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Carbon Dioxide Pipelines:
Role in Responding to Carbon Emissions

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A growing number of carbon capture, utilization, and storage 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. A more detailed review of CO_2 pipelines is available at www.uh.edu/uh-energy.

Background

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 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 generated by these activities. 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; and (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 steam power plants or 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 to combat rising CO_2 levels, 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 the 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 the construction and operation, and the broader journey toward a sustainable world, connecting various industries and safely moving the captured CO_2 to its secure end destination.

CO_2 Pipelines in the United States

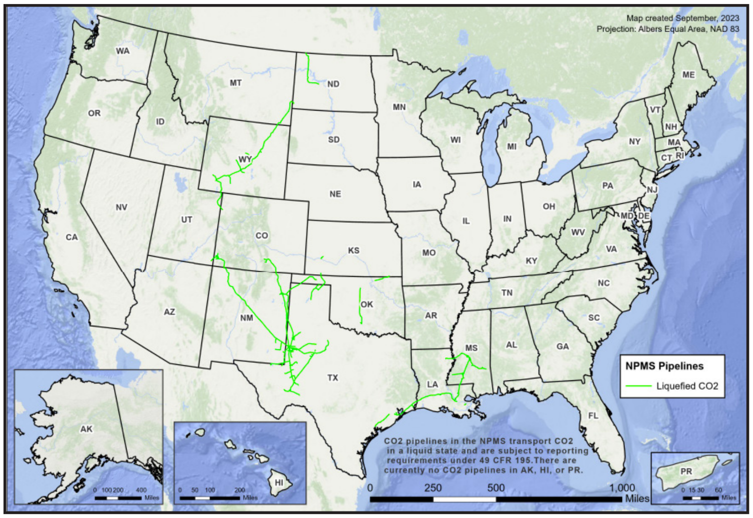


Figure 1. Current CO_2 Pipeline Network in the United States.[5]

The United States is a global leader in carbon management and the deployment of CCUS. The U.S. has an extensive CO_2 pipeline network spanning 5,385 miles1 (Fig. 1), with a capacity to transport 80 million tons of CO_2 annually[2]. The CO_2 is transported as a high-pressure fluid at temperatures ranging from 500 Fahrenheit to 1100 F. 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 a thousand facilities (Fig. 2), and increasing its capacity to transport around 930 million tons of CO_2 each year[3] Achieving this expansion by 2035 will require significant investment, site characterization, and permitting across multiple storage basins and sites[4]. It will also require significant investment and effort to engage with a broad range of stakeholders across the communities impacted by these pipelines.

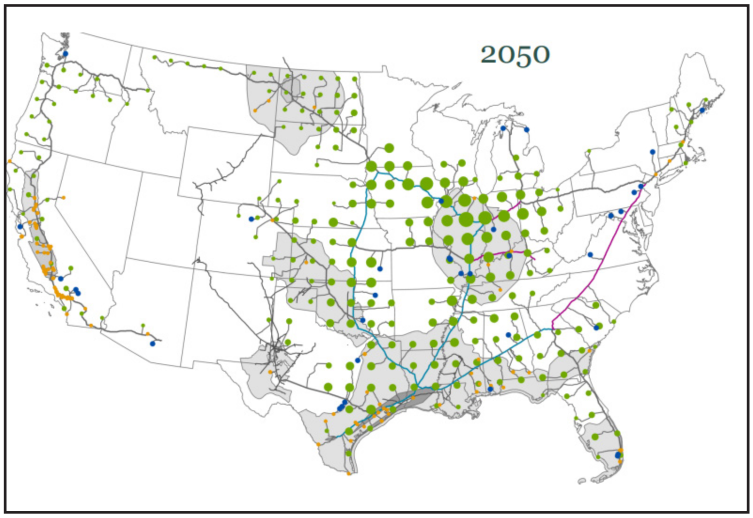


Figure 2. Planned expansion of the CO_2 pipeline network by 2050.[6]

While there are alternative means of transporting CO_2, such as trucks, railways, and ships, pipelines hold a distinct advantage when it comes to achieving large-scale connectivity. A few of the advantages are:

o They excel at high-volume transport, safely and economically moving large quantities of CO_2.
o Established safety protocols, engineering standards, and regulatory oversight.
o Reliable means of transporting captured emissions consistently and continuously. This is crucial for industries that depend on steady operations.
o Seamlessly integrate with various industrial processes, such as power plants, cement manufacture, and chemical facilities. This integration streamlines the CCUS process and minimizes logistical complexities.

