pipelines:** CO_2 pipelines are specialized infrastructure to efficiently transport captured carbon dioxide from emission sources to storage or utilization sites. These pipelines are designed and constructed to handle the unique properties and safety considerations of transporting compressed carbon dioxide. Pipelines are best used when large quantities of CO_2 need to be transported over contiguous land masses, on a continuous basis rather than in batches.

- **Shipping:** When crossing oceans, specially designed ships are the go-to method for CO_2 transportation. These vessels are equipped to safely carry liquefied CO_2 under pressure and at low temperatures. This makes them advantageous for locations with offshore geological storage or when engaging in international (over long distances) CO_2 commerce. An excellent example of CO_2 shipping is the Norwegian Northern Lights project.

- **Road Transport:** Specialized tanker trucks are designed to contain CO_2 in liquid state under pressure and are best suited for transporting smaller volumes of CO_2 over shorter distances. Often, they are used during the preliminary stages of CCUS projects or for pilot initiatives.

- **Rail Transport:** CO_2 can be transported in its liquid state using specialized rail cars. This method is particularly beneficial for moving medium volumes or distances, especially when a rail system already connects the capture facility to the designated storage site.

- **Modular Systems:** Compact carbon integrated systems offer a solution to capture, liquefy, and prepare CO_2 for transportation. This approach is ideal for isolated areas or smaller emission points where establishing permanent infrastructure may not be cost-effective.

While each transportation method has its advantages, pipelines have emerged as a predominant choice for large-scale CCUS initiatives, especially in the continental United States. Let's delve deeper into the benefits of CO_2 pipelines in the carbon management landscape.

3.2 Why Use Pipelines?

There are several compelling reasons to use CO_2 pipelines:

- **High-Volume Transport:** Pipelines tailored for CO_2 are built to handle substantial amounts of carbon dioxide. Given that major sources like power stations or industrial sites generate massive CO_2 volumes on a continuous basis, pipelines serve as the only cost-effective means to transport these quantities[6]. **(Table 1)**

- **Safety:** When correctly built and maintained, pipelines are considered one of the safest methods for CO_2 transportation. Within these pipelines, carbon dioxide is typically maintained in a supercritical state, demonstrating both liquid and gaseous properties. This is discussed in more detail below.

- **Reliability and Consistency:** Pipelines offer a consistent avenue for CO_2 transport. They allow steady, continuous delivery through a dedicated system. In contrast, all the other available transportation methods are intermittent operations, which depend on the movement of trucks, railcars, and ships to and from specified locations at designated times, often with transshipment between modes of transportation. This is a complex logistical challenge, as the CO_2 cargoes share roads, rails, docks, and shipping lanes with other carriers and other cargoes. They are therefore vulnerable to logistical disruptions that are often unrelated to CO_2 transportation, such as road and rail congestion or capacity limits.

- **Reduced Carbon Footprint:** Once set up, pipelines have a minimal operational carbon footprint, particularly in contrast to vehicles or ships that currently are likely to run on carbon-intensive fuels and consequently emit greenhouse gases.

- **Geographic Flexibility:** Pipelines are versatile, capable of navigating mountains, valleys, and even underwater terrains. Their design adaptability facilitates linking CO_2 sources with storage sites that might be remote or situated in difficult locations.

- **Direct Integration:** Pipelines can be directly linked with storage sites, facilitating efficient transfer. The direct connection ensures minimal handling between capture and storage, reducing the chances of leaks or inefficiencies.

- **Scalability:** As more facilities adopt CCUS, existing pipeline networks can be expanded or integrated to handle the rising demand.

The advantages of CO_2 pipelines are similar to those of other existing energy services, including oil and gas pipelines. These pipeline networks are crucial for the transfer of vital resources across the value chain. Several CCUS projects have also been proposed in Southeast Asia, Australia, and elsewhere around the world. While the regulatory and permitting issues are different from those in the U.S., and the geology may dictate different methods of CO_2 storage, the lessons learned during the U.S. buildout of CCUS, and the accompanying CO_2 pipeline expansion will provide valuable insights as the technologies spread globally.

Table 1. Transportation Capacities (Capacity Basis 100,000 Tons/day)

Method of Transport	Capacity (Tons)	Capacity (trips/day)
Pipelines	890 to 103,000 Tons/Day	1 - 100 trips/day
Shipping	46,000 Tons/Vessel	2.2 trips/day
Rail	80 to 83 Tons/Railcar	15 - 16 Unit Train trips/ day of 80 cars
Truck	18 Tons/Tanker	5555 Truck trips/day

3.3 How Do We Transport CO_2 in Pipelines?

Carbon dioxide can be moved in pipelines in various phases, depending on the specific requirements and conditions. Phase transformation refers to the change of a substance from one state of matter (or phase) to another, such as from solid to liquid or from liquid to gas. For substances like CO_2, these transformations are influenced by temperature and pressure. Understanding these transformations is vital for various industrial applications, especially for substances like CO_2 with distinct and useful properties in each phase. Here's a basic overview:

- **Gaseous Phase:** Normally, CO_2 exists as a gas. However, transporting CO_2 by pipeline in gaseous form requires moving larger volumes and is less efficient due to the lower density of the gas.
- **Liquid Phase:** Liquid CO_2 doesn't occur at atmospheric pressure. However, CO_2 can be compressed into a liquid form. This liquid phase is generally observed in specific industrial processes or pressurized equipment.
- **Supercritical Phase:** When CO_2 is maintained at conditions of pressure and temperature beyond its critical point, it becomes a supercritical fluid. The critical point of a substance is a unique temperature and pressure where the difference between liquid and gas phases vanishes. For CO_2, this occurs at a temperature of approximately 31.04°C (87.8 F) and a pressure of 7.39 megapascals, or MPa, (~ 1,070-pound force per square inch (psi))[7]. **(Figure 2)** Supercritical CO_2 is especially beneficial for pipeline transportation due to its combined characteristics of gases (flowability) and liquids (density), optimizing transport efficiency.
- **Dense Phase:** The term "dense phase" describes CO_2 at a temperature and pressure where it behaves as a high-density fluid but is not necessarily supercritical. Dense phase CO_2 is often used because the near water-like density allows for a more compact and efficient storage or transportation system.

CO_2 is transported in pipelines primarily in its supercritical state. This transportation method is chosen for reasons related to efficiency, safety, and the physical properties of CO_2:

- **Efficiency:** Supercritical CO_2 has the density of a liquid, which means pipelines can transport a large quantity of CO_2 in a relatively compact volume, maximizing the amount of CO_2 that can be moved through the pipeline and optimizing transportation efficiency.
- **Safety:** In its supercritical state, CO_2, a non-flammable material, poses less risk of a significant leak following a pipeline rupture. Additionally, in the event of a leak, supercritical CO_2 tends to descend (as it is denser than air) rather than disperse rapidly into the atmosphere, making it somewhat easier to manage and contain.
- **Minimized Compressibility:** CO_2's compressibility is reduced in its supercritical state and resembles that of a liquid. This means changes in pressure along the pipeline don't result in significant volume changes, ensuring stable and predictable flow rates.
- **Energy Considerations:** Transporting CO_2 in its supercritical state reduces the energy required compared to transporting it as a gas. This leads to cost and energy savings over the transportation life cycle.

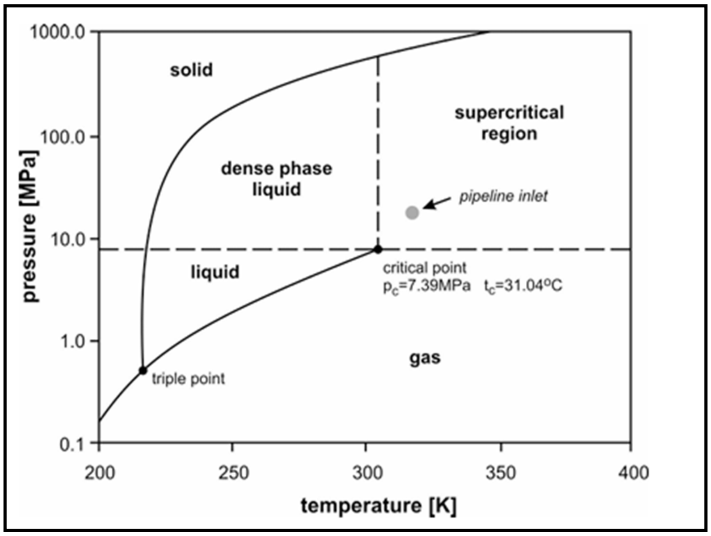

Figure 2. The phase behavior of CO_2[2] showing the different regions of temperature and pressure where different phases of CO_2 exist. The critical point is observed at 7.39 MPa and 31.04 0C

- **Lack of Phase Changes:** In the supercritical state, CO_2 doesn't undergo phase transitions (from liquid to gas or vice versa) under normal transportation conditions. This eliminates concerns about condensation or vaporization within the pipeline, which could impact flow dynamics or introduce additional safety concerns. 3.4

[2] Witkowski, A. S., Majkut, M., & Rulik, S. (2014, March). Analysis of pipeline transportation systems for carbon dioxide sequestration. Archives of Thermodynamics, 35(1), 117-140. Retrieved from https://doi.org/10.2478/aoter-2014-0008

3.4 CO_2 Pipelines in the United States – Current and Potential

The United States is a global leader in carbon management and deployment of CCUS. The U.S. has an extensive CO_2 pipeline network spanning 5,385 miles with a capacity to transport 80 million tons of CO_2 annually. The CO_2 is transported as a high-pressure fluid. The pipelines are typically made of carbon-manganese steel material, such as API grades X60 or X80. This existing network has primarily been used to transport CO_2 to oil-producing fields to support enhanced oil recovery (EOR) efforts. However, the current network falls far short of what is required to make CCUS truly impactful. Projections in support of climate goals indicate this system will need to grow substantially by 2050, expanding to 65,865 miles to enable capture from over 1,000 facilities and increasing its capacity to transport around 930 million tons of CO_2 each year[8]. Achieving this expansion by 2050 will require significant investment, site characterization, and permitting across multiple storage basins and sites. It will also require significant investment and effort to engage with a broad range of stakeholders across the communities impacted by these pipelines.

The utilization of CO_2 pipelines in the U.S. has a long history, primarily driven by the oil and gas industry's use of CO_2 for enhanced oil recovery[9] and, more recently, by environmental concerns related to climate change and the expansion of CCS programs globally.

• **Early Use in Enhanced Oil Recovery (EOR):** CO_2 pipelines in the U.S. were primarily developed to support EOR operations. In EOR, CO_2 is injected into mature oil fields to increase the amount of crude oil that can be extracted. The injected CO_2 acts as a solvent and displaces oil from rock pores, making it easier to pump to the surface. The first significant CO_2 EOR project began in the 1970s at Scurry Area Canyon Reef Operator's Committee (SACROC), West Texas, and as its success became evident, more pipelines were constructed to connect CO_2 sources (primarily natural reservoirs) to oil fields. We note that many of the early EOR cases were based on CO_2 from natural sources rather than anthropogenic sources. Using CO_2 for EOR has an important additional benefit. According to the U.S. Department of Energy, the CO_2 injected to stimulate additional oil recovery remains in the formation and is permanently sequestered. The U.S. Geological Survey of 2020 estimates that reservoirs suitable for the CO_2-EOR process could produce an average of 29,000 million barrels (MMbbl) of oil and an average total of 8,400 million metric tons (Mt) of CO_2 could be securely stored beneath the surface due to employing the CO_2-EOR method[10]. **(Figure 3)**

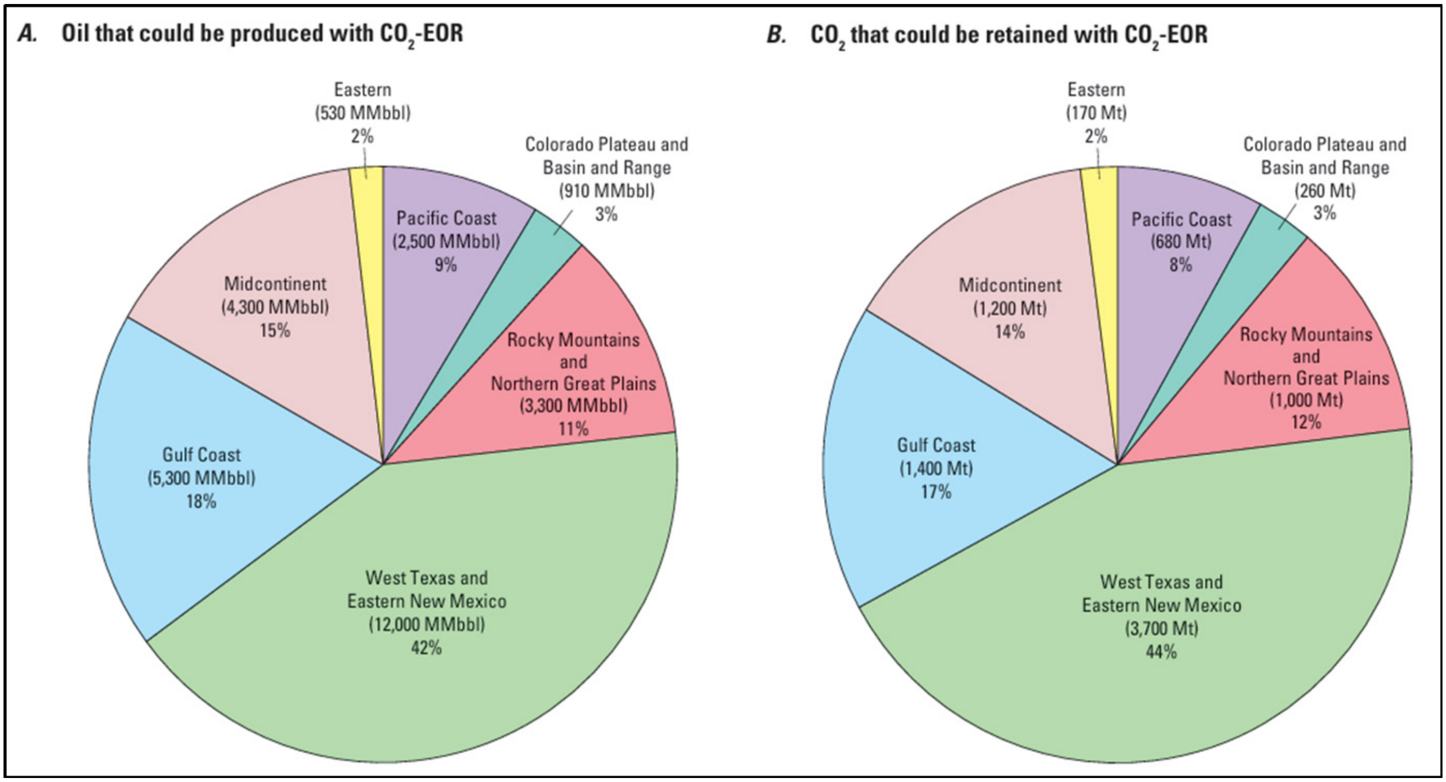

Figure 3. Distribution of the regional average estimates by the USGS Survey of 2020 for: (A) Recoverable volumes of oil that could be produced by CO_2 -EOR; and (B) Amount of subsurface CO_2 that could be sequestered[3] through CO_2 -EOR.