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.

Storage

Oil and natural gas are trapped in subsurface reservoirs, shales, or carbonate rocks. Similarly, naturally occurring CO_2 from natural biological activity, igneous activity, and chemical reactions between rocks and fluids accumulate in the natural subsurface environment and are trapped in similar formations.

Subsurface storage opportunities for CO_2 are shown in Fig. 3.1. The oil and gas industry has injected CO_2 into subsurface formations for more than 50 years to stimulate reservoirs and produce more hydrocarbons. To mitigate the impact of CO2 on the environment, it will be captured and permanently stored underground.

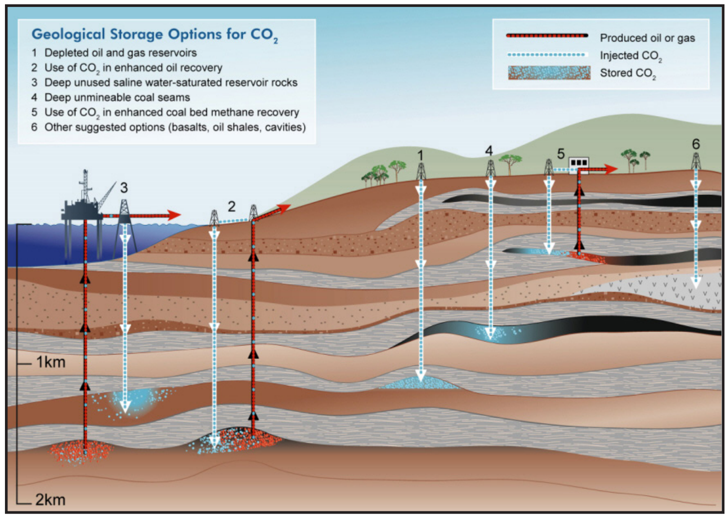


Figure 3. Options for storing CO_2 in deep underground geological formations.[7]

To successfully store CO_2 underground, several key issues must be dealt with. State and federal regulations, as well as industry practices, must ensure that CO_2 is safely injected into the subsurface and that it remains where it has been injected.

o **Site selection:** Pore space (microscopic cavities in the rock) must be assessed to determine their capacity, and it must be determined that the formation itself and the cap rock on top of the formation will not allow the CO_2 to migrate to the surface or beyond the boundaries of the storage site.

o **Permitting:** Injection wells for CO_2 are considered Class VI wells and have special regulations that ensure proper drilling and pumping procedures are followed. Class VI permit requirements are rigorous and in most instances are administered by the Environmental Protection Agency (EPA). That agency has given a few states "primacy," under which the state can administer the permit program in accordance with EPA standards.

o **Sub-Surface Monitoring:** Injection flows and pressures must be monitored during drilling, injection, and storage to ensure pressures do not exceed what is safe for the storage site. Additionally, storage site selection and drilling methods adopted are chosen so as to not take place in a formation that could be prone to induced seismicity.

o **Surface monitoring** for the presence of excess CO_2 to provide early detection in the event of a release is also essential. Data from current CO_2 storage projects demonstrate that monitoring techniques can detect movement of CO_2 in the storage reservoirs and while data is limited, no release to the surface has been detected[8].

Utilization of Transported CO_2

Transport through pipelines goes beyond the safe and efficient delivery of the captured carbon dioxide; it enables the use of that CO_2 in applications that can potentially make significant contributions to sustainability. Some of the ways in which transported CO_2 is utilized are:

o Enhanced Oil Recovery: CO_2 is injected into depleted oil reservoirs to enhance oil production. This not only increases oil yields but also ensures the long-term storage of CO_2 deep underground.
o Transported CO_2 is used in the cultivation of algae, which thrives on CO_2 and sunlight. Algae can serve as a vital component in the production of biofuels, offering a renewable and environmentally friendly alternative.
o The food and beverage industry relies upon CO_2 pipelines to provide carbon dioxide for use in producing carbonated beverages and food processing.
o CO_2 is used in concrete carbonation, a sustainable construction technique. By injecting CO_2 into concrete mixtures, the material becomes stronger and more resilient while simultaneously locking away carbon dioxide in a solid form.

These uses highlight the potential of captured CO_2 and the pivotal role CO_2 pipelines play in driving innovation towards decarbonization.

Regulations

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 CO2 into the atmosphere obviously defeats the purpose of capturing it in the first place.

A number of regulations and industry practices are in place to limit the risks. In the United States, regulation of CO_2 pipelines 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. 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 learn from incidents and so-called "near misses."

Generally, individual states regulate CO_2 pipelines on state lands and private lands within the state. Texas and New Mexico are illustrative.

Both Texas and New Mexico permit a pipeline operator to build a pipeline to move CO_2 from a specific source to a specific destination as a private or proprietary line. Texas also allows a CO_2 pipeline to be built and operated as a "common carrier line". In that case, the operator can seek to exercise the right of 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 the use of the pipeline by its customers, and they must publish their rates or tariffs for all to see. Using eminent domain rests 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. Nevertheless, use of the eminent domain process is often contentious and provokes significant negative reactions from impacted landowners and communities.

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.

Challenges and Measures

It is important to note that most CO_2 pipelines, like the majority of existing oil and natural gas pipelines are located underground. The right of way is excavated, and the pipeline installed and then buried, with the surface land restored as near as possible to its pre-excavation condition. While CO_2 pipelines offer a promising solution to several environmental challenges, they also present hurdles, in part because they are buried and out of sight. A few of the primary challenges are:

o **Pipeline Integrity Issues:** Pipeline integrity refers to the continuous process of maintaining and ensuring a pipeline is fit for use. CO_2 pipelines face threats including corrosion, mechanical stress, material degradation, and welding defects. These issues can weaken the pipeline structure and compromise its ability to safely transport CO_2.

o **Geological Issues:** CO_2 pipelines often traverse diverse terrains and landscapes, making them susceptible to geological hazards. Landslides, subsidence, and erosion can disrupt pipeline stability and lead to potential leaks or ruptures. Additionally, seismic events pose a significant threat in regions prone to earthquakes.

o **Third-Party Damage:** The risk of third-party interference, such as accidental damage caused by construction activities or excavations near pipelines, is an additional layer of concern.

In navigating these challenges, ongoing monitoring, maintenance, and rigorous inspections are essential. Reputable operators follow best practices developed through INGAA, in addition to standards set by state and federal (PHMSA) regulations, to reduce the risks from CO2 and other pipelines. Community members seeking more information about a proposed pipeline should ask if measures such as the following will be used for the new project:

o In-Line Inspection: A technique where specialized inspection tools, often referred to as "smart pigs," are inserted into pipelines to assess their internal condition. These smart pigs employ multiple technologies to address different issues:

o Magnetic flux tools identify and measure metal wall loss.

o Ultrasonic tools can identify wall loss but also detect crack-like defects, weld defects, and longitudinal cracks.

o Geometry tools measure the pipe bore from inside the line and identify dents, deformations, and other changes to the pipeline.

o Cathodic Protection: An electrochemical technique that uses a low electrical current to prevent corrosion of the metal pipeline. This technique has been used since the 1930s to protect long pipelines.

o Geological Surveys and Site Investigations: To assess soil properties, and geological features, thorough surveys are required.

o Geological Monitoring: Implementing programs to continuously monitor ground movement, slope stability, and other geological parameters along the pipeline.

o Advanced Leak Detection Systems: Utilizing advanced technologies like acoustic sensors, infrared imaging, and fiber optics to promptly detect leaks in CO2 pipelines, especially in high-consequence areas.

o Ensuring participation in the National 811 program, also known as the "Call Before You Dig" program. It provides landowners and contractors with free marking of underground lines to ensure that they are not inadvertently damaged.

o Emergency Response Plans: Emergency response plans outline actions to be taken in the event of pipeline incidents. These plans ensure a rapid and effective response to mitigate environmental and community impacts and should be devised in cooperation with local first responders to ensure appropriate action is taken and necessary equipment will be available. The plans typically provide emergency response training for first responders.

By incorporating these measures, CO_2 pipelines can be managed with a strong emphasis on safety, integrity, and environmental responsibility. For a more detailed review of integrity issues, causes, and solutions, see **Appendices I, II & III**.

Having emphasized the importance of safety, integrity, and environmental responsibility, we examine a real-world case highlighting the potential risks and consequences of CO_2 pipeline transport.