[3] Warwick, P. D., Attanasi, E. D., Blondes, M. S., Brennan, S. T., Buursink, M. L., Cahan, S. M., Doolan, C. A., Freeman, P. A., Karacan, C. Ö., Lohr, C. D., Merrill, M. D., Olea, R. A., Shelton, J. L., Slucher, E. R., Varela, B. A., ... Varela, B. A. (2022, February 1). National assessment of carbon dioxide enhanced oil recovery and associated carbon dioxide retention resources—Summary. USGS. Retrieved from https://pubs.usgs.gov/publication/fs20213057

Table 2. Current CO_2 Pipeline Network in the United States

U.S. Regions with Large-Scale CO_2 Pipeline Systems in Operation	**Miles of Pipeline**
Permian Basin (W. TX, NM, and S. CO)	2,600
Gulf Coast (MS, LA, and E. TX)	740
Rocky Mountains (N. CO, WY, and MT)	730
Mid-Continent (OK and KS)	480
Other (ND, MI, Canada)	215 + (minor pipelines)

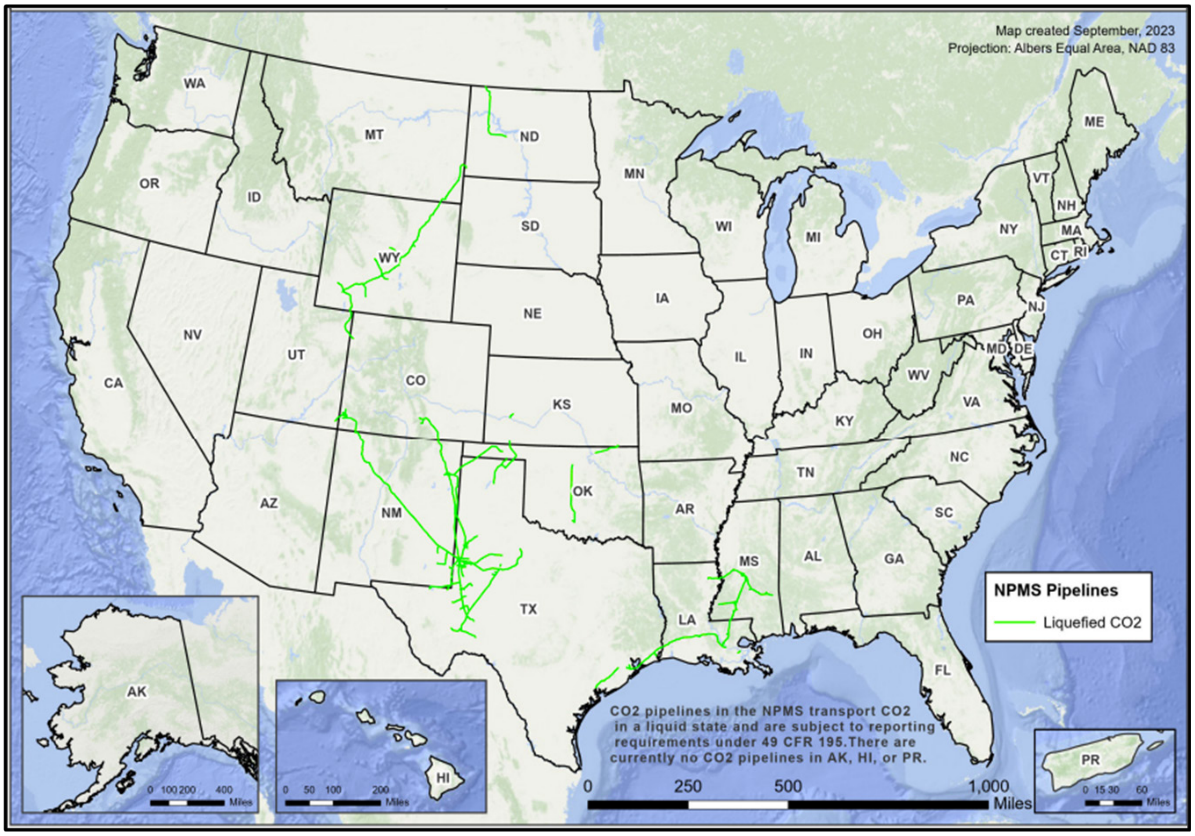

Figure 4. Current CO_2 Pipeline Network in the United States

• **Current State:** Today, the U.S. boasts one of the world's most extensive networks of CO_2 pipeline systems[11], as shown in **Table 2** and **Figure 4** illustrating the current U.S. CO_2 pipeline network. The vision for the future is even more ambitious. Several CCUS projects have been proposed in keeping with climate efforts, which would require expanding the infrastructure.

• **Growth:** Over the decades, the network of CO_2 pipelines expanded, especially in oil-rich regions like the Permian Basin. The infrastructure has continued to expand, driven by the economic benefits of EOR and technological advances in pipeline construction and operation.

[4] PHMSA, US Department of Transportation. (2024, March 11). Active CO2 pipelines in the NPMS. National Pipeline Mapping System. Retrieved from https://www.npms.phmsa.dot.gov/Documents/NPMS_CO2_Pipelines_Map.pdf

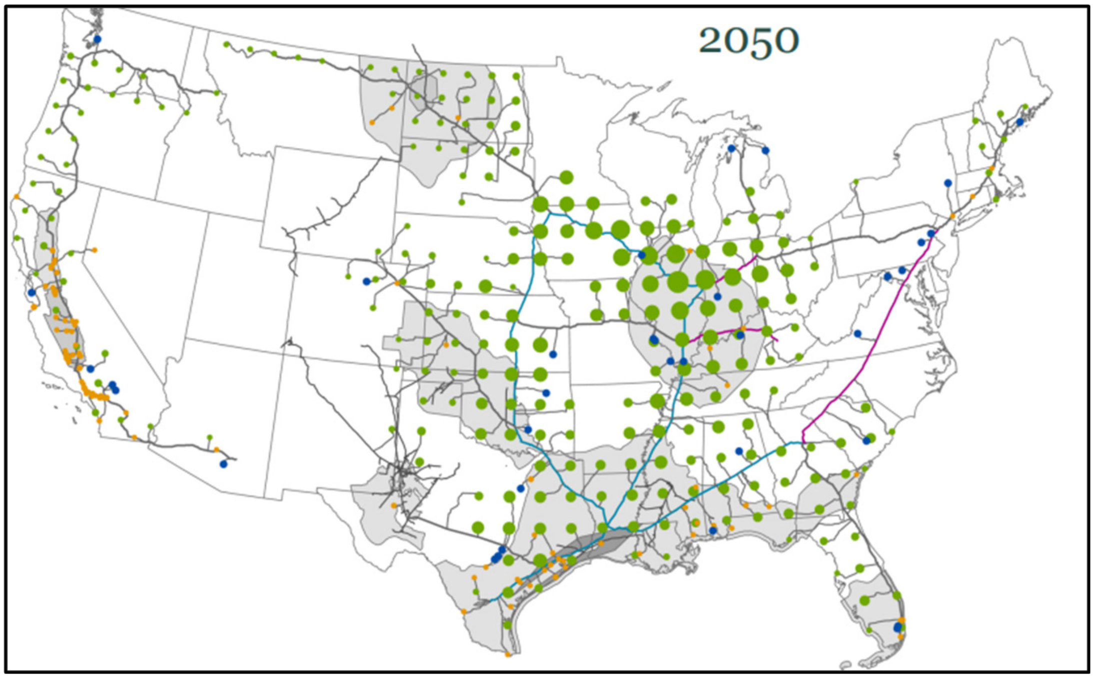

Figure 5. Planned expansion of the CO_2 pipeline network by 2050[5]

Plans call for integrating various sources of CO_2 emissions and carrying that CO_2 over long distances to the sequestration sites. By 2050, according to the Princeton University Report on Zero Emissions (E+ Scenario), which envisions aggressive electrification, the CO_2 pipeline system is expected to grow to 65,865 miles[12] **(Figure 5)**, and it would be able to transport about 930 million tons of CO_2 annually.

CO_2 pipelines have evolved from serving a niche function within the oil industry to critical infrastructure components in the country's energy and environmental strategies.

But any conversion would be far from simple, primarily because CO_2 pipelines generally operate at higher pressures, from 1200 psi to 2200 psi. While pipelines used for transportation of hydrocarbons and CO_2 are similar in nature, i.e. both are constructed using stainless steel and carry pressurized fluids, CO_2 is usually carried at a higher pressure in its supercritical phase, while hydrocarbons are transported at a lower pressure, 200 psi-1500 psi, as a gas or liquid[13], with the higher pressures employed for intermediate weight hydrocarbons (C2, C3 and C4). The process of converting a hydrocarbon pipeline to transport CO_2 involves:

• Installation of dehydration systems to reduce the water content in the CO_2 stream.

• Installing crack arrestors every ~ 1,600 feet to allow the pipeline to handle higher pressure.

• Upgrading pipeline materials with corrosion resistant internal linings and coatings.

• Implementing a control system to monitor and manage CO_2 transport.

• Installing valves and control equipment to handle pressure surges due to the impurities in the CO_2 stream and the supercritical state.

An analysis by the National Petroleum Council found that repurposing a natural gas pipeline would, at best, have a cost equivalent to that of a new pipeline. While repurposing a line with an existing right of way would eliminate one problem, it would likely be more expensive than constructing a new pipeline designed specifically for CO_2 transport[14] and would not eliminate the need for changes to the operating permits.

3.5 Repurposing Existing Pipelines

We have observed the advantages of pipelines over alternative transportation methods and the expertise in the United States in building such infrastructure. The existing U.S. pipeline network of crude oil, at 84,432 miles, and petroleum products, at 64,082 miles, would seem to provide a potential opportunity to repurpose these existing pipelines. Converting these pipelines would be attractive for few reasons:

• It could potentially reduce the overall cost and time required to build new pipelines.

• As the country transitions to cleaner sources of energy, this will result in decommissioning a large number of pipelines. These could be converted to other uses, including CO2 pipelines.

[5] Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, E. J., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K., & Swan, A. (2021). Net-Zero America: Potential pathways, infrastructure, and impacts. Princeton University. Retrieved from https://netzeroamerica.princeton.edu/the-report

4. Managing Challenges and Risks – Regulations and Permitting

The launching of a large-scale CO_2 pipeline project involves three major steps:

- **Pre-Construction:** Securing the right-of-way, obtaining public consent, and obtaining necessary permitting requirements for the construction of the pipeline
- **Construction:** Constructing the pipeline with periodic inspection and final commissioning after verification of matching requirements.
- **Operation:** Operating the pipeline with operations and maintenance in compliance with rules and regulations of jurisdiction.

Each of the steps involves several complex activities and gives rise to challenges and risks. A challenge arises when an event has already happened or has a very high chance of happening. A pipeline rupture resulting from someone driving a backhoe into a buried line is a risk, whereas corrosion in a pipeline is a challenge or an issue. In either case, the situation could result in a leak with associated implications. And in either case, actions can be taken to lessen the chances of a release of CO_2 if not prevent it.

There are several regulations, both federal and state, in place to guide the proper management of each of the above three steps and minimize risks and impacts. The guidelines are generally enforced through permits. Securing the appropriate permits and adhering to them is critical for safely operating a pipeline. In the following sections, we share the different regulations governing the activities in the different phases of the project and the challenges and risks that they aim to address.

To date, limited federal legal frameworks have been developed to govern CO_2 pipeline infrastructure. Instead, the majority of regulations are determined at the state level, resulting in a patchwork of regulations across the country. Academic studies on this subject have revealed that the resultant patchwork may cause uncertainty and inefficiency, thereby impacting the cost and economic benefits derived from the pipelines while introducing political complications[15].

Additionally, people in the communities through which the pipelines traverse need to feel comfortable with the safety of the pipelines and their operations. Without the consent of the communities, the construction and operation of a pipeline can be halted. This highlights the importance of proper stakeholder management, which is dealt with in more detail in a subsequent section.

4.1 Land Use and Rights-of-Way (ROW)

The initial phase for launching a large-scale project revolves around securing suitable land. This typically involves engaging with federal and state authorities, along with obtaining public consent.

The foundation of the permitting procedure lies in land usage and rights-of-way. This is necessary to ensure not only the efficient operation of the pipelines but also to safeguard property rights and accountability for environmental concerns.

To understand why permitting is needed, we must start with the associated legal terminology:

- **Land Use:** The planning, allocation, and management of land for various purposes, considering ownership, environmental, social, and economic considerations. For CO_2 pipelines, land use involves identifying suitable routes that minimize impacts on communities, ecosystems, and existing infrastructure.
- **Right of way (ROW):** A legal authorization that grants the holder the right to access and use a designated strip of land for a specific purpose, such as constructing and operating a pipeline. ROW grants are typically secured through negotiation with the landowner or eminent domain proceedings and provide the necessary legal framework for pipeline construction.
- **Eminent domain:** A legal concept that allows governments or authorized entities to acquire private property for public use. This process requires just compensation for the property owner and typically involves public projects deemed to be in the public interest, such as transportation and energy infrastructure.

The process of land use and obtaining ROW is crucial for CO_2 pipeline projects for several reasons:

- **Access and Development:** CO_2 pipelines often cross both private and public lands to connect production sources with sequestration sites. Securing the necessary land access ensures the pipeline can be developed and operated.
- **Regulatory Compliance:** Compliance with legal and regulatory requirements is essential for the safety, integrity, and environmental responsibility of CO_2 pipelines. Adequate land use planning and ROW acquisition ensures alignment with relevant laws.
- **Community and Environmental Impact:** The process helps assess and minimize the impact of pipeline construction on communities, cultural resources, sensitive habitats, and other environmentally significant areas.
- **Property Owner Rights:** Eminent domain processes aim to balance public interest and private property rights by ensuring property owners receive fair compensation for the use of their land.

To initiate a CO_2 pipeline project, the operating entity must satisfy regulations set in place by federal, state, and local authorities. Critical aspects of these regulations include:

• **Surveying and Mapping:** Accurate surveying and mapping of the pipeline route is necessary to determine the exact location of the pipeline and its impact on existing land use and ownership.

• **Land Use and Subsurface Access:** Both include establishing appropriate agreements with the landowners and stakeholders. The land use involves surface-level operations and maintenance needed to install and operate the pipeline. Subsurface access involves allowing the use of the subsurface for the pipeline to transit someone's property. In both cases, the landowners are compensated accordingly, keeping in mind the effect of operations and construction above and below the surface, respectively.

• **Permitting and Approvals:** Acquiring the necessary permits and approvals from federal, state, and local regulatory bodies is a fundamental step. These permits authorize the use of specific lands for pipeline construction and operation and often specify the requirements for such use.

• **Safety Standards:** Pipelines must adhere to strict safety standards and regulations to protect public safety and the environment. Safety measures include construction standards, ongoing inspections, maintenance, and emergency response plans.

• **Environmental Impact Assessment:** Evaluating the potential environmental impact on the surrounding ecosystem is crucial. This assessment helps in understanding and mitigating adverse effects and ensuring compliance with environmental regulations, following National Environmental Policy Act (NEPA) guidelines.

• **Public Engagement and Consent:** Engaging with the public and local communities is vital for obtaining social acceptance and addressing concerns. Public hearings and consultations are often held to address questions, gather feedback, and obtain consent.

• **Property Rights and Compensation:** Ensuring landowners' property rights are respected, and that they are fairly compensated for any land use or disruption caused by the pipeline, is an important aspect of ethical and legal considerations.

• **Relocation Assistance:** In some cases, pipeline construction may require relocating residents or businesses. Regulations may include provisions for providing relocation assistance to affected individuals or entities.

• **Long-Term Monitoring and Maintenance:** Establishing protocols for ongoing monitoring, maintenance, and potential land restoration post-pipeline construction is crucial to ensure the sustained health of the land and surrounding environment.

Case of Midwest Pipelines:
Three major companies—Summit Carbon Solutions, Navigator Ventures, and Wolf Carbon Solutions proposed an ambitious project involving the installation of approximately 3,650 miles (5,874 km) of new carbon dioxide pipelines across the American Midwest. The primary goal is to bolster carbon capture efforts and reduce emissions. However, the plan has given rise to concerns, primarily related to the chosen route traversing predominantly rural areas and farmlands. These concerns revolve around pipeline efficiency, safety, and the potential impacts on local communities.

Negotiations and Community Concerns: Obtaining agreements from landowners to facilitate pipeline construction was delayed as negotiations continued, amplifying public apprehension and concerns that the companies might resort to eminent domain to secure the required rights-of-way. Communities near the proposed routes pursued legal intervention to address these issues, centering on concerns for the well-being of their communities and potential repercussions for the farming sector. These concerns were compounded by real-world incidents, such as the pipeline rupture in Satartia, Mississippi, which intensified the debate over the safety and necessity of such extensive projects.

Due to the challenges and the lengthy wait time in obtaining easements from farmers and other landowners, Navigator announced in the fall of 2023 that it had canceled the planned project and, facing similar obstacles, the Summit line has been placed on hold.

4.1.1 Land Use & ROW - State Regulations

Generally, individual states regulate CO_2 pipelines on state lands and on private lands within the state. Texas and New Mexico are illustrative. Both states permit an operator to build a pipeline to move CO_2 from a specific source to a specific destination as a private or proprietary line[16]. That is, the line is purpose-built for a project, and sources and destinations outside of that project do not have to be accommodated. Texas also allows a CO_2 pipeline to be built and operated as a "common carrier line" – i.e., a private or public entity that transports goods for a fee. In this case, the operator can seek to exercise eminent domain to obtain a right of way but must do so by agreeing to certain obligations. For example, they must establish equal rates for service, and they must publish their rates or tariffs for all to see. Using eminent domain must rest on a finding of the importance of the overriding public good provided by a project and requires fair and reasonable compensation to the property owner.

Other states have taken varied approaches. In Mississippi, the use of eminent domain is more restricted when it comes to the development of CO_2 pipelines. Eminent domain is specifically authorized for pipelines designed to transport CO_2 for the secondary or tertiary recovery of liquid hydrocarbons. However, under current regulations, pipelines intended exclusively for transporting CO_2 for storage will not be granted eminent domain rights.

Illinois stands out as one of the few Midwestern states with a dedicated CO_2 pipeline statute. The Illinois CO_2 Act has a broad scope, encompassing pipelines that transport CO_2 from any source contributing to emissions reduction and giving responsibility to the Illinois Commerce Commission. Importantly, the Illinois CO_2 Act empowers CO_2 pipeline developers with eminent domain authority, declaring CO_2 transportation as a public utility. However, it also requires developers to thoroughly attempt to acquire the needed property by other means before invoking eminent domain, and it does not permit pipeline operators to function as common carriers.

Iowa has no specific CO_2 pipeline law; however, "liquefied carbon dioxide" falls under the category of hazardous liquids[17]. Oversight of hazardous liquid pipelines is vested in the Iowa Utilities Board, which holds authority to approve their locations and routes, and to grant eminent domain rights when necessary. Applicants are required to provide detailed information of affected lands, address property owner concerns, explore alternative routes, and conduct informational meetings before submitting their applications to the board. Iowa extends significant eminent domain authority to pipeline developers and does not mandate that they function as common carriers. Numerous other states have yet to comprehensively tackle the matter of siting CO_2 pipelines and defining eminent domain provisions. In such cases, responsibility falls upon pipeline operators to proactively engage with the appropriate governmental authorities and ensure adherence to both federal and state regulations.

The timeline for the development of a CO_2 pipeline project largely depends on the level of familiarity state agencies possess regarding pipeline regulation. Where state agencies are well-versed in pipeline oversight, the project may progress more smoothly and swiftly. However, in states where there is limited prior experience with pipeline regulation, there could be an additional learning curve, which may extend the overall time required to develop the project.

4.1.2 Land Use & ROW - Cultural and Environmental Justice Concerns

A new EPA study highlights how the gravest consequences of climate change disproportionately affect underserved communities, which are the least equipped to handle challenges like heatwaves, air pollution, floods, and other repercussions. The report specifically points out that communities of racial and ethnic minorities bear a heavier burden of climate change's adverse effects[18].

The key conclusions of the EPA analysis reveal that Black and African American populations are anticipated to suffer more from climate change across all six evaluated impacts, more so than any other group.

For instance, with a global temperature rise of 2°C (3.6°F), Black and African American communities are:

- 34% more likely to reside in areas facing the sharpest increase in childhood asthma diagnoses, which escalates to 41% with a 4°C (7.2°F) temperature increase.
- 40% more likely to live in locations where extreme temperature-related fatalities are expected to rise the most, jumping to 59% with a 4°C warming.

Hispanics and Latinos, who are significantly represented in sectors like construction and agriculture that are directly exposed to weather changes, also face heightened risks from extreme heat. With a 2°C global warming scenario, Hispanic and Latino individuals are 43% more likely to be in areas facing the most significant decreases in work hours due to extreme heat.

As highlighted in this paper, adopting CO_2 pipelines helps to transport the captured emissions, proving beneficial for the environment and helping to tackle climate change. In addition, pipelines can also provide opportunities to utilize CO_2 as a fuel or a feedstock in various industrial processes such as construction, agriculture, and sustainable fuels, thus creating employment opportunities for the underserved communities. It is important to consider the history of industrial development in these areas.

Polluting industries are often located in low-income, racially diverse areas, where residents face greater societal challenges, proliferating as a consequence of industrialization[19]. This pattern reflects a reality where industrial facilities, attracted by lower land costs and less stringent regulatory oversight, often establish themselves in economically disadvantaged areas. The influx of such industrial operations brings a host of environmental, health, and civic concerns, ranging from increased pollution, exposure to harmful chemicals, disruption of community cohesion, and socio-economic disparities. Despite a national decline in toxic exposures, such improvements are less noticeable in marginalized communities. For example:

- A survey examining spills from unconventional oil and gas activities uncovered 6,600 incidents across four states between 2005 and 2014, primarily involving wastewater, crude oil, drilling residues, and fracking fluids. Around 17.4 million individuals, mostly in rural areas and within a mile of these sites, face increased risks. These communities, often dependent on unmonitored groundwater, are particularly susceptible to the water pollution which can result from such operations[20].

This uneven development, if not carefully managed, can endanger cultural sites important to indigenous tribes, disrupt natural habitats for various species, damage archaeological sites with ancient fossils, and threaten critical ecological reserves like forests and biospheres.

Industry often cites the jobs that industrial development can provide as the key benefit to the host community. In practice, however, underrepresented and underserved communities of color are often less likely to obtain employment in the surrounding industries due to a lack of required skills, career awareness, and workforce development programs.

According to a study by the Greater Houston Partnership (GHP) and the Houston Energy Transition Institute (HETI), 40% of jobs in the Houston area are linked to the energy sector, with stable employment in oil refining and petrochemicals. Approximately 921,000 mid-skill jobs require at least a high school diploma, constituting 30% of the region's total employment. However, 855,000 area residents aged 25 or older lack the necessary qualifications for these mid-skilled positions. A significant portion of these residents hail from disadvantaged or underserved communities. This discrepancy highlights a critical challenge in workforce development and the need for targeted educational and training programs to bridge this gap.

The complex interplay between climate change, industrial development, historic negative impacts from development, and the need for communities to actually benefit from development highlights the need for equitable environmental policies and practices that protect the most vulnerable populations, reduction or elimination of historic emissions, and health impacts and the workforce training programs. We need a new paradigm, based on a collaborative approach joining industrial developers, federal and state government entities, communities, and academia to develop innovative strategies to resolve this imbalance.

Communities must have adequate resources to mitigate the impacts of both climate change and industrial development as well as a realistic opportunity to participate in the economic benefits that will flow from development of pipelines.

4.1.2.1 Land Use & ROW - Cultural and Environmental Justice Concerns - Federal Regulation

The National Historic Preservation Act (NHPA) mandates a consultation process for activities that might affect historic properties. This includes a wide range of stakeholders, such as state and tribal historic preservation offices, American Indian and Alaskan Native tribes, and others.

- **Challenges and Limitations:** NHPA's effectiveness varies depending on project specifics and the level of public engagement. While the consultation process is mandatory, it does not necessarily lead to the preservation of all significant properties.

The National Environmental Policy Act (NEPA), requires federal agencies to evaluate the environmental effects of major actions, including their impact on minority and low-income populations, and since President Bill Clinton's 1994 executive order, environmental justice considerations have increasingly been integrated into NEPA assessments.

- **Criticism and Revision Efforts:** The integration of environmental justice considerations into NEPA is a significant step, yet it is still evolving. The reliance on guidance documents rather than binding regulations has been a point of criticism, with calls for more enforceable and consistent measures.

4.1.2.2 Land Use & ROW - Cultural and Environmental Justice Concerns – State Regulations

States have enacted a variety of laws addressing cultural, heritage, and environmental justice concerns related to pipeline construction. These laws vary significantly in scope and approach. A few examples include:

- **Restrictions on Eminent Domain:** New York and Louisiana have enacted laws that limit the use of eminent domain for pipelines, especially in sensitive areas like graveyards and tribal lands.

- **Protection of Agricultural and Historical Resources:** Illinois requires agreements to mitigate agricultural impacts. Other states focus on protecting historical or archaeological resources.

- **Incorporation into General Environmental Permits:** Some states integrate the review of historical and archaeological resources into their broader environmental permitting processes.

4.1.2.3 Land Use & ROW - Cultural and Environmental Justice Concerns- Implications & Challenges

- **Balancing Global Benefits and Local Impacts:** While CO_2 pipelines are crucial for environmental sustainability on a global level, balancing their benefits with the local impacts is a complex task. This balance requires careful consideration of environmental justice, cultural heritage, and community engagement.

- **Variability in Effectiveness:** The effectiveness of both federal and state regulations in protecting environmental justice interests is variable and highly dependent on specific project contexts and the extent of public and community involvement.

- **Need for Stronger Legal Frameworks:** The criticisms of NHPA and NEPA highlight a need for more robust, legally binding frameworks to ensure that environmental justice considerations are not just advisory but enforceable.

This analysis underscores the intricate interplay between environmental sustainability goals and the need to safeguard local communities' rights and heritage. The effectiveness of regulatory frameworks in addressing these concerns remains a critical area for ongoing evaluation and improvement.

4.1.2.4 Land Use & ROW - International Regulations and Cross-Border Management

The majority of global CO_2 pipeline infrastructure are in the United States, presumably due to its resilient hydrocarbon sector and federal incentives for carbon capture projects. However, other countries, including Canada, Australia, and members of the European Union (EU), are also pursuing significant CO_2 pipeline projects, each with its own regulatory approach.

In Canada, the province of Alberta has reported eight proposed CO_2 transportation projects through 2030, with six already in operation. If a CO_2 pipeline crosses provincial or international borders in Canada, the federal Canada Energy Regulator (CER) assumes exclusive Canadian oversight.

In the EU, various CO_2 pipeline networks are in development, including substantial offshore systems, particularly in northern Europe. Germany's largest pipeline company is planning a significant land-based CO_2 pipeline network to support the country's circular CO_2 economy. Currently, Germany lacks federal legislation pertaining to CO_2 transportation and storage. The German Technical and Scientific Association for Gas and Water (DVGW) has established technical standards for CO_2 pipeline safety and operation, but the regulations regarding the siting of CO_2 pipelines are not well-defined[21].

Our research suggests several factors can impede cross-border CO_2 pipeline projects:

- **Regulatory Divergence:** Different countries have varying regulatory approaches and oversight. These differences can create challenges for companies operating across borders, as they must navigate multiple regulatory frameworks.
- **Jurisdictional Issues:** In Canada, the CER has jurisdiction over CO_2 pipelines that cross provincial or international borders, which can complicate the approval process. The need to satisfy both provincial and federal authorities can lead to delays and additional administrative hurdles.
- **Evolving Legislation:** In the global context, uncertainty caused by evolving legislation is likely to add challenges. For example, in Germany, the absence of federal legislation pertaining to CO_2 transportation and storage may create uncertainty for companies planning cross-border projects.
- **International Collaboration:** For cross-border CO_2 pipeline networks, international collaboration and agreements may be necessary to address regulatory, technical, and legal challenges.
- **Infrastructure Compatibility:** Cross-border CO_2 pipelines may need to interface with existing infrastructure, including storage sites and industrial emitters. Ensuring compatibility and alignment between different infrastructure systems can be a logistical challenge.

Establishing consistent frameworks for the international and cross-border transport of CO_2 is essential. Currently, many countries are at the initial phases of adopting CO_2 pipeline technology, and as a result, collaborative efforts are in their early stages.

4.2 Managing Challenges and Risks – Pipeline Construction & Operations

As observed before, CO_2 is often transported in a supercritical state at high pressures. Operating risks include pipeline damage, corrosion, leaks, and blowouts. Accidental releases from CO_2 pipelines can counteract the benefits.

A leaking CO_2 pipeline can displace oxygen in the surrounding air, causing a variety of health problems – including headaches, dizziness, elevated blood pressure, difficulty breathing, and even death – and, if not mitigated quickly, raising the risk of harm to waterways, fish, and other wildlife. Because it is colorless and odorless, it can be difficult to detect a leak. And any leak of CO_2 into the atmosphere obviously defeats the purpose of capturing it in the first place. These are the most significant risks in the transportation of CO_2 by pipelines. These discharges of CO_2 into the atmosphere may be the result of a number of factors and is discussed further in the paper.

In the next several sections, we indicate the challenges and risks (safety, environmental and geologic) in the installation and operation of CO_2 pipelines. Also included are federal and state regulations, along with industry practices to address them.

4.2.1 Managing Challenges and Risks – Pipeline Construction & Operations - Safety Regulations

In the United States, regulation of CO_2 pipeline safety falls under the jurisdiction of the Pipeline and Hazardous Materials Safety Administration (PHMSA), a federal agency under the Department of Transportation. These regulations are essential to ensure the safety and reliability of CO_2 pipelines, reducing the risk of accidents, damage to the environment, and harm to public health. PHMSA's rules are in Title 49 of the Code of Federal Regulations (CFR), specifically in Part 195 for hazardous liquid pipelines. (CFR :: 49 CFR Part 195 -- Transportation of Hazardous Liquids by Pipeline).

The regulations stipulate standards for the design, construction, and testing of new pipelines to ensure safe operation. Many of the challenges and safety procedures related to CO_2 pipelines are no different than those faced by other pipelines, including those carrying chemicals, oil, and natural gas, although the risks in the event of an accident or leak vary. INGAA, the Interstate Natural Gas Association of America, serves as the trade association representing the owners and operators of natural gas and CO_2 pipelines. The INGAA Foundation, whose membership consists of pipeline operators and their associated supply chain, maintains a members-only "lessons learned" repository to ensure all members can learn from incidents and so-called "near misses." Broadening the availability of such information to a broader public is likely to grow stakeholder engagement and confidence.

Generally, individual states regulate CO_2 pipelines on state lands and private lands within the state. Federal safety regulation by PHMSA generally preempts state regulation for major interstate CO_2 pipelines, though states can adopt the same or stricter rules. States have more leeway in regulating intrastate pipelines, including adopting more stringent safety standards as long as they are compatible with PHMSA's minimum standards. For example, Arizona and Texas impose additional requirements on intrastate pipelines, such as construction restrictions and emergency response protocols.

Additionally, PHMSA enforces standards for safe pipeline operations. These standards require operators to implement measures to maintain pipeline integrity throughout the pipelines' operational life. This includes regular inspections, maintenance, and integrity management programs aimed at identifying and addressing potential risks. Pipeline safety regulations use the concept of "High Consequence Areas" (HCAs) to identify specific locations and areas where a pipeline incident could have the most significant adverse consequences on the environment or the community. Within HCAs, operators are required to provide additional focus, efforts, and analysis to ensure the integrity of pipelines. HCAs include schools, hospitals, community centers, and cities and towns with high population density.

Enhancements to CO_2 pipeline operations include emergency response protocols, spill prevention and response plans, and measures to protect against third-party damages. By enforcing these standards and suggesting best practices, PHMSA works to ensure CO_2 pipelines are operated with attention to safety, reliability, and environmental protection.

4.2.2 Managing Challenges and Risks – Pipeline Construction & Operations – Environmental Regulations

The environmental risks posed by construction of CO_2 pipelines include potential damage to wildlife and habitats, contamination from leaks or spills, localized air pollution during construction, and long-term emissions from associated facilities.

As with safety regulations, there are several federal and state standards that provide review processes to address environmental concerns from operation of pipelines.

CO_2 pipeline projects are subject to several federal environmental laws, including the Endangered Species Act, the Fish and Wildlife Conservation Act, the Clean Water Act (CWA), and the Clean Air Act The key federal review processes include:

- Army Corps of Engineers: Under the CWA and the Rivers and Harbors Act of 1899, the regulates discharges into federal waters and construction affecting navigable waters and thus has a role regarding pipelines that cross certain bodies of water.

- National Environmental Policy Act (NEPA): NEPA sets standards for environmental review for a wide range of activities linked to federal agencies, including the construction and operation of CO_2 pipelines.

A recent study by the Sabin Center for Climate Change Law at Columbia University noted the varying practices of states granting permits under different conditions[22].

- Land Use and Environmental Review: States like Alabama and Louisiana have specific requirements for pipeline construction across protected lands, such as submerged state lands and designated natural and scenic rivers.

- Water Quality Standards: States have varying levels of authority and approaches to regulate water quality, often interacting with or supplementing the CWA.

Other states employ various methods for environmental permitting of pipelines. Notably, California and New York have NEPA-like requirements under the California Environmental Quality Act (CEQA) and the New York State Environmental Quality Review Act (SEQRA), respectively, demanding significant environmental reviews for projects. Some states, like Texas and Oklahoma, display ambiguities in regulatory authority, particularly in areas like water quality certifications and protection of wetlands.

Permits are required to maintain and operate pipelines. Permits provide the industry with direction and establish standards to ensure the safety of the public and environment. Permitting agencies such as the ones mentioned above can be either federal and/or state and are charged with enforcement of regulations.

4.2.3 Managing Challenges and Risks – Pipeline Construction & Operations – Pipeline Integrity

Our comprehensive examination of CO_2 pipeline operations has provided insight into their complex procedural aspects. They share some similarities with the existing network of oil and natural gas pipelines, in that the planned route is excavated, and pipelines are buried with the surface land restored as close as possible to its pre-excavation condition. While CO_2 pipelines can play a role in reducing emissions, they also come with an array of challenges, due in part to the fact that they are buried and out of sight, with concerns ranging from structural integrity to geological complexities. Industry best practices and regulations at both the federal and state level address these risks to either eliminate them entirely or design a comprehensive methodology to deal with any adverse impacts.

Pipeline integrity refers to the ability of a pipeline system to perform its intended function safely and reliably without compromising the safety of people, the environment, or the pipeline itself. It involves maintaining structural soundness, preventing leaks or ruptures, and ensuring operational efficiency over its lifespan. Several factors can affect pipeline integrity:

• **Third-Party Damage:** Unauthorized digging, construction, or excavation near pipelines can lead to accidental damage, potentially causing leaks or ruptures.

• **Corrosion:** Corrosion is one of the most common threats to pipeline integrity. The interaction of pipeline materials with the environment, such as moisture and soil conditions, can lead to corrosion, weakening pipeline walls and potentially causing leaks or failures.

• **Mechanical Stress:** External forces like ground movement, heavy equipment, and construction activities can stress pipelines, leading to deformation, cracking, or rupture.

• **Fatigue:** Repeated pressure cycles, temperature changes, and other operational stressors can result in material fatigue, leading to cracks and structural weaknesses in the pipeline.

• **Material Degradation:** Over time, materials used in pipelines may degrade due to environmental factors, including exposure to corrosive substances or extreme weather changes.

• **Welding Defects:** Improper welding practices or defects in welded joints can create weak points in the pipeline, making it susceptible to failure.

• **Temperature and Pressure Variations:** Fluctuations in temperature and pressure during operations can induce stress and strain on the pipeline, potentially leading to failures.

• **Chemical Compatibility:** The transported substance's interaction with pipeline materials can cause chemical reactions that degrade the pipeline over time.

• **Insufficient Inspection and Maintenance:** Inadequate or irregular inspections and maintenance can result in undetected issues that worsen over time, eventually leading to pipeline failure.

• **Age:** As pipelines age, they become more susceptible to various forms of degradation, including corrosion, material fatigue, and other wear-and-tear factors.