Case of Satartia, Mississippi

A CO_2 pipeline managed by Denbury Gulf Coast Pipelines ruptured near the community of Satartia, Mississippi, in 2020, the result of a landslide triggered by heavy rainfall, which placed excessive stress on a weld in the pipeline. While the cause of the rupture was not caused by the CO_2 in the pipeline, the subsequent release of CO_2 prompted the evacuation of 200 residents, and 45 people required medical attention due to breathing difficulties. The incident brought new attention to CO_2 pipelines and has prompted heightened regulatory focus. PHMSA cited the following reasons for the incident involving Denbury's role:

o Operations and maintenance procedures did not account for soil instability as a potential threat, despite prior knowledge of such risks.

o The integrity management program did not address geological hazards or ways to prevent them.

o The company's dispersion model for emergency events did not account for the region's topographical features and did not anticipate that a release could impact Satartia.

o Aerial checks did not spot any issues at the pipeline location before the accident.

o There was a delay in notifying local responders, resulting in confusion and delays in the emergency response.

Updated Rule Making by PHMSA

PHMSA's failure investigation report[9] highlighted two key issues that should be prioritized through regulatory measures:

a) pipeline company awareness and mitigation efforts to address integrity threats due to changing climate, geohazards, and soil stability issues, and
b) improved public engagement efforts to ensure public and emergency responder awareness of nearby CO_2 pipelines and pipeline-related facilities, including what to do if a CO_2 release occurs, especially in low-lying areas with topographical features such as rivers and valleys.

To enhance CO_2 pipeline safety following the Satartia incident, PHMSA has taken the following actions:

o It is creating new rules for CO_2 pipelines that will include guidelines for emergency preparedness, training, and response, ensuring pipeline operators can effectively handle unexpected situations.

o It has distributed an updated nationwide advisory to all pipeline operators stressing the need for improved planning and risk reduction strategies. This advisory highlights risks associated with land movements and geohazards.

o It is proactively conducting research and supporting research to model, identify, and implement improved safety protocols to prevent similar incidents.

o On May 26, 2022, PHMSA issued a Notice of Probable Violation, Proposed Civil Penalty and Proposed Compliance Order, proposing a fine of $3.9 million for Denbury Gulf Coast Pipeline, LLC, emphasizing the importance of strict compliance with safety regulations[10]. Ultimately, the company paid $2.8 million.

Incident Reporting

PHMSA maintains a comprehensive database that catalogs incident details spanning the past two decades[11]. Over the last 20 years, the database reports that CO_2 pipelines have recorded a relatively low incident count of 105 nationwide. This stands in contrast to other hazardous liquid categories. CO_2, crude oil, and refined petroleum products belong to the hazardous liquid classification. Appendix IV outlines the length of crude oil, refined petroleum products, and CO_2 pipelines, as well as the number of incidents and incident rates by year. CO_2 pipelines rank as the safest of the three categories, and the highest incident rate for CO_2 lines, which occurred in 2006, was less than 0.002 incidents per mile. This data provides insight into the safety record of CO_2 pipelines when compared to their counterparts, highlighting their ability to maintain generally safe operations over the past two decades.

Planned Pipelines and Rights-of-Way

In a recent development, three major companies—Summit Carbon Solutions, Navigator Ventures, and Wolf Carbon Solutions—proposed an ambitious project involving approximately 3,650 miles (5,874 km) of new carbon dioxide pipelines across the American Midwest. The primary goal was to bolster carbon capture efforts, especially from ethanol production, and reduce biogenic emissions. However, the plan drew concerns, primarily related to the chosen route that crossed predominantly rural areas and farmlands. These concerns involve pipeline efficiency, safety, and the potential impact on local communities. While community opposition and permitting delays caused operators of the Navigator line to cancel the project in the fall of 2023, and the Summit line has been put on hold for similar reasons, both illustrate the problems facing the pipeline industry.

Negotiations and Legal Complexities: The process of obtaining agreements from landowners to facilitate pipeline construction encountered lengthy delays, as negotiations continued between the companies and concerned landowners. These delays amplified public apprehension, driven by concerns that the companies would resort to the use of eminent domain to secure the required rights-of-way. In this context, it is vital to understand terms like "rights-of-way," referring to legal authorization to cross another's land for specific purposes like pipeline construction, and "eminent domain," which grants the government or authorized entities the authority to acquire private property for public use, provided fair compensation is offered to property owners. In many cases involving CO_2 pipelines, the landowner retains the ability to use the property once construction is complete. Nevertheless, it is easy for landowners and communities to feel they are being forced to accept a development that is undesirable and unsafe. These terms highlight the complex legal and ethical aspects underpinning the ongoing debate between companies, affected communities, and landowners.