Tools, technologies, processes, and regulatory requirements all are used to address the need to maintain pipeline integrity and thus safety. Let's take a deeper dive into these. Industry and pipeline regulators utilize a combination of rules and strategies to address these risks. The most common are:

• **Integrity Management Programs (IMPs):** These programs encompass risk assessment, routine inspections, and preventative measures to address potential threats.

• They prioritize a proactive approach to recognizing and mitigating integrity issues. Pipeline operators develop a comprehensive integrity management program which covers risk assessment, inspection schedules, anomaly identification procedures, and strategies for remediation. Typically, these programs are mandated and reviewed by the regulatory agency.

• **In-Line Inspection (ILI) Tools:** ILI tools can detect anomalies including corrosion, cracks, dents, and welding defects. Smart pigs, also known as pipeline inspection gauges, are widely used in this practice. **(Figure 6)** Equipped with advanced sensors and data collection technologies, these devices are inserted into pipelines, enabling them to identify anomalies for a range of purposes and applications.

A few of the most common ILI tools include:

• **Magnetic Flux Leakage (MFL) Pigs:** MFL pigs use strong magnets and sensors to detect and measure metal loss due to corrosion or other defects in the pipeline wall. They are particularly effective for inspecting ferrous pipelines.

• **Ultrasonic Inspection Pigs:** Ultrasonic pigs use high-frequency sound waves to detect and measure flaws in the pipeline, including wall thickness, corrosion, and weld defects. They are versatile and can be used for both ferrous and non-ferrous pipelines.

• **Caliper Pigs:** Caliper pigs are designed to measure the internal diameter of pipelines to detect deformities or restrictions. They are commonly used to identify dents, lack of ovality, or other irregularities that may affect the flow of fluids.

• **Geometry Pigs:** Geometry pigs are equipped with sensors to measure the internal geometry of the pipeline. They can identify deformations, bends, and changes in diameter.

• **Mapping with Corrosion Inspection Pigs:** These pigs are used to create a detailed map of the pipeline's internal condition. They combine mapping sensors with corrosion detection capabilities to provide a comprehensive assessment.

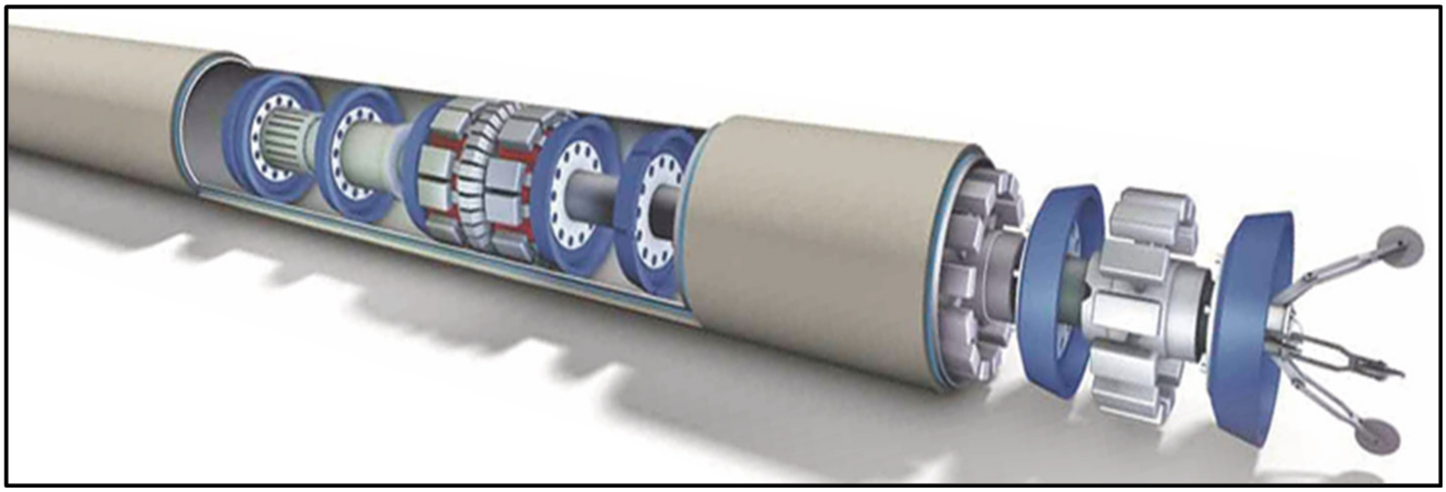

Figure 6. Smart pig[6]

- **High-Resolution Inspection Pigs:** These pigs are equipped with high-resolution sensors, providing more detailed data about the pipeline's condition. They are often used for critical pipelines or when a higher level of precision is required.

- **Chemical Injection Pigs:** These specialized pigs are used to inject chemicals, inhibitors, or coatings into the pipeline to protect against corrosion or to clean the interior surfaces.

Depending on the situation, operators select the most appropriate pig.

- **Direct Assessment:** This approach entails a thorough evaluation of the pipeline's state, involving examinations for external corrosion, internal corrosion, and stress corrosion cracking. It comprises data collection, analysis, and the implementation of remedial measures to bolster integrity.

- **Cathodic Protection:** This is a commonly used technique to prevent corrosion by introducing a controlled electrical current into the pipeline. The current counters the electrochemical processes responsible for corrosion, preserving the pipeline material and prolonging operational life. In the case of a buried CO_2 pipeline, cathodic protection can be implemented by installing sacrificial anodes or impressed current systems. These measures provide protection against corrosion induced by soil moisture.

- **Hydrostatic Testing:** This procedure is widely used to assess the strength, integrity, and leak-tightness of pipelines. It involves filling the pipeline with water and pressurizing it to a level higher than its maximum operating pressure. This elevated pressure is maintained for a specified duration, and during this time, the pipeline is inspected for any signs of leaks, deformation, or structural weaknesses. After the test is completed successfully, the liquid is typically drained from the pipeline, which can then be prepared for normal operation. If leaks or other issues are detected, repairs or remediation actions are undertaken before the pipeline is put into service. A hydrostatic test is typically conducted before a new line is put into service, but it may also be used to check a pipeline already in use after emptying the line for inspection.

- **Pipeline Leak Detection Systems:** Utilizing a range of technologies such as acoustic, thermal, and pressure sensors, these systems are designed to promptly identify leaks. This continuous monitoring capability improves response times and reduces the potential environmental and safety impact of leaks. For instance, a pipeline company can implement distributed acoustic sensing (DAS) along a CO_2 pipeline to detect subtle leaks or stress-induced vibrations, allowing for timely intervention.

- **High-Consequence Areas (HCAs):** As defined by PHMSA, these are specific portions of the pipeline route characterized by dense population (with 50,000 or more people or a density of at least 1,000 people per square mile), environmental sensitivity, and public spaces (concentrated populations in cities, towns, villages, or designated residential or commercial areas). In addition to the standard measures, PHMSA requires the operating entity to implement additional measures in an HCA, which involves performing a risk analysis of the segment to identify extra precautions for enhancing public safety and environmental protection. Actions may range from adopting damage prevention practices, enhancing corrosion monitoring through better cathodic protection, setting more frequent inspection schedules, and installing emergency flow restricting devices (EFRDs). It also requires the shut-off segment to be isolated by two remote-controlled valves (RMV), where the "shut-off segment" is the pipeline section between upstream and downstream valves surrounding an HCA-affected area. Valve spacing must ensure protection at both ends of a pipeline segment with RMVs or equivalent technologies, with specific distances of a maximum of 15 miles between valves, not to exceed 7½ miles from shut-off segment endpoints.

[6] Energy Transfer. (2021, February). In-line inspection tools - Smart pig. Retrieved from https://www.energytransfer.com/wp-content/uploads/2021/02/SmartPIG-FN.pdf

- **Maximum Allowable Operating Pressure (MAOP):** The maximum pressure at which a pipeline is allowed to operate based on its design and the materials used is called the MAOP. Techniques such as finite element analysis are used to evaluate the pipeline's structural integrity under different operating conditions and pressure scenarios to determine the maximum safe operating pressure. Doing so ensures the line is not subject to undue operating pressures.

- **Remote Monitoring and Automation:** The incorporation of remote sensors and automated control systems provides the capability to continuously monitor pipeline conditions in real time. Sensors are placed strategically along a CO_2 pipeline to remotely track essential data such as temperature, pressure, and vibration. This proactive approach ensures that operators receive alerts when deviations occur, helping identify and address potential integrity issues swiftly.

- **Research and Innovation:** The industry, in partnership with academia, furthers research and development in advanced materials, inspection technologies, and integrity management strategies to allow the industry to proactively address evolving challenges. This can include developing corrosion resistant coatings, composite materials for pipelines, and corrosion resistant alloys.

In addressing pipeline integrity, the industry leverages these multifaceted responses, employing both established methods and cutting-edge innovations to safeguard operations, protect the environment, and prioritize public safety.

4.2.4 Managing Challenges and Risks – Pipeline Construction & Operations – Geological Challenges:

CO_2 pipelines often traverse diverse terrains, including landslide-prone regions and those with potential sinkholes and geological faults, which all can lead to pipeline damage or failure if not accounted for during route planning and construction. Proper terrain assessment, engineering expertise, and robust construction techniques can minimize the potential impact on pipeline integrity. The geological risks include:

- **Landslides:** Landslides can damage or bury pipelines, disturb their alignment, and expose them to external forces.

- **Subsidence:** A geological phenomenon where the ground sinks or settles, subsidence can cause pipelines to bend, deform, or rupture.

- **Fault Movements:** Movement along faults can cause shifts in the ground, leading to pipeline stress, strain, or displacement.

- **Erosion:** Erosion can expose pipelines and weaken supporting soil.

- **Seismic Events:** Fault movement can provoke earthquakes causing landslides and ground liquefaction and resulting in pipeline damage.

- **Groundwater Fluctuations:** Changes in groundwater levels can lead to soil instability, erosion, and pipeline exposure.

- **Compaction and Settlement:** Compaction and settlement are two related but distinct geotechnical processes that can have significant implications for pipelines and other infrastructure.

    - Compaction refers to the process by which soil or other granular materials become more tightly packed due to the application of loads or pressure. It often occurs during the installation of pipelines or the construction of buildings and roads.

    - Settlement is the downward movement of the ground surface, or an object (such as a pipeline) supported by soil or other materials. It can occur due to natural processes, consolidation of soil layers, and changes in moisture content. Settlement can be differential, meaning that different parts of the pipeline settle at different rates or amounts. Differential settlement can lead to uneven stress distribution and alignment shifts in the pipeline.

- **Karst Terrain Features:** Karst terrain is a unique type of landscape characterized by the dissolution of soluble rocks, such as limestone, dolomite, and gypsum, by water over time. This dissolution process leads to the formation of various karst features, including sinkholes, caves, and underground rivers. Any of the above formations can impact the structure of pipelines.

- **Volcanic Activity:** Volcanic events can result in ground movement, ash deposition, and terrain alterations, all of which can damage pipelines.

- **Human Activities:** Excavation, construction, and other human activities can also trigger ground movement and damage pipelines.

These geological challenges can threaten CO_2 pipelines and their safe operation. Industry and PHMSA have formulated a set of procedures and regulatory requirements to be followed by operators to prevent geohazards. These are:

- Geohazard Assessments

- Geological Engineering Studies

- Geotechnical Monitoring

- Mitigation Measures

- Emergency Response Planning

The tools, technologies, practices, and programs used to address these matters typically include:

- **Geological Surveys and Site Investigations:** Operators perform comprehensive geological surveys and site investigations to evaluate soil properties, geological characteristics, and potential risks along the pipeline route. Prior to the construction of a CO_2 pipeline, a geological team conducts in-depth analyses of soil samples, assesses the stability of the terrain, and identifies regions susceptible to landslides or subsidence.

- **Engineering Design and Alignment Optimization:** Pipeline engineers design and refine the pipeline alignment to avoid fault zones or erosion-prone regions, when possible, significantly lowering the probability of geological challenges.

- **Ground Improvement Techniques:** During pipeline construction, ground improvement methods can bolster soil stability. These include soil reinforcement, grouting, and compaction. For instance, a soil compaction procedure is applied to increase the load-bearing capacity of soil in regions susceptible to settling.

- **Slope Stabilization Measures:** To prevent landslides and erosion along steep sections of the pipeline route, engineers install retaining walls, slope mesh, or erosion control blankets to stabilize slopes and protect the pipeline from movement.

- **Monitoring and Early Warning Systems:** Sensors are placed along the pipeline route to continuously monitor ground displacement, subsidence, and other geological change in real time. The sensors trigger alerts if movement exceeds pre-defined thresholds.

- **Emergency Response Plans:** Emergency response plans are prepared to address geological risks, outlining actions that should be taken in the event of landslides, subsidence, or other ground-related incidents. The plans include procedures to shut down the pipeline, evacuate nearby communities, and create a safe perimeter to identify and contain any leaks.

These measures are essential for managing and mitigating geological risks, ensuring safe and reliable operation while minimizing potential impacts on the environment and surrounding communities.

4.3 Managing Challenges and Risks – Impacts & Mitigation

CO_2 pipelines are not immune to challenges in maintaining their integrity, and they are also subject to geological factors that can influence their safety and reliability. However, the consequences of an incident extend far beyond the pipes themselves, potentially impacting both local communities and the environment. Regulatory measures have been implemented to mitigate these adverse effects and ensure safe operations. In this section, we discuss observations regarding the impacts of CO_2 pipelines and the measures and regulations in place to address them.

4.3.1 Managing Challenges and Risks – Health & Safety Impacts and their Mitigation

Ensuring the health and safety of local communities is an overarching priority for any project. Safety concerns revolve around the potential for leaks, ruptures, or accidents, which can release carbon dioxide into the surrounding environment.

Primary concerns for health and well-being include:

- **Noise:** Pipelines, which involve the use of heavy machinery, drilling, and excavation during construction and the use of large compressors and pumping stations in the operational phase, can result in elevated noise levels in the surrounding areas.

- **Air Quality:** Construction activities and movement of heavy machinery can generate dust. Wind can carry this dust over a distance, impacting air quality in the surrounding area.

- **Oxygen Deprivation:** A CO_2 leak can displace oxygen in the surrounding air, leading to oxygen deficiency in the environment. Since CO_2 is colorless and odorless, it is difficult to detect a leak until oxygen levels have become dangerously low.

- **Traffic Congestion:** Construction can involve transporting heavy machinery, materials, and equipment to the construction site. This can increase traffic congestion on local roads and highways, which hampers day-to-day activities.

- **Dry Ice Formation:** Leaking CO_2 can cool rapidly and freeze moisture in the air, leading to the formation of “dry ice” (solid CO_2). This can pose a physical hazard if it accumulates on surfaces or pathways or comes in contact with skin.

- **Emission of Impurities:** CO_2 pipelines may carry small amounts of impurities like hydrogen sulfide (H2S) along with carbon dioxide. H2S is a toxic and highly flammable gas that can be present in certain natural sources of CO_2, especially those originating from natural gas fields.

- **Releases Due to High Pressure:** Inadequate pressure management or malfunctioning safety systems can lead to high-pressure buildup within the pipeline. This can potentially cause a pipeline rupture.

To ensure the safety of nearby communities, industry and PHMSA have formulated a set of regulations and practices that operators are expected to follow, including:

- **Design Requirements:** CO_2 pipelines must adhere to specific safety-oriented design criteria, including the use of appropriate materials, approved welding procedures, and sound engineering practices. These regulations ensure the pipeline's structural integrity meets rigorous standards and enhances safety during operation.

- **Operations and Maintenance:** Operators are responsible for maintaining and operating CO_2 pipelines to minimize potential risks. They are required to have defined procedures for routine operations and protocols to manage abnormal operating conditions to help prevent incidents.

- **Public Awareness and Damage Prevention:** Operators must educate the public and stakeholders about CO_2 pipeline presence, location, and safety measures.

- **Monitoring and Leak Detection:** Operators must implement monitoring systems to detect leaks, abnormal pressure fluctuations, and other irregularities in CO_2 pipeline operation.

- **Record Keeping:** Operators must maintain meticulous compliance records, documenting adherence to all safety regulations.

- **Pipeline Operator Qualifications:** Operators must ensure that all individuals involved in critical tasks related to CO_2 pipeline operation, maintenance, and emergency response possess appropriate qualifications and expertise.

- **Emergency Response:** Operators are required to identify vulnerable areas and formulate emergency response plans to address accidents, spills, and other incidents impacting public safety and the environment.

The tools, technologies, practices, and programs used to address these issues typically include:

- **Adhering to Standards:** Procuring and installing the equipment according to both industry standards and PHMSA regulations, including high-quality carbon steel pipelines, which are resilient and have a longer life.

- **Advanced Leak Detection Systems:** Using advanced technologies like acoustic sensors, infrared imaging, and fiber optics to promptly detect leaks.

- **Continuous Monitoring:** Implementing 24/7 monitoring of CO_2 pipeline conditions, pressures, and potential leaks using automated systems. Installing remote sensors along pipeline routes to transmit real-time data to a central control center, enabling swift response to anomalies.

- **Impurity Control:** Monitoring and controlling the concentration of impurities in the CO_2 stream, which can include hydrogen sulfide, sulfur oxide, and nitrogen oxide. Ensuring their concentration is limited to avoid damage to the pipeline and impacts to the local vicinity in case of a leakage.