Community Concerns: People living near proposed the pipeline routes sought legal intervention to address the issues. Their primary concern centered on the well-being of their communities and the potential repercussions for the farming sector. These concerns were compounded by real-world incidents, such as the one in Satartia, Mississippi, which intensified the debate over the safety and necessity of such extensive projects.

Stakeholder Management

Working with stakeholders requires a proactive approach by pipeline owners to minimize community objections and ensure successful infrastructure deployment and operation. The key aspects of a sound stakeholder approach are:

o **Community Engagement:** Transparent, two-way, and open communication channels with local communities are vital to addressing community concerns, meeting the community's aspirations, collaborating on shared environmental values and goals, and gathering valuable insights. Conversations must move seamlessly from the operator to the community and vice versa. Allowing members of the community to speak for themselves and have their issues addressed can foster trust and cooperation.

o **Outreach:** Effective outreach is essential to disseminate accurate information. Outreach initiatives should encompass public awareness campaigns, informational meetings, and educational programs. Clear, community-specific, and concise information allows stakeholders to make informed decisions and can dispel misconceptions and fears. Outreach should also include feedback mechanisms to integrate community knowledge and input.

o **Fear and Misinformation:** It is critical to proactively address concerns and counter misconceptions. Easily understandable, and consistent messaging can help alleviate anxieties and build trust among stakeholders. This is also essential for preventing the spread of misinformation and delays in emergency response in case of an accident.

o **Land Acquisition:** Land use, particularly in agriculture-dependent areas, is a significant stakeholder concern. CO_2 pipeline operators must consider the impact on agricultural activities and landowners, including engaging with farmers and other landowners to understand their concerns. Implementing measures to minimize disruptions to agriculture and compensating landowners fairly can mitigate conflicts and ensure continued stakeholder support.

Safety Considerations

In addition to the measures proposed by PHMSA, our study has identified various potential impacts during pipeline development and operation, including CO_2 pipelines. These include soil erosion, pollution, habitat disturbance, noise, and traffic congestion resulting from excavation activities, as well as concerns specific to CO_2 related to oxygen levels, and pipe rupture due to high pressures. To ensure the safety of local communities and the surrounding environment, addressing the potential risks proactively is crucial. Collaborative efforts are essential to address the following:

Construction Issues:

o Erosion Control: Implement erosion control measures such as sediment barriers to prevent soil erosion and protect the surrounding ecosystem.

o Traffic Management: Schedule the transport of heavy machinery and materials during off-peak hours to minimize traffic congestion and reduce the impact on local roads.

o Habitat Protection: Establish construction buffer zones to safeguard critical habitats, preserving local biodiversity.

o Noise Reduction: Employ noise mitigation measures, such as erecting sound barriers or using quieter construction equipment, to minimize noise pollution in the vicinity.

o Dust Control: Institute best management practices to minimize fugitive dust, including reducing driving speeds, and utilizing water and additives as well as tackifiers to stabilize soil piles.

Operational Issues:

o Gas Monitoring: Continuously monitor CO2 concentrations in and around pipeline facilities using advanced sensors. A variety of technologies are available and easily implemented.

o Leak Detection and Repair: Implement a rigorous program for prompt and accurate leak detection and rapid repair of leaking pipelines.

o Pressure Safety: Install pressure relief valves and safety mechanisms that automatically activate in case of excessive pressure, ensuring the integrity of the pipeline system.

These safety considerations and corresponding measures can mitigate potential risks and ensure the secure development and operation of CO2 pipelines while prioritizing the environment and local communities.

Benefits

CO_2 pipelines offer a range of benefits that could address critical challenges of emissions reduction and foster sustainable development. These benefits include:

o Mitigating Climate Change: One of the foremost benefits of CO_2 pipelines is their role in mitigating climate change. This proactive approach aligns with international climate goals and demonstrates a commitment to combating climate change.

o Technological Advancements: Innovation is driving the development of cutting-edge technologies related to carbon capture, transport, and utilization. These advancements have broader applications beyond CO_2 pipelines, benefiting other sectors and industries.

o Economic Benefits: CO_2 pipeline projects contribute to the local and national economies. During the construction phase alone, projects like those proposed by Navigator Ventures and Summit Carbon Solutions generate a substantial number of jobs. Navigator had said it would employ 8,000 individuals[12], while Summit projected the creation of 11,000 jobs[13] during the construction phase. Additionally, these projects would have generated tax revenues for local communities. Such projects also bring indirect and induced benefits to the local community through new jobs in related sectors, essential services, and new investments across all sectors of the economy.