- **Public Awareness Campaigns:** Launching educational campaigns to inform the public, local communities, and other stakeholders about the presence of a CO_2 pipeline and related safety measures. The national 811 program, also known as the "Call Before You Dig" program, is an industry initiative aimed at preventing damage to underground utility lines including oil, gas, and CO_2 pipelines during excavation or construction projects.

- **Emergency Shut-Off Systems:** Integrating emergency shut-off valves with leak detection systems to enable automatic shutdown in case of a detected leak.

- **Worker Training and Qualification:** Ensuring personnel engaged in operations, maintenance, and emergency response are well-qualified. Providing specialized training to workers on responding to CO_2 leaks, emphasizing safety protocols and the use of protective equipment.

- **Collaboration with First Responders:** Establishing partnerships with local emergency response agencies to ensure coordinated actions during pipeline emergencies. Conducting joint training exercises with firefighters and emergency medical services to enhance their ability to respond effectively to CO_2 incidents.

Our research has identified essential practices that need to be consistently implemented by industry to mitigate community impact. These practices address both pipeline construction and pipeline operation.

<u>Construction Phase:</u>

- **Noise Control:** Implementing noise mitigation measures, such as erecting sound barriers or using quieter construction equipment. For instance, contractors can schedule heavy construction activities during daytime hours to minimize disruptions at night.

- **Air Quality Control:** Applying dust control measures, such as regular watering of construction sites, using dust suppressants, and minimizing soil disturbance. Construction engineers can use windbreaks and screens to prevent dust from spreading to nearby areas. They should also maintain construction access roads to minimize dust from moving vehicles.

- **Traffic Congestion Control:** Developing comprehensive traffic management plans to minimize disruptions and congestion during construction, e.g., schedule transportation of heavy machinery and materials during off-peak hours to reduce impact on local roads. Project managers should coordinate with local authorities to ensure road closures or detours are communicated to residents in advance.

Operational Phase:

- **Avoiding Oxygen Deprivation:** Continuous monitoring of CO_2 concentrations should be implemented in and around pipeline facilities using advanced sensors. This includes installing early warning systems that trigger alarms when CO_2 concentrations exceed safe levels, allowing prompt responses and evacuations if necessary.

- **Addressing CO_2 Leaks and Dry Ice Formation:** Engineers should incorporate preventive measures into pipeline systems and facilities to reduce the risk of leaks. It is essential to establish leak detection and repair processes to promptly identify and rectify CO_2 emissions, thereby preventing the formation of dry ice. Additionally, protocols should be developed for the safe removal of dry ice accumulations, with a primary focus on ensuring the well-being of both workers and residents.

- **Avoiding High-Pressure Releases:** Effective pressure monitoring and control systems should be installed to forestall pressure escalation inside the pipeline. One strategy involves installing pressure relief valves and automatic safety mechanisms that engage when pressure levels approach unsafe operating limits, effectively averting pipeline ruptures.

Using these strategies, contractors, operators, and stakeholders can minimize risks and protect communities by maintaining pipeline integrity.

4.3.2 Managing Challenges and Risks – Environmental Impacts and their Mitigation

Transportation and storage of CO_2 have far-reaching impacts on the environment in which the pipelines and storage facilities are situated. Pipelines traverse diverse landscapes, often crossing environmentally sensitive areas, making it imperative to safeguard the natural world, from protecting vital water bodies to preventing pollution of underground aquifers and preserving the richness of ecosystems.

The primary concerns about pipelines' environmental impact are:

- **Habitat Disturbance:** Pipeline construction may require clearing vegetation and altering the natural landscape. This can disrupt local ecosystems, disturb wildlife habitats, and lead to loss of biodiversity.

- **Soil and Water Contamination:** Excavations are required to lay the pipeline underground. This can cause soil erosion, sediment runoff, and potential contamination of nearby water sources.

- **Acidification:** Acidification refers to lowering the pH of a substance. In the context of CO_2 pipelines, it is related to the formation of carbonic acid when CO_2 dissolves in water. Acidification of water bodies can harm fish and shellfish by affecting their growth, reproduction, and overall health. It can also disrupt food chains and aquatic ecosystems.

- **Geological Containment Integrity:** In geological storage sites, such as depleted oil and gas reservoirs or saline aquifers, the integrity of the containment structure is crucial. There is a risk of CO_2 leakage if the geological formations have faults or fractures that allow the gas to migrate.

- **Induced Seismicity:** The injection of CO_2 into geological formations can induce seismic activity if pressure changes within the formation lead to the movement of existing faults. Induced seismicity may damage structures, disrupt communities, and pose safety risks.

- **Land Subsidence:** Land subsidence can also occur if the injection of CO_2 leads to pressure changes within the geological formation. When CO_2 is injected, it can displace fluids that were originally present in the reservoir, such as water or oil. Infrastructure near the storage facility can be damaged or compromised as the ground sinks. This can lead to structural instability and increased maintenance costs.

Once again, in view of these impacts, PHMSA and industry have developed both practices and regulations to ensure safety of the environment and water bodies. These include:

- **Environmental Impact Assessments:** These are comprehensive studies to evaluate the potential environmental effects of a project. This includes assessing the impact on ecosystems, air and water quality, soil, and other environmental factors. PHMSA regulations incorporate NEPA requirements, ensuring environmental impacts are considered and disclosed before CO_2 pipeline projects are approved and permitted.

- **Spill Response Plans:** Spill response plans outline procedures for addressing leaks, spills, or other releases of hazardous materials, including CO_2. Regulations mandate spill response plans to ensure operators are prepared to respond swiftly and effectively to leaks and minimize the environmental impact.

- **Ecological Sensitivity Analysis:** Ecological sensitivity analysis involves assessing the vulnerability and importance of ecosystems and habitats along the pipeline route. Current regulations mandate that operators conduct ecological sensitivity analyses to identify and protect ecologically sensitive areas.

- **Monitoring and Reporting:** This involves regular observation and measurement of pipeline operations, integrity, and potential environmental impacts. Reporting entails providing relevant data to regulatory authorities.

- **Mitigation Measures:** These measures are implemented to reduce or offset the negative environmental impacts of a project. PHMSA requires CO_2 pipeline operators to develop and implement mitigation plans to minimize the potential harm to ecosystems, air quality, and water bodies.

The tools, technologies, practices, and programs typically used to address these issues include:

- **Leak Detection and Repair (LDAR) Programs:** LDAR programs establish systematic monitoring and identification of leaks using technologies such as infrared cameras and gas sensors. This allows leaks to be promptly addressed.

- **Environmental Monitoring Systems:** Continuous tracking tools can monitor environmental parameters near the pipeline route, such as air quality, water quality, and soil conditions. For instance, sensors are installed along the CO_2 pipeline to monitor air quality for changes in CO_2 concentrations. If levels rise unexpectedly, alarms are triggered to alert operators to a potential leak.

- **Erosion and Sediment Control Measures:** Pipeline engineers implement strategies to prevent soil erosion and sedimentation during pipeline construction, reducing impacts on nearby water bodies. This can include implementing silt fences and erosion control blankets to prevent soil erosion and sediment runoff into nearby streams and rivers during construction.

- **Habitat Restoration and Compensation:** Operators plan activities to restore or enhance ecosystems that may have been disrupted by pipeline construction or operation. After construction, an operator undertakes habitat restoration by replanting native vegetation and restoring wetlands in affected areas.

Our research has identified crucial procedures that must be uniformly adopted within the industry to reduce the impact on the community. These can be divided into two stages: design/construction and operation.

<u>Design/Construction Phase:</u>

- **Habitat Restoration:** Implementing habitat preservation and restoration plans, including replanting native vegetation in disturbed areas. Construction buffer zones will help protect critical habitats.

- **Excavation Measures:** Implementing proper erosion control measures, such as sediment barriers, to prevent soil erosion and sediment runoff into nearby water sources. Regular inspections can ensure excavation areas are properly managed and restored after construction.

- **Geological Containment Integrity:** Conducting thorough geological assessments before selecting storage sites to identify faults, fractures, and potential migration pathways that could compromise containment integrity. Geologists working with operators must select storage sites with natural seals (impermeable rock layers) to prevent upward migration of CO_2.

<u>Operation Phase:</u>

- **Seismic Monitoring:** Injection pressures and seismic activity must be monitored and controlled to minimize the risk of inducing seismic activity.

- **Land Subsidence:** The rate of CO_2 injection should be controlled to avoid excessive pressure changes that could cause significant land subsidence. They also need to develop strategies to manage the movement of fluids displaced by injected CO_2.

These procedures are designed to minimize and mitigate the environmental impact of transporting CO_2 via pipelines and its storage. While these examples provide a general overview, specific methods and technologies can vary based on factors such as location.

4.4 Managing Challenges and Risks – Stakeholder Management

Effective stakeholder engagement is a cornerstone of responsible and safe CO_2 pipeline construction and operation, exemplified by lessons learned from incidents like the one in Satartia, Mississippi, and the complexities surrounding the Midwest pipeline project. In both cases, the need for diligent engagement with stakeholders, including local communities and landowners, became glaringly apparent.

In the context of CO_2 pipelines, stakeholder engagement is not just a legal requirement but a strategic necessity. The key aspects of stakeholder management are:

- **Community Engagement:** Engaging with local communities is a fundamental component of stakeholder management for CO_2 pipelines. Transparent, two-way, and open communication channels are vital to address community concerns and gather valuable insights. Conversations must move seamlessly from the operator and their contractors to the community and vice versa. Allowing the community to speak for itself and have its issues heard and addressed ensures residents are well-informed, fostering trust and cooperation.

• **Informed Decision-Making:** Stakeholder engagement ensures those affected by or living near CO_2 pipeline projects have access to accurate information. It empowers them to understand the purpose, potential benefits, possible risks, risk mitigation strategies and environmental considerations of these pipelines.

• **Building Trust:** Transparent and inclusive engagement builds trust between project proponents and the community. When residents feel their voices are heard and their concerns are taken seriously, they are more likely to support the project's goals.

• **Fear and Misinformation:** It is critically important to proactively address concerns and provide information to eliminate misconceptions. Clear and consistent messaging helps alleviate anxieties and builds trust among stakeholders.

• **Land acquisition:** Land use, particularly in agricultural areas, is a significant stakeholder concern. CO_2 pipeline projects must carefully consider the impact on agricultural activities and landowners. Engaging with farmers and landowners to understand their needs and concerns is essential. Implementing measures to minimize disruptions to agriculture and compensating landowners fairly can help mitigate conflicts and ensure stakeholder support.

• **Local Expertise:** Communities possess valuable local knowledge about their environment, culture, and history. Involving them in decision-making allows project planners to tap into this expertise, leading to more informed and culturally sensitive decisions.

• **Tailoring Solutions:** Public engagement allows project planners to tailor solutions to meet local needs. Community input can shape the pipeline's route, safety measures, and environmental protections, ensuring a more harmonious coexistence.

• **Legal and Regulatory Requirements:** Many jurisdictions require evidence of public engagement as part of the permitting process for CO_2 pipelines. Demonstrating that public concerns are being addressed can facilitate regulatory approvals.

• **Social License to Operate:** Beyond the legal requirements, constructive public engagement helps project proponents obtain a social license to operate. This reflects the community's acceptance and approval of the project's presence and goals.

• **Long-Term Support:** Engaging the community fosters a sense of ownership and support for the project. An engaged community is more likely to stand behind the project during its operation and maintenance phases.

American Petroleum Institute (API) recently published a new recommended practice API RP 1185 developed by the pipeline industry. It aims to enhance the way pipeline operators and stakeholders, including the public, communicate and interact regarding pipeline operations and safety. Here are the key aspects of API RP 1185 Pipeline Public Engagement[23]:

• **Enhancing Public Engagement:** The RP is spearheaded by leaders in the pipeline industry and safety advocacy, including representatives of both industry and the nonprofit Pipeline Safety Trust. API 1185 seeks to transform the traditional one-way communication model into a more dynamic dialogue with the public, ensuring that messages are not just delivered but also received and understood by the audience.

• **Integration with Pipeline SMS Framework:** API 1185 is designed to be used together with the API 1173 Pipeline Safety Management System (SMS) framework. The aim is to go beyond the traditional focus on operational improvements and safety objectives in isolation, ensuring that the public is actively involved in discussions and decisions related to pipeline safety.

• **Engagement Elements:** The Engagement Elements framework outlines a comprehensive set of processes designed to be applied throughout the entire pipeline lifecycle, from early siting and design to abandonment or decommissioning.

The framework consists of six primary elements:

• Commit and Align

• Identify, Understand, and Confirm

• Plan and Prepare

• Share Information

• Ask, Listen, and Respond

• Monitor, Evaluate, and Adjust

These elements serve as a guide for pipeline operators to assess and refine their current stakeholder engagement practices or to create, implement, and evaluate a new engagement strategy.

5. Benefits of CO_2 Pipelines

The deployment of CO_2 pipelines offers a range of advantages that contribute to fostering sustainable development. These benefits span various dimensions:

- **Helping to Address Climate Change:** One of the foremost benefits of CO_2 pipelines is their role in mitigating climate change. By transporting captured CO_2 to a site for beneficial use or secure storage, these pipelines can help curb the rise in global temperatures. This cooling effect will help preserve ecosystems and reduce the risk of extreme weather events, contributing to a more sustainable planet. This approach aligns with international climate goals and demonstrates a commitment to combating climate change.

- **Promoting Sustainable Living:** CO_2 pipelines enable the adoption of cleaner energy strategies that can convert captured CO_2 into valuable low-carbon resources, including fuels, chemicals, and materials, ultimately reducing reliance on fossil fuels.

- **Technological Advancements:** Innovation fueling the development of technologies utilizing CCUS benefits various sectors and industries. Research is underway to use CO_2 in areas such as Coal Bed Methane (CBM) displacement, enhanced natural gas extraction, enhanced shale gas extraction, enhanced geothermal systems, and in-situ leach mining of uranium ore[24]. Pipelines to move the CO_2 from the capture site to the use site will be essential.

- **Economic Benefits:** CO_2 pipeline projects contribute to the local and national economies. Navigator had announced plans to employ 8,000 individuals as part of the Midwestern CO_2 pipeline project before withdrawing, while Summit projected the creation of 11,000 jobs[25] during the construction phase. These direct construction jobs also would have spawned additional induced jobs to support the work, generating tax revenues for local communities, funding essential public services and infrastructure development.

- **Upskilling and Reskilling Opportunities:** Given the range of technologies either directly or indirectly dependent on CO_2, pipelines are a key ingredient in the mix of jobs that the energy transition can provide. Reskilling and upskilling offer real community benefits in terms of both protecting existing employment and creating opportunities in new career categories. This could have a special impact in traditionally underserved and disadvantaged communities.

The Dakota Institute recently completed an economic analysis focusing on the impact of CO_2 pipelines within the state of South Dakota[26]. While the study's findings pertain specifically to South Dakota and are focused on the now-stalled Navigator and Summit pipelines, they offer insight into the potential advantages associated with investments in such infrastructure.

- The study assessed the economic ramifications of the Navigator and Summit pipelines, breaking down the analysis into two distinct phases: the construction phase (2024 to 2025), and the operational phase (2025 to 2034).

- It anticipated the pipelines would have a significant positive influence on South Dakota's economy, projecting a cumulative increase of $3.3 billion in the state's GDP over both phases.

- During the construction phase, it projected a $952 million boost to the state's GDP over two years, equivalent to nearly 0.70% of the state's annual GDP.

- The operational phase was expected to contribute an additional $2.35 billion to the state's GDP over 10 years, representing an annual increase of 0.35%. This increase can be attributed to factors including clean fuel and carbon capture and storage tax credits, a strengthened corn basis, and the economic activities associated with pipeline operations.

- It was estimated that the pipelines would generate 7,105 jobs, with 5,353 jobs created during the construction phase and 1,752 during the operational phase.

However, it is crucial to acknowledge that these potential economic benefits are now uncertain due to the cancellation of the Navigator project and the decision to postpone the Summit pipeline.

6. Lessons Learned, Best Practices and Areas for Improvement

6.1 Lessons Learned – Incident Reporting

PHMSA maintains a comprehensive database that catalogs incident details spanning the past two decades[27]. This is updated annually. Over the last 20 years, the database shows that CO_2 pipelines have recorded 105 incidents. **(Appendix IV)** This number is low when compared to other hazardous liquid categories. By far the most significant incident is the Satartia, Mississippi, rupture, which occurred in 2020.

Case of Satartia, Mississippi

On February 22, 2020, the 24-inch Delhi CO_2 pipeline managed by Denbury Gulf Coast Pipeline experienced a rupture near Satartia, Mississippi[28]. The rupture was a result of a landslide triggered by heavy rainfall, which placed excessive stress on a weld in the pipeline. Consequently, there was a release of CO_2, prompting a local evacuation and necessitating medical attention for 45 people who reported breathing difficulties.

PHMSA cited the following concerns involving Denbury's role in the incident:

- Operations and maintenance procedures did not account for soil instability as a potential threat, despite prior knowledge of such risks.
- The integrity management program did not address geological hazards or ways to prevent them.
- Aerial checks did not spot any issues in the pipeline location before the accident.
- The dispersion modelling of CO_2 underestimated the area potentially affected by a release.
- There was a delay in notifying local responders, causing confusion and delaying emergency response.