The Dakota Institute recently completed a study of the economic impact of CO_2 pipelines in the state of South Dakota[14]. The results, while specific to South Dakota, offer additional insights into the benefits these infrastructure investments can provide. According to the study, the Navigator and Summit pipelines would have generated approximately $3.3 billion in economic impact during the construction and operational phases; $925 million would come from the construction phase in 2024-25. The operational phase would have added $2.35 billion to the state GDP from the combined impacts of pipeline operations, clean fuel and CCS tax credits, and a stronger corn basis, according to the study, which forecasts the creation of 7,105 jobs between 2024 and 2034. Of those, 5,353 jobs were to be part of the construction phase, with 1,752 permanent jobs created during the operational life of the project.

Best Practices

To prevent incidents like those in Satartia, Mississippi, CO_2 pipeline owners can adopt a set of best practices aimed at ensuring safety, compliance, and effective stakeholder engagement. Communities and landowners should query developers on their plans to address these issues when discussing specific projects in their communities:

o Following Regulations: Compliance with PHMSA regulations and other relevant guidelines is paramount. This includes systematic monitoring and assessment of pipeline integrity, conducting regular inspections, and promptly addressing any identified issues.

o Adopting Technology: Owners should employ advanced monitoring and control systems that provide real-time data on pipeline conditions. These technologies include leak detection systems, remote sensors, and predictive analytics, which enable early detection of potential issues and rapid response to mitigate risks.

o Engaging with Stakeholders: Effective stakeholder engagement is a cornerstone of best practices for pipeline owners, whether they are building a proprietary line or a common carrier. Beyond regulatory requirements, it is crucial to actively engage with the communities and individuals residing near pipeline routes. This engagement should involve not only sharing information but also listening to and addressing concerns, understanding the community's expectations, and working together to accelerate emissions reduction while meeting the community's socioeconomic aspirations. Consideration of community responses and input is vital for building trust and fostering cooperation. Concerns and responses will vary between communities, and there is no one-size-fits-all solution.

o Emergency Response Planning: Robust emergency response planning is a non-negotiable best practice. Pipeline owners should develop comprehensive emergency response plans that outline procedures for addressing various scenarios, including leaks, ruptures, and other incidents. Collaboration with local emergency responders and training programs, such as Exxon Mobil's partnership with Texas A&M University's Engineering Extension Service[15], can equip first responders with the knowledge and skills to effectively manage emergencies.

By incorporating these best practices, CO_2 pipeline owners can significantly reduce the likelihood of incidents, ensure the safe and responsible operation of their pipelines, and credibly, symbiotically, and sustainably coexist with impacted communities.

Best Practices
Pipeline operators can significantly reduce the risk of accidents, as well as improve relationships with people living and working in the path of a CO_2 pipeline, by following some essential best practices.

• Follow all regulations set by the Pipeline and Hazardous Materials Safety Administration, including regular monitoring and assessment of pipeline integrity, scheduled inspections, and promptly addressing any identified issues.
• Use the latest technology to provide real-time data on pipeline conditions to catch problems early and allow a rapid response. These technologies include leak detection systems, remote sensors, and predictive analytics.
• Actively engage with people living near pipeline routes, addressing concerns in order to build trust and foster cooperation. Understand there is no one-size-fits-all solution.
• Develop comprehensive emergency response plans that outline procedures for addressing leaks, ruptures, and other incidents. Work with local emergency responders and training programs to ensure they have the information and skills to effectively manage emergencies.

Conclusion

Ensuring the safety of CO_2 transportation requires a balance between protecting the community, the environment, and continued economic development through fossil energy use. Striking this balance requires a commitment to safety, compliance, and proactive dialogue with stakeholders to realize the benefits of CO_2 pipelines while addressing legitimate concerns. Moreover, the related socioeconomic benefits and regional connectivity will be invaluable in forging a sustainable and interconnected future.