Following its investigation, PHMSA took the following actions:

- In 2022, it initiated a rulemaking process to enhance safety requirements for new or replacement sections of onshore hazardous liquid pipelines, including supercritical CO_2 pipelines.
- On May 26, 2022, it issued a Notice of Probable Violation, a Proposed Civil Penalty, and a Proposed Compliance Order, recommending a $3.9 million fine for Denbury[29] and emphasizing the importance of strict compliance with safety regulations. Following negotiations, PHMA reduced the financial penalty, stating that there was no violation of regulations, and Denbury paid $2.8 million.
- PHMSA has distributed an updated nationwide advisory to all pipeline operators, stressing the need for improved planning and risk reduction strategies. The advisory highlights risks associated with land movement and other geohazards, as demonstrated by the 2020 incident in Satartia.
- PHMSA is conducting research to identify and implement improved safety measures to prevent similar incidents in the future.
- In April 2023, PHMSA held a CO_2 Public Meeting to inform their rulemaking decisions, covering topics such as public awareness, emergency response, dispersion modeling, safety measures for other pipeline constituents, leak detection, and geohazards.
- PHMSA announced it would initiate a new rulemaking to improve the safety of CO_2 pipelines that includes emergency preparedness and response standards, although as of November 2023, specific regulations had not been proposed.

6.2 Best Practices

Over the years, operating companies, regulatory agencies, and industry groups have collaborated to identify best practices for CO_2 pipelines to ensure safe and environmentally responsible operation. Here are some essential best practices:

- **Regulatory Compliance:** Operators must develop a robust compliance management system to ensure adherence to regulations and standards set by PHMSA and other regulatory authorities.
- **Leak Detection and Monitoring:** Advanced leak detection and monitoring systems should be implemented to ensure CO_2 leaks or anomalies are identified and addressed. Real-time monitoring reduces response time and minimizes environmental impact in the event of a leak.
- **Stakeholder Engagement:** Effective stakeholder engagement is a cornerstone of best practices for pipeline owners, whether they are building a proprietary line or a common carrier. Affected landowners, communities, and stakeholders should be consulted and engaged throughout the project life cycle. Operators should address concerns, provide information, and involve stakeholders in decision-making.
- **Collaboration with Local Authorities:** Collaborating with local government agencies and emergency services to conduct drills and simulations related to pipeline incidents can enhance

preparedness, demonstrating measures in place to manage and mitigate potential risks. For example, ExxonMobil's partnership with Texas A&M University's Engineering Extension Service[30] equips first responders with the knowledge and skills to effectively manage emergencies.

• **Resource Mobilization:** First responders must have sufficient resources, such as emergency response equipment, medical supplies, and communication tools, near pipeline routes in rural areas to facilitate rapid response to incidents.

• **Quality Assurance and Training:** Operators and their contractors should establish and maintain rigorous quality assurance programs for construction and operation. All personnel should receive adequate training and certifications to perform their roles effectively.

• **Technology Adoption:** Operators and regulators should pursue and embrace advances in pipeline technology, such as corrosion-resistant coatings, monitoring sensors, and automated inspection tools, to enhance safety and efficiency. The technologies used should be sufficient to adequately monitor for leaks and other safety-related issues and should be updated on a timely basis.

• **Effective Communication:** Project developers and permitting agencies should ensure communications take place in the languages spoken in the affected community. As an example, the Houston Independent School District reports about 100 languages are spoken in its schools. While not all languages can be accommodated, the major languages in each community should be used.

• **Benefits for All Sides:** Throughout both the community engagement and permitting processes, project developers should strive to ensure communities impacted by the project will also benefit from it. Benefits should focus on community needs rather than on what is easy or common.

• **Continuous Improvement:** Operators should regularly assess the effectiveness of implemented practices and learn from incidents and near-misses. A culture of continuous improvement to enhance safety and environmental performance should be established. The INGAA Foundation "Near-miss Repository" is a good example of this.

6.3 Areas for Improvement – Research and Innovation

Investing in research and innovation is vital to the rapid expansion of pipeline networks, particularly for CO_2 transportation. This is not merely about regulatory compliance, but is a fundamental aspect of responsible infrastructure management. PHMSA is currently funding $2.6 million in projects related to leak detection, with an additional $2 million in industry cost-sharing[31] expanding the impact. One such project is underway at Texas A & M University:

• *Determination of Potential Impact Radius of CO_2 Pipelines Using Machine Learning Approach:* The objective is to establish a computational fluid dynamics model to simulate the release and dispersion of supercritical CO_2 from pipeline ruptures[32]. It utilizes simulation results to design a database consisting of CO_2 dispersion data under different conditions and then applies machine learning analysis to predict dispersion ranges and health consequences. This work could lead to better dispersion models and improved community safety.

Appendix V lists all current projects funded by PHMSA.

Another recent study evaluated the impact of pipelines on various aspects of the environment and society, Modeling Ecological Constraints on a CO_2 Pipeline Network[33].

• The study focused on the integration of ecological considerations into the planning and optimization of CO_2 pipeline networks utilizing the CCUS infrastructure model, SimCCS. SimCCS is a pivotal economic-engineering software tool, designed to facilitate comprehensive decisions regarding CCUS infrastructure development. Its application spans government, academia, industry, and research entities, providing insights into both the potential and preferred pathways for establishing CCS infrastructure, including CO_2 pipelines.

• They leveraged this model to estimate the trade-offs between private costs and environmental and social impacts in the context of CO_2 pipeline routing and sink locations.

• The study focused on the Southeastern United States, modeling seven scenarios with varying averages given to environmental impacts. It found the optimal path for CO_2 pipeline networks is sensitive to environmental and social impact considerations.

• A small increase in pipeline length and cost can significantly avoid large environmental and social impacts. The study developed custom spatial layers to identify environmental and social impacts. These layers included core habitat for at-risk species, areas of historical and cultural value, and other issues.

6.3.1 Areas for Improvement - Regulatory Barriers and Reforms

Our research has uncovered many challenges that hamper CO_2 pipeline development, ranging from operational inefficiencies and socioeconomic environmental concerns to regulatory complexities. We previously discussed operational and environmental challenges, but the regulatory framework remains a major challenge. We address this through a series of thoughtfully crafted recommendations, designed not only to overcome the identified barriers but also to propel the initiative towards sustainable success.

Barriers

- **Jurisdictional Uncertainty:** There is often a lack of clear jurisdiction over CO_2 pipelines at both federal and state levels. This arises because CO_2 differs from other substances typically transported by pipelines, leading to gaps and legal uncertainties. As a result, the scope and boundaries of state regulatory authority over CO_2 pipelines are often not well-defined, creating a patchwork of regulations that can either encourage or discourage development.

- **Distinct Approach:** The distinct approach taken by each state toward regulation impacts a pipeline's ability to access eminent domain authority and cross public lands. This inconsistency is notable because CO_2 pipelines are not usually economically regulated at the federal level and are not generally required to act as common carriers, thereby affecting their access to land rights and public land crossings under the federal Mineral Leasing Act.

- **Fragmented Regulatory Processes:** Regulatory approvals, permitting processes, land acquisition/access, and environmental responsibilities are fragmented and vary significantly across states and projects. This fragmentation leads to a broad range of permitting requirements that can slow the development of CO_2 pipelines without meaningfully improving their overall impacts.

- **Lack of Comprehensive Safety Standards:** There is an absence of comprehensive federal safety standards for CO_2 pipelines. This, coupled with the pipeline rupture at Satartia, Mississippi, has resulted in public backlash and delays in new CO_2 pipeline construction. The rupture highlighted the need for updated safety standards and more effective emergency management practices.

Recommendations

- **Regulatory Clarity:** Both federal and state governments should establish comprehensive regulatory schemes for CO_2 pipelines, addressed with explicit statutory language and regulations.

- **Decoupling Economic Regulation from Land Acquisition/Access:** The federal and state governments should separate right-of-way for CO_2 pipelines from their economic regulation, addressing issues raised by the "common carrier" classification.

- **Centralization of Permitting Processes:** Right-of-way acquisition, eminent domain processes, and environmental permitting should be formalized and centralized. This could be done by creating dedicated state-level siting processes. A centralized review of proposed pipelines to issue comprehensive permits is recommended.

- **Safety Standards and Emergency Management:** Federal lawmakers should expand PHMSA's safety standards to include all CO_2 pipelines. State lawmakers and regulators should also assess the need for supplemental emergency management practices and ensure state-level safety regulators have sufficient jurisdiction over intrastate CO_2 pipelines.

7. Conclusion

CO_2 pipelines play a pivotal role in the carbon capture, utilization, and storage landscape, facilitating the safe and efficient transport of captured carbon dioxide emissions. From an environmental perspective, these pipelines could contribute significantly to reducing greenhouse gas emissions, a critical step in mitigating climate change. By efficiently conveying CO_2 from capture sites to storage or utilization facilities, pipelines help prevent the release of CO_2 into the atmosphere, thereby lessening the carbon footprint of certain industries and power generation plants. This environmental benefit aligns with the global imperative to address climate concerns and transition to more sustainable energy practices.

However, the deployment of CO_2 pipelines is not without risk to local communities. The transportation of pressurized CO_2 requires stringent safety measures to prevent leaks or accidents that could adversely affect nearby populations and ecosystems. Sound business processes, regulatory oversight, and pursuit and use of advanced technology can help to ensure the integrity of pipeline systems, minimizing potential risks to communities and the environment. Additionally, the potential misuse of land for pipeline construction, particularly in agricultural areas, raises concerns about land displacement and disruptions to vital sectors like farming. Balancing the economic advantages of CCUS with land usage considerations necessitates careful planning and stakeholder engagement.

Economically, CO_2 pipelines stimulate innovation and drive technology development in the CCUS field. They create opportunities for job growth in construction, operation, and maintenance, as well as induced jobs in the service sector, contributing to local economies. Nevertheless, as with any infrastructure development, there are challenges, including negative public perception, land rights, and the imperative for community engagement. In this delicate equilibrium, fostering innovation while addressing societal concerns remains paramount for the successful integration of CO_2 pipelines within the broader context of sustainable energy and environmental stewardship.

Appendix I

8. 0 Preparation of CO_2 for Transport

CO_2 pipelines form an infrastructure network designed to transport carbon dioxide from its source to storage or utilization sites. The operation of these pipelines requires a delicate ballet of engineering, technology, and environmental considerations, encompassing everything from initial capture and compression to precise flow regulation, advanced monitoring, and safety protocols. Meticulous planning and advanced systems combine to move CO_2 efficiently, safely, and with minimal environmental impact. Here is a breakdown of the major operational aspects:

8.1 Identification of the Source

CO_2 sources are broadly classified in two categories:

8.1.1 Natural Sources

These are processes or natural occurrences that release CO_2 without human intervention. Examples include:

• **Volcanic Eruptions:** Volcanoes emit a combination of gases during eruptions, and CO_2 is one of the primary components. While these emissions are episodic, they can be significant, especially during major eruptions.

• **Respiration:** All aerobic organisms, ranging from tiny microbes to large mammals, including humans, consume oxygen and release CO_2 in the process.

• **Oceanic Emissions:** The oceans contain a vast reservoir of dissolved CO_2. As water temperature changes, the solubility of CO_2 in the water shifts, leading to either absorption or release of CO_2 into the atmosphere. In regions of upwelling, where deep, CO_2-rich waters rise to the surface, CO_2 can be released into the atmosphere.

• **Natural Gas Fields:** Some underground reservoirs of natural gas have a high concentration of CO_2, which may be released during extraction.

While natural sources release significant amounts of CO_2, they are often balanced by natural sinks. For instance, during photosynthesis, plants absorb CO_2 and release oxygen.

8.1.2 Anthropogenic Sources

There are human-induced activities that lead to the release of CO_2. The modern industrial era has seen a significant uptick in these emissions, which now dominate global CO_2 levels. Examples include:

• **Fossil Fuel Combustion:** This represents the most significant anthropogenic contributor to CO_2 emissions. From coal power plants and vehicles running on gasoline to industrial heaters, the combustion of fossil fuels emits vast amounts of CO_2.

• **Cement Production:** The process of producing cement includes limestone calcination, a step that releases CO_2. With the rise in urbanization and infrastructure expansion, emissions from cement manufacturing have increased.

• **Deforestation:** Trees and forests act as carbon sinks, storing CO_2. When they are cut down and burned or left to rot, the stored carbon dioxide is released back into the atmosphere.

• **Industrial Processes:** Beyond the combustion of fossil fuels, industrial operations also release CO_2. In steel production, for example, carbon aids in extracting iron from ore, resulting in CO_2 emissions.

Understanding the source of CO_2 is essential because the technologies and strategies for capture can vary significantly. For example, CO_2 from natural gas fields can be relatively concentrated and pure and requires less processing than that from coal combustion, which is relatively dilute and may contain various pollutants.

8.2 Pre-Capture Processes

Before capturing CO_2 can commence, several preparatory processes may be necessary, especially when dealing with industrial and fossil power plant emissions. These preliminary processes ensure the CO_2 is in an appropriate state to be effectively captured and any potential impurities or conditions that could impede the capture process are addressed. Here is an in-depth look:

8.2.1 Cooling of Flue Gases

Flue gases are the emissions released from the combustion of fuels. They are typically hot and may contain a mix of gases including nitrogen, oxygen, CO_2, water vapor, and pollutants such as nitrogen oxides and sulfur oxides. These gases can be at temperatures ranging from 300°C to 600°C or even higher after combustion and must be cooled to a temperature suitable for the capture technology before they can be processed for post-combustion carbon capture. This is often achieved by passing the gases through heat exchangers or cooling towers.

8.2.2 Particulate Removal

Particulates are tiny solid particles suspended in gases. They could be ash, soot, or other minute debris from combustion processes. The presence of particulates can hamper CO_2 capture, as they can clog equipment or react with capture agents, and need to be filtered out. Electrostatic precipitators and fabric filters (baghouses) are commonly used technologies. In an electrostatic precipitator, an electric charge attracts and removes particles from the flue gas. A baghouse forces flue gas through bags made of filtering fabric, capturing the particulates. In industries with significant solid fuel combustion, like cement production, particulate removal is vital to ensure the longevity of downstream equipment and the efficiency of CO_2 capture.

8.2.3 Desulfurization

Many fuels, particularly coal, contain sulfur compounds that, when burned, form sulfur oxides (SOx), which can interfere with some CO_2 capture processes and are also harmful air pollutants. Flue gas desulfurization (FGD) removes sulfur oxides from flue gases. One common method is the "wet scrubbing" process, where flue gas is passed through a slurry of limestone or lime. The sulfur oxides react with the calcium compounds in the slurry, forming gypsum as a byproduct, while the cleaned gas then exits the scrubber. The formed gypsum can then be processed and used in construction or other applications. Large coal-fired power plants often have FGD units to process flue gas for subsequent CO_2 capture.

8.2.4 NOx Removal

Nitrogen oxides (NOx) represent a group of gases formed during combustion in air, especially at high temperatures. Like SOx, they can interfere with some CO_2 capture processes and are pollutants. There are various methods to tackle NOx emissions. One common method is selective catalytic reduction (SCR). In SCR, a reagent (commonly ammonia or urea) is introduced into the flue gas stream in the presence of a catalyst. This mixture facilitates a chemical reaction in which nitrous oxide gases are converted mostly into nitrogen (N2) and water (H2O), both of which are environmentally benign. The choice of catalyst and specific operating conditions (like temperature) are crucial for the efficiency of the process. Modern combustion engines, like those in some vehicles or large generators, may use SCR to reduce NOx emissions and condition exhaust gases for subsequent processing.

Depending on the source and the specific capture technology chosen, some or all the above processes might be employed.

8.3 Capture Technologies

Carbon capture technologies comprise various methods to trap CO_2 emissions at their source, preventing their release into the atmosphere. These approaches offer unique solutions to a shared challenge, from post-combustion techniques that capture CO_2 after burning fossil fuels to direct air capture methods that seize CO_2 straight from the ambient air. Here are the main capture technologies used for CO_2:

8.3.1 Post-Combustion Capture

This method involves capturing CO_2 after the fossil fuel has been burned and the combustion process is complete. The resulting flue gas, which contains CO_2, nitrogen, and water vapor, is passed through a solvent (often an amine-based solution) that binds to the CO_2. Amines are organic compounds derived from ammonia (NH3). Alkanol amines are frequently used in post-combustion CO_2 capture processes as they have an affinity for CO_2, allowing them to "capture" or bind to it. When flue gas is bubbled through a solution of amines, CO_2 reacts with the amines to form carbamate compounds, effectively removing CO_2 from the gas stream. This loaded amine solution is then heated to release and recover pure CO_2, regenerating the amines for reuse. In coal-fired power plants, flue gas cooling is essential before introducing the gas to an amine-based scrubbing solution since excessive heat could degrade the amines. Similarly, pollutants such as particulate matter, SOx and NOx in the flue gas must be removed prior to bubbling of CO_2 in the amines.

8.3.2 Pre-Combustion Capture

CO_2 is captured before the fossil fuel is combusted, often after it is converted into a synthesis gas (syngas). Fossil fuels are gasified to produce a mixture of hydrogen and carbon monoxide. The carbon monoxide is then “shifted” into CO_2 using steam, producing additional hydrogen in the process. The resultant CO_2 is captured using a solvent, similar to the post-combustion process, leaving behind hydrogen, which can be burned cleanly. Integrated gasification combined cycle (IGCC) power plants use this technique to produce electricity from cleanly burning hydrogen, capturing CO_2 before combustion.

8.3.3 Oxy-Fuel Combustion Capture

This process involves the combustion of fossil fuels in nearly pure oxygen instead of air. When fuels are combusted in pure oxygen, the resultant flue gas is mainly water vapor and CO_2. After the water vapor is condensed, nearly pure CO_2 is left, which can be easily captured and compressed for transportation or storage.

8.3.4 Chemical Looping Combustion

Chemical looping combustion is a system where metal oxides combust fossil fuels without direct contact between air and fuel. Metal oxides release oxygen to combust the fuel, producing a concentrated stream of CO_2. The reduced metal is then regenerated using air and cycled back to release oxygen for combustion. This cyclic process ensures a constant separation of nitrogen and CO_2.

8.3.5 Calcium Looping

Calcium looping is a high-temperature process that uses limestone (calcium carbonate) as a sorbent to bind with CO_2 and release it upon heating. In a reactor, calcium carbonate is decomposed to produce calcium oxide and CO_2. The calcium oxide then reacts with the CO_2 in the flue gas to form calcium carbonate again. This cyclic process continuously captures and releases CO_2.

8.3.6 Direct Air Capture (DAC)

Direct air capture refers to processes that capture CO_2 directly from the ambient air rather than from large emission sources such as power plants. DAC systems generally use large fans to circulate ambient air through a solid sorbent or a solution, which selectively bind with CO_2. Once the solid sorbent or solution is saturated with CO_2, it undergoes a regeneration process, usually involving heat or chemicals, to release the concentrated CO_2. This CO_2 can then be compressed, transported, and stored. A key distinction between DAC and other capture technologies is DAC's independence from specific emission sources. It can be deployed anywhere, underscoring its flexibility.

DAC offers a solution to diffuse CO_2 emission sources, like those from transportation, where point-of-source capture isn't always feasible. This technology is gaining traction, especially as interest in negative emission strategies grows. These aim not only to reduce emissions but also to actively extract CO_2 from the atmosphere. Each method offers unique advantages and challenges, and the choice often depends on specific operational needs and economic considerations.

8.4 Compression of Captured CO_2

Once carbon dioxide is captured, it must be prepared for transportation and storage. Compression is a crucial step. The captured CO_2 is pressurized into a dense phase, either a liquid or supercritical state. This condensed form reduces its volume, facilitates handling, and ensures it can be transported efficiently, whether via pipeline or other means. The compression process typically employs either centrifugal or reciprocating compressors to achieve the desired pressure and density. The methods and technologies used are chosen based on specific requirements like the source of CO_2, its initial state, and its intended use after compression.

8.4.1 Initial Compression

Freshly captured CO_2 is initially in a gaseous state and occupies a large volume. Initial compression is the first step in preparing it for transportation or storage. This typically involves using centrifugal compressors, machines specifically designed to compress gases using the principles of rotation. The primary components are as follows:

- **Impellers:** Resembling fans yet crafted for compressors, impellers feature curved blades mounted on a disk. As they spin, they impart energy to the CO_2, making it accelerate and move faster.

- **Diffusers:** Stationed around the compressor's impellers, diffusers are static channels. After the CO_2 gains speed from the impellers, it flows into the diffusers. The combined effect of the spinning impellers and the diffusers amplifies the pressure of the CO_2.

A power plant capturing CO_2 might use large centrifugal compressors to handle the high flow rates of CO_2 gas being processed.

8.4.2 Intercooling

As gas is compressed, its temperature typically increases. High temperatures can reduce the efficiency of subsequent compression stages and damage equipment. Between compression stages, the compressed CO_2 passes through heat exchangers (intercoolers). These remove the heat generated during compression, cooling the CO_2 before it enters the next stage. A CO_2 compression setup might use water or air-cooled intercoolers between compression stages, much like the radiator in a car cools the engine.

8.4.3 Final Compression and Supercritical State

The end goal of the compression process is often to get CO_2 into its supercritical state, facilitating transportation and storage. In enhanced oil recovery (EOR), supercritical CO_2, due to its unique properties (higher density than gas and lower viscosity than liquid), is injected into oil reservoirs to help extract more oil.

8.5 Pre-Transport Conditioning of CO_2

Before CO_2 can be transported, especially through pipelines, it must undergo a series of conditioning steps to ensure it meets the required specifications. This conditioning minimizes potential hazards and prevents damage to infrastructure. Here is a detailed look at the key processes:

8.5.1 Dehydration

Dehydration is the process of removing water from the CO_2 stream. Water in CO_2 can react by forming carbonic acid, which is corrosive and can damage transportation infrastructure. The following methods are used for dehydration:

- **Glycol Dehydration:** When CO_2 comes into contact with a glycol solution (often tri-ethylene glycol), any water in the stream is absorbed. The dried CO_2 is then separated from the glycol, which is regenerated for reuse. This method is prevalent in the natural gas industry and is adopted for CO_2 due to its efficiency.

- **Molecular Sieves:** CO_2 is passed through solid adsorbents that trap water in their microscopic pores. These sieves are often used when very low water content is desired.

8.5.2 Purity and Removal of Contaminants

This involves removing impurities other than water from the CO_2 stream to achieve a specified purity level. Certain impurities can be hazardous during transportation or unsuitable for specific applications or storage conditions. Achieving a high purity ensures safe and efficient transport and storage. The following methods are used to remove contaminants:

- **Membrane Separation:** This method uses permeable membranes, which allow CO_2 to pass through but block or slow other contaminants. Depending on the membrane material and structure, different impurities can be separated. This is a common method for removing hydrocarbons or other gases from the CO_2 stream.

- **Adsorption:** This method employs solid substances designed to selectively latch onto certain contaminants within the CO_2 flow. When the adsorbent material reaches its capacity, it can be refreshed. Substances like activated carbon or zeolites are effective in extracting specific volatile organic compounds and other undesired elements.

- **Amine Scrubbing:** This is a liquid solvent method where contaminants are absorbed by amine solutions, such as Monoethanolamine (MEA) or Diethanolamine (DEA). The amine solution binds with specific impurities and separates them from the CO_2. This method is predominantly used for removing acid gases like hydrogen sulfide or carbon dioxide from natural gas, but it can be adapted for CO_2 purification in some circumstances.

By ensuring proper dehydration and purification, the CO_2 is prepared to meet strict transport standards, optimizing safety and efficiency throughout the transportation chain.

8.6 Materials Used for Pipeline Construction

Many factors must be considered during the design and construction of CO_2 pipelines. A few of the challenges include presence of impurities in the CO_2 stream, free water (H2O), and corrosion. Hence, it is crucial to grasp the factors that confer resilience upon these pipelines, allowing them to withstand the chemical properties of their contents amid changing weather and topographical conditions. Material selection is an important consideration. Some materials include:

- **Carbon Steel:** Pipeline construction often relies on carbon steel, with American Petroleum Institute grade 5L X65 being a common choice among X60, X65, and X80. This grade features low-carbon steel, containing less than 1.4% manganese by weight. The "X65" designation signifies a minimum yield strength of 448 MPa (65,000 psi) and a minimum ultimate tensile strength of 530 MPa (77,000 psi).

- **Corrosion Resistant Alloys (CRA):** These are materials specifically designed and engineered to resist degradation and deterioration when exposed to various corrosive environments. The most common CRAs are stainless steels that contain at least 10.5% chromium. Other CRAs may contain nickel, molybdenum, titanium, and/or other corrosion-resistant elements. These alloys are chosen to provide resistance to specific types of corrosion, such as general corrosion, pitting corrosion, crevice corrosion, or stress corrosion cracking. In the context of CO_2 pipelines, CRA materials are chosen to counteract the corrosive effects of carbon dioxide exposure, where CO_2 can react with free water present in the pipe to form carbonic acid, which is corrosive to metals.

- **Internal Linings & Coatings:** Epoxy linings are applied to the inside of pipelines. The lining serves as a protective layer, preventing direct contact between steel and CO_2, thereby mitigating corrosion risks. For coatings, fusion-bonded epoxy is used on the pipeline's exterior, which shields the pipeline from corrosion and external environmental factors. As discussed in section 8.5.1, CO_2 must not be introduced into the pipeline until it has been dehydrated. If not, the free water present in the fluid can degrade the pipeline.

8.7 Pumping Stations and Flow Regulation

Pumping stations and flow regulation are important to maintaining a consistent flow. (Figure 7) It is also important to avoid extreme pressure changes, which can impact the pipeline structure.

8.7.1 Pumping Stations

Pumping stations, also known as booster stations, are equipped with pumps that boost the pressure of the CO_2 flowing through a pipeline. These stations are strategically located along the pipeline to ensure continuous and efficient flow. Over long distances, the pressure and flow rate of CO_2 in a pipeline decreases due to frictional losses and other factors. Pumping stations restore the required pressure to keep the CO_2 moving at an optimal rate. Here are a few methods that are used:

• **Centrifugal Pumps:** These pumps use a rotating impeller to accelerate the CO_2. This acceleration results in an increase in pressure. The centrifugal force moves the CO_2 outward from the center of the impeller, and this kinetic energy is converted into potential energy in the form of increased pressure. Centrifugal pumps are often used in large-scale operations due to their ability to handle significant flow rates. For example, large CO_2 transportation networks for enhanced oil recovery (EOR) operations often employ centrifugal pumps.

• **Positive Displacement Pumps:** These pumps operate by capturing a fixed amount of CO_2 and then pushing (or displacing) that captured amount out into the discharge pipeline. Two types of these pumps are reciprocating and rotary pumps. They are ideal for tasks that need stable, accurate flow rates and for managing supercritical CO_2, which has properties similar to a liquid.

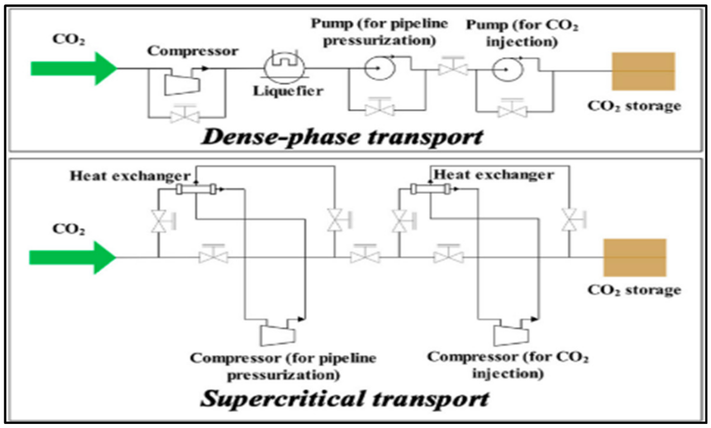

Figure 7. Sample flow depiction of CO_2 for dense and supercritical phase[7]

8.8 Monitoring, Measurement, and Control in CO_2 Transportation

Building upon the basic principles of pumping and flow regulation, CO_2 transportation also incorporates advanced monitoring, measurement, and control mechanisms. These intricate systems are designed to continuously supervise, measure, and adjust the flow of CO_2 throughout the transportation system. Their primary objectives are to maintain safety, enhance operational efficiency, and swiftly respond to any anomalies or variations within the pipeline.

8.8.1 Monitoring Devices

Ensuring the safety and efficient movement of the CO_2 hinges on the ability to keep a keen eye on its flow and condition. Specialized monitoring devices are designed to track, record, and relay real-time information as the CO_2 navigates the transportation system. Below is a summary of components used in monitoring:

• **Sensors:** Devices that detect and respond to external stimuli, converting physical changes into electronic signals. They constantly measure various parameters like pressure, temperature, flow rate, and even potential leak detection. In one of the most basic applications, pressure sensors along a CO_2 pipeline can provide real-time data to control centers, alerting operators if pressures exceed safe levels.

• **Remote Telemetry Units (RTUs):** Electronic devices connected to sensors and instruments that gather data and transmit it to a central system. RTUs enable remote monitoring and data collection from far-flung areas of a pipeline, e.g., an RTU at a distant pumping station can send data on local flow rates and pressures back to a central control room.

• **Supervisory Control and Data Acquisition (SCADA) Systems:** A computer-based system that gathers and analyzes data in real time. SCADA systems offer centralized monitoring and control over pipeline networks, providing real-time data visualization, trend analysis, and rapid response capabilities. For example, in the event of a sudden drop in pressure suggesting a potential leak, a SCADA system can instantly notify operators, pinpoint the location, and even initiate automatic valve closures to isolate the affected area.

8.8.2 Measurement

While monitoring offers a real-time window into the dynamics of CO_2 transportation, accurate measurement ensures the quantitative assessment of this flow, providing precision and clarity. Measurement tools and techniques quantify specific attributes of the CO_2 stream, such as volume, density, and pressure. This granular data aids in optimizing operations, ensuring safety, and adhering to regulatory standards. The tools employed for this purpose are:

• **Differential Pressure (DP) Flow Meters:** DP flow meters measure the flow rate of a fluid by analyzing the pressure difference across a flow restriction in a pipeline. They operate based on the principle that when CO_2 flows through a restriction or constriction in the pipeline (like an orifice plate, venturi, or flow nozzle, (Figure 8) a pressure drop occurs. By measuring this differential pressure across the restriction, the flow rate of the CO_2 can be determined.

• **Coriolis flow meters:** Also known as mass flow meters, these measure the mass flow rate of a fluid directly, making them especially useful for applications where mass, rather than volume, is the primary concern. When applied to CO_2 pipelines, these meters offer a highly accurate means to monitor and control the flow of carbon dioxide. Coriolis flow meters function on the Coriolis effect. When a fluid flows through a vibrating tube, the mass flow rate of the fluid causes a detectable shift in the vibration of the tube due to the Coriolis force. This shift can be measured and correlated to the mass flow rate of the fluid.

• **Ultrasonic flow meters:** These devices use sound waves

[7] Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. (2020). Carbon dioxide transport via pipelines: A systematic review. Journal of Cleaner Production, 266, 121994. Retrieved from https://doi.org/10.1016/j.jclepro.2020.121994

(ultrasound) to measure the velocity of a fluid flowing in a pipeline, and by extension, its volumetric flow rate. When utilized in CO_2 pipelines, they offer a non-intrusive method to monitor and control the flow of carbon dioxide. They operate by transmitting ultrasonic waves through the CO_2, with the difference in transit times of these waves used to calculate the fluid's velocity and thus its flow rate.

• **Thermal mass flow meters:** These devices measure the mass flow rate of a fluid based on its thermal properties. When applied to CO_2 pipelines, these meters provide a direct means to monitor and control the flow of carbon dioxide without the need for additional temperature or pressure compensation.

Figure 8. Sample Schematic of Differential Pressure Flow Meters[8]

They operate based on the principle of heat transfer. By introducing a known quantity of heat into the CO_2 flow and measuring the resultant temperature change, the mass flow rate can be determined directly.

8.8.3 Control Mechanisms

Beyond observing and measuring, the primary objective is to control the CO_2 transportation network. The control systems respond to data obtained from monitoring and measurement tools and proactively adjust and maintain the desired parameters within the transportation network. The equipment involved in this process includes:

• **Control Valves:** Control valves are essential components in many industrial processes, including CO_2 pipelines. They regulate the flow of CO_2 by varying the size of the flow passage as directed by a signal from a controller. They can be operated manually, although they are typically automated in modern CO_2 pipelines, using electric, pneumatic, or hydraulic actuators, where these actuators adjust the valve position based on signals from a control system.

• **Pressure Relief Valves (or Safety Relief Valves):** These are safety devices designed to open and relieve excess pressure from pipelines. If the pressure exceeds a predetermined level, the valve will open and release some of the CO_2 to bring the pressure back down to a safe level.

• **Shutdown Valves (SDV):** These are automated valves that quickly shut off the flow of CO_2 in emergency situations. They're typically fail-safe, meaning they'll go to their safe state in the event of a power or signal loss.

• **Block Valves:** The primary function of these valves is to stop or regulate the flow of CO_2, allowing for sections of the pipeline to be isolated for maintenance, emergency shutdown, or flow control. They can be operated manually or automatically.

To maintain the pipelines' durability, it is standard procedure to periodically adjust or replace these devices. It is worth highlighting that the devices and components employed in a CO_2 pipeline may differ depending on the precise operational needs and the pipeline's design.

[8] Emerson. (2020). The engineer's guide to DP flow measurement: Chapter 1 - DP flow meter [2020 edition]. Retrieved from https://www.emerson.com/documents/automation/gated-en-6291778.pdf

Appendix II

9. Storage

Much of the CO_2 that is captured and transported is destined for storage – usually geological storage – as a means to prevent its release into the atmosphere.

Geological storage is an inherent natural process prevalent for millions of years within the Earth's upper crust. CO_2, generated through biological processes, volcanic phenomena, and chemical interactions within rocks and fluids, naturally accumulates in subsurface environments, where it can be found in diverse forms, such as carbonate minerals, dissolved within solutions, gas mixtures, and in its phases, including the supercritical state. There are distinctions between natural carbon storage and engineered techniques, yet the deliberate injection of CO_2 into carefully selected deep geological formations has proven a highly effective strategy for long-term CO_2 sequestration.

The practice of injecting CO_2 into underground geological formations for EOR began in Texas during the early 1970s. A recent report by the U.S Department of Energy stated that North America possesses 2,400-21,000 billion tons of CO_2 storage resources[34], and at present, there are around 80 CO_2-EOR projects in operation[35], collectively injecting up to 35 million metric tons of CO_2 per year. Most of this CO_2 comes from naturally occurring accumulations, with 3 million to 5 million metric tons from anthropogenic sources, such as gas processing and fertilizer plants. Notably, the SACROC project in Texas was the world's first large-scale commercial CO_2-EOR project, utilizing anthropogenic CO_2 since 1972[36].

Geological storage involves the initial compression of CO_2 to its supercritical state, marked by elevated pressure and temperature. The density of CO_2 increases at depths greater than approximately 800 meters, and the injected CO_2 assumes a dense supercritical form. The injection of CO_2 into deep geological formations or saline aquifers involves technologies originally developed and used by the oil and gas industry. These technologies encompass well-drilling techniques, injection methodologies, computer simulations for assessing the dynamics of storage reservoirs, and monitoring methods. There is significant potential for these established technologies to be repurposed and customized to fulfill the requirements of geological storage.

Storage can be accommodated in diverse geological settings within sedimentary basins. The suitability of these sedimentary basins hinges, in part, on their geographical positioning within the continental plate. Sedimentary basins that have developed in mid-continent areas or near the periphery of stable continental plates are particularly well-suited for long-term CO_2 storage due to their inherent stability and structural characteristics. Major locations in the United States favorable to CO_2 storage encompass the Appalachian Basin, Gulf of Mexico Basin, Northern Colville Foreland Basin, and West Atlantic Basin[37]. (Figure 9) Within these basins, oil fields, depleted gas fields, deep coal seams, and saline formations are possible storage formations[38]. **(Figure 10)**

- **Deep Saline Aquifers**: These are porous rock formations deep underground filled with brine (a salt solution in water). They are the most common and widespread onshore storage option, offering vast potential capacity. CO_2 is injected into these formations, where it is stored beneath an impermeable cap rock. Deep saline formations are believed to have by far the largest capacity for CO_2 storage.

- **Un-mineable Coal Seams:** Instead of storing CO_2 in the pore spaces of rocks, as with oil/gas reservoirs, CO_2 can be absorbed onto the surface of coal. Though this method is not fully developed, the storage of CO_2 in coal beds, in conjunction with enhanced coal bed methane (ECBM) production, is potentially attractive because of the prospect of enhanced production of methane.

- **Basalt Formations:** These formations are rich in minerals that react with CO_2 to form solid carbonate minerals, turning CO_2 into stone. This mineralization process ensures a permanent and safe storage solution.

- **Geological Storage for Industry:** Various industries that produce concentrated CO_2 emissions, such as cement manufacturing and hydrogen production, can potentially store their emissions underground using geological formations.

- **Depleted Oil and Gas Reservoirs:** Since they have held oil or gas for millions of years, depleted reservoirs are considered reliable for storing CO_2. This process is promising in some areas, as these structures are well known, and significant infrastructure is already in place. Additionally, CO_2 can be used for enhanced oil recovery, where the gas is injected into the reservoir to help extract more oil, with the CO_2 then remaining stored in the depleted reservoir. This is generally classified as "Carbon Capture and Use," as there is a commercial value in the additional oil that is recovered. (Appendix III)

- **Above-ground Storage:** Above-ground storage refers to the containment of CO_2 in facilities located at the Earth's surface, as opposed to deep underground. These are primarily temporary, serving as a transitional holding for CO_2 before it is further transported or utilized. This type of storage is commonly found at industrial sites where CO_2 is used in manufacturing processes, food and beverage production, or greenhouse operations.

Geologic carbon dioxide sequestration and enhanced oil recovery both involve the injection of CO_2 into the Earth's subsurface. These procedures are subject to regulatory oversight under the Safe Drinking Water Act (SDWA), designed to protect underground sources of drinking water. In conjunction with regulatory scrutiny, the Department of Energy assumes a crucial role in advancing the domain of subterranean carbon storage.

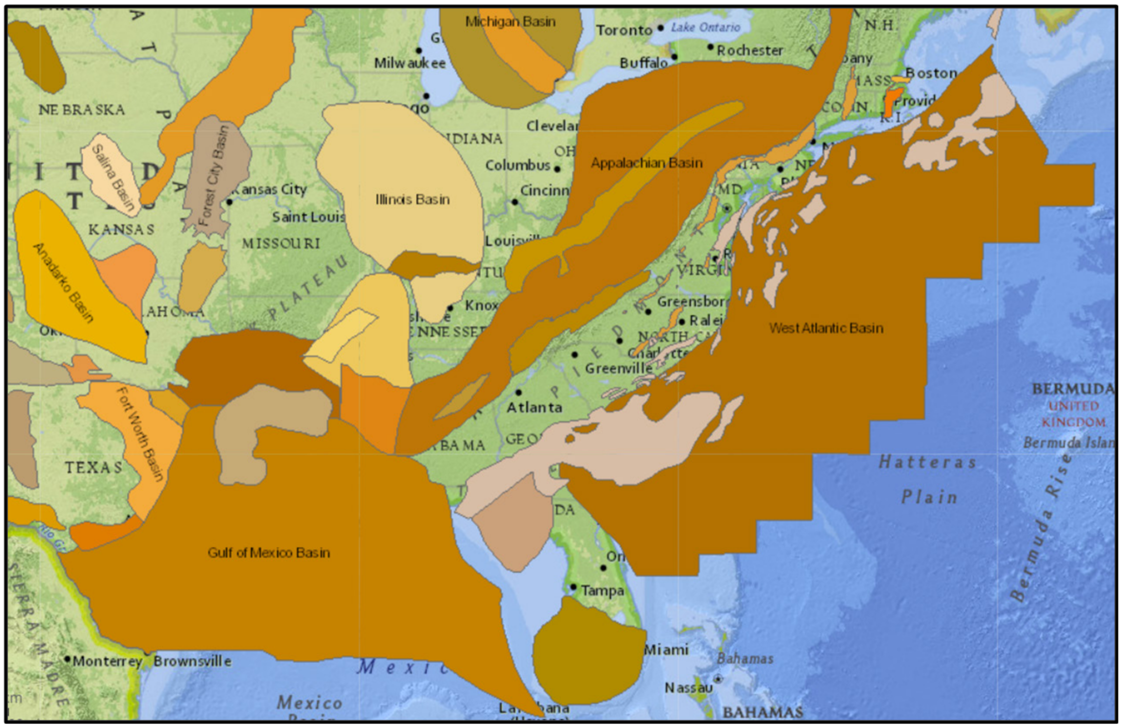

Figure 9. A few of the largest sedimentary basins in the US for storage of CO_2[9]

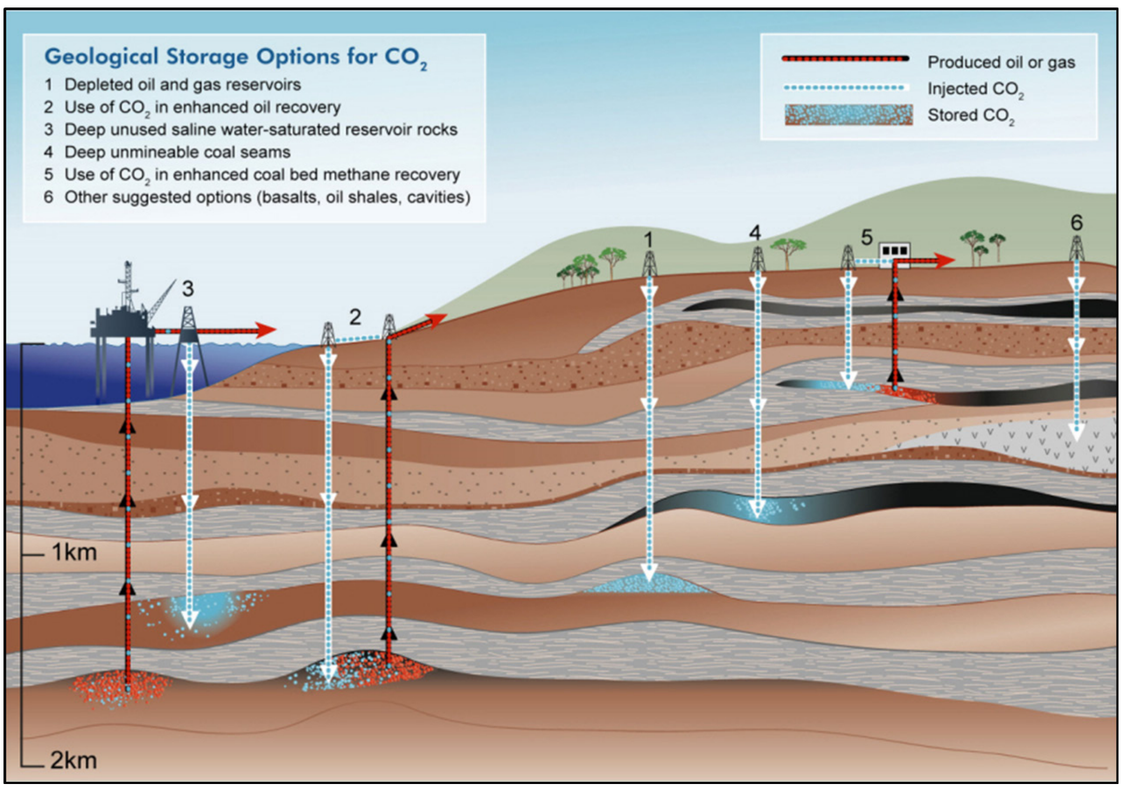

Figure 10. Options for Geological Storage of CO_2[10]

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To successfully store CO_2, underground, several key issues must be managed:

- **Federal and State Roles:** The task of supervising relevant segments of the SDWA which pertain to underground injection and carbon storage is shared between the U.S. Environmental Protection Agency (EPA) and individual states that have been granted regulatory authority. The EPA assumes several key responsibilities. It formulates regulations governing underground injection practices, provides guidance to aid in the implementation of state programs, and in certain instances, directly manages underground injection control programs within states.

- **Critical Importance of Site Selection:** A thorough assessment of microscopic cavities within the rock is crucial to determine the capacity for CO_2 storage. Equally important is the assessment of the impermeability of the formation itself and the cap rock that overlays it. Impermeable layers are essential to prevent CO_2 from migrating toward the surface or escaping beyond the storage site.

- **Class VI Wells:** EPA has categorized underground injection wells into distinct classes. Underground Injection Control Class VI is specifically tailored for the geological sequestration of CO_2. These regulations are designed to ensure proper drilling and pumping procedures are followed. This includes rigorous oversight of well construction, materials used, and sealing of the wellbore to prevent leakage or migration of CO_2.

- **Continuous Monitoring of Injection Flows and Pressures:** Throughout the process, from drilling to injection and long-term storage, there is continuous monitoring of injection flows and pressures. The objective is to ensure pressures within the storage formation do not exceed safe limits. This is vital to prevent potential breaches or integrity failures within the geological storage site. Additionally, careful consideration is given to avoid drilling in formations that could be susceptible to induced seismicity, which can be triggered by high-pressure injection.

Appendix III

10. Utilization

Researchers and industry are exploring ways to harness CO_2 to create tangible benefits across diverse sectors as an alternative to geological storage. Some examples are:

- **Chemical and Fuel Production:** CO_2 can be used as a feedstock for chemicals and fuels through various chemical reactions. For instance, CO_2 can be converted to methanol, used in a range of industrial applications, including as a fuel additive, or as a precursor for other chemicals.

- **Algae Cultivation and Biofuels:** Considered to be in the experimental phase, CO_2 can be used to enhance the growth of algae in controlled environments. The harvested algae can then be used to produce biofuels, animal feed, or other products.

- **Carbonated Beverages and Food Processing:** Captured CO_2 can be purified and repurposed for use in beverages and food processing. The food and beverage industry uses CO_2 for carbonation in soft drinks, beers, and sparkling water. It is also used to create dry ice, which is the solid form of CO_2 and is used for food preservation.

- **Mineral Carbonation:** Mineral carbonation involves the reaction of CO_2 with certain types of rock or minerals to form stable carbonate compounds. This can be used for both carbon storage (see discussion of basalt formations in Appendix II) and utilization. When CO_2 reacts with minerals, it forms solid compounds that can be permanently stored or used in various industrial applications.

- **Concrete Carbonation:** CO_2 can be injected into concrete mixtures during the production process to accelerate the natural carbonation of concrete. This results in the formation of calcium carbonate, which improves the concrete's strength and durability while sequestering CO_2.

- **Enhanced Oil Recovery:** As noted in Appendix II, captured CO_2 is used in the oil and gas industry for enhanced oil recovery. Injecting CO_2 into depleted oil reservoirs can help extract additional oil that was previously inaccessible, while also securely storing the CO_2 underground.

- **Greenhouses:** CO_2 captured from industrial emissions can be supplied to greenhouse operations to enhance plant growth. This can lead to increased crop yields and better-quality produce, contributing to more efficient and sustainable agricultural practices.

Appendix IV

PHMSA Pipeline incidents from 2003-2022[39], where all Incidents were reported under system type as HAZARDOUS LIQUID and commodity as CO_2. From the data and reporting, it is evident incidents have occurred in the past and can continue to occur due to various factors, but over the span of 20 years, the data show no fatalities as per the PHMSA and other authorities, which suggests pipelines have been comparatively safe. By considering the monitoring and risk prevention measures implemented by the pipeline industry and with both state and federal regulations in place, it is possible to further mitigate incidents and build pipelines using better designs and construction materials for greater endurance and adaptability.

Table 3. CO_2 Pipeline Incidents

PHMSA Pipeline Incidents: (2004-2023)

Incident Type: All Reported **System Type:** HAZARDOUS LIQUID **State:** (All Column Values)

Offshore Flag : (All Column Values) **Commodity:** CO_2

Calendar Year	Number	Fatalities	Injuries	Total Cost as Reported	Barrels Spilled	Net Barrels Lost
2004	3	0	0	$74,101	8,182	8,182
2005	2	0	0	$3,888	2,401	2,401
2006	7	0	0	$763,912	25,086	25,086
2007	4	0	1	$115,425	24,540	24,540
2008	7	0	0	$11,444	103	103
2009	4	0	0	$153,134	1,077	1,077
2010	6	0	0	$212,521	329	329
2011	4	0	0	$168,770	2,542	2,542
2012	2	0	0	$5,823	19	19
2013	5	0	0	$270,387	52	52
2014	5	0	0	$32,948	2,190	2,190
2015	7	0	0	$67,224	1,281	1,281
2016	9	0	0	$71,029	1,709	1,709
2017	9	0	0	$132,993	218	218
2018	5	0	0	$299,047	406	406
2019	4	0	0	$375,395	480	480
2020	6	0	0	$4,035,553	50,903	50,903
2021	6	0	0	$68,885	882	882
2022	3	0	0	$10,977	699	699
2023	4	0	0	$22,292	3,084	3,084
Grand Total	**102**	**0**	**1**	**$6,895,748**	**126,186**	**126,186**

Appendix V

List of leak detection and related projects funded by PHMSA, and in collaboration with industrial and academic institutions.[40] These projects utilize various technologies, such as 3D modeling, optical gas imaging, and Leak Detection and Quantification (LDAQ).

Ongoing Pipeline Leak Detection Research

Currently 6 active projects related to Leak Detection with a total of $2.6 million in PHMSA funding and an additional $2 million in cost sharing.

Project	Contractor	Goals
An Autonomous Unmanned Aerial System Inspection Platform for High-Efficiency 3D Pipeline/Route Modeling/Change-Detection and Gas Leak Detection-Localization	University of Nebraska	To enhance the quality and efficiency of UAS pipeline and route inspections, and to evaluate and enhance the performance of OGI (optical gas imaging) pipeline leak detection-localization
Pre-Commercial Development and Field Testing of a Portable Mercaptan Sensing Device for Gas Industry Applications	Northeast Gas Association	Develop and validate portable technology that measures the concentration of mercaptans in gas industry field applications.
Advancing Hydrogen Leak Detection and Quantification Technologies Compatible with Hydrogen Blends	Gas Technology Institute	Investigate the impact of hydrogen injection on leakage dynamics and on existing leak detection equipment
Accelerating Pipeline Leak Detection Quantification Solutions Through Transparent and Rigorous Scientific Validation	Colorado State University	Investigate and document existing technology service provider leak detection and quantification (LDAQ) methodologies and their applicability to complex pipeline environments.
Innovative Leak Detection Methods for Gas and Liquid Pipelines	Pipeline Research Council International	Develop improved algorithms to better estimate pipeline inventories short of full pipeline transient modeling applications. Develop a new algorithm for enhanced zone balancing calculations. Develop pattern identification methods to identify how corrected zone balances shift based on changes in system flow. Develop recommended practices to troubleshoot facilities with high error probabilities.
Field Validation Demonstrations to Advance Pipeline Leak Detection Beyond Current Capabilities	Siemens Energy Inc	Develop and test spontaneous leak detection system capable of pinpointing ruptures via detection and evaluation of pressure waves.

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration

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Figure 11. PHMSA-funded leak detection projects[11]

[11] PHMSA Office of Pipeline Safety. (2023, October 31 - November 1). PHMSA Research and Development Forum 2023. [Presentation by Andrea Ceartin, PE, Core Program Manager, R&D Team, Engineering and Research Division]. Retrieved from https://primis.phmsa.dot.gov/meetings/FilGet.mtg?fil=1471

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