Ultimately, CO_2 pipelines are essential in the context of removing carbon dioxide emissions, mitigating climate change, and enabling the transition to cleaner, more sustainable energy sources. They also bring significant positive economic benefits to the communities in which they operate. However, any effort to expand their use to reap these benefits will rely upon both the reality and the public perception that they can be constructed and operated safely.

This paper, along with the accompanying white paper, offers a roadmap for getting there through a neutral assessment of the risks and benefits of these pipelines and recommended best practices to ensure their operation is rooted in responsible environmental stewardship and respectful engagement with the communities they affect

APPENDIX I

PIPELINE INTEGRITY ISSUES	CAUSES	RESOLUTION
FRACTURES: A FRACTURE REFERS TO A BREAK IN THE PIPELINE'S STRUCTURE, RESULTING IN A DISCONTINUITY IN THE DESIGN AND FLOW.	Mechanical stress, material defects, and corrosion.	**Welded repair sleeves**: Installing a full encirclement sleeve around the damaged area. **Composite wraps**: Wrapping the damaged section with fiber reinforcement (fiberglass or carbon fiber) around the damaged area. **Epoxy or resin injection**: The method involves introducing a specially formulated epoxy or resin into a crack or defect to restore structural integrity and prevent further deterioration.
EXTERNAL DAMAGE: EXTERNAL DAMAGE, SUCH AS EXCAVATION WORK, CONSTRUCTION ACTIVITIES, OR NATURAL DISASTERS LIKE LANDSLIDES OR EARTHQUAKES, CAN DAMAGE CO_2 PIPELINES.	Mechanical impacts from heavy machinery or other objects can cause punctures or dents in the pipeline, compromising its integrity.	**Composite wraps**: Fiber-reinforced polymer wraps can provide reinforcement and protection for superficial damages, such as scratches or minor dents. **Welded repair sleeves**: For more extensive damage that has not fully compromised the pipeline, a full-encirclement sleeve can be welded over the affected section to reinforce it. **Pipe section replacement**: For severely damaged areas, especially if the pipe wall's integrity is significantly compromised, the best approach might be to cut out the damaged section and replace it with a new piece, which is then welded in place.
PIPE JOINT FAILURES: THE CONNECTION BETWEEN PIPE SEGMENTS, KNOWN AS PIPE JOINTS, CAN BE VULNERABLE. THESE JOINTS MAY FAIL IF NOT INSTALLED PROPERLY OR UNMONITORED, LEADING TO RUPTURES.	Corrosion, thermal stress, material, and welding defects.	**Rewelding**: If the joint fails due to a welding defect, the joint might need to be ground out and rewelded. **Fusion-bonded epoxy (FBE) coating joints**: This is a thermosetting epoxy powder applied to the outer surface of steel pipes. **Joint replacement**: For severe failures, cutting out and replacing the whole common area may be necessary, using a new joint and ensuring proper installation and welding.

APPENDIX II

ENVIRONMENTAL RISKS	CAUSES	RESOLUTION
PIPELINE LEAKAGE: THE PRIMARY ENVIRONMENTAL CONCERN IS THE RELEASE OF CO_2 DUE TO PIPELINE LEAKS.	Corrosion	• Regularly inspect the pipeline for signs of corrosion using advanced inspection technologies such as **corrosion probes and inline inspection tools (smart pigs).** Implement corrosion-resistant coatings on the pipeline's interior and exterior surfaces. • **Utilize cathodic protection systems** to prevent corrosion by creating an electrochemical barrier. • **Epoxy or resin injection**: The method involves introducing a specially formulated epoxy or resin into a crack or defect to restore structural integrity and prevent further deterioration.
	Material degradation	• Use **corrosion-resistant stainless steel,** which is less prone to degradation from the CO_2 transported. • **Perform material testing in a controlled environment** to simulate pipeline conditions, ensuring the material's durability over time.
	Faulty valves	• Establish a **quarterly valve inspection schedule**, during which trained technicians visually inspect valve components, assess their functionality, and perform any necessary maintenance. • **Utilize smart valve monitoring systems** that can detect deviations from normal valve operations, such as irregular pressure changes.
PIPELINE LEAKAGE DUE TO DAMAGE FROM ACCIDENTS BY THIRD PARTIES.	External Damages	• Install highly visible markers and signs indicating the presence of the pipeline along construction routes.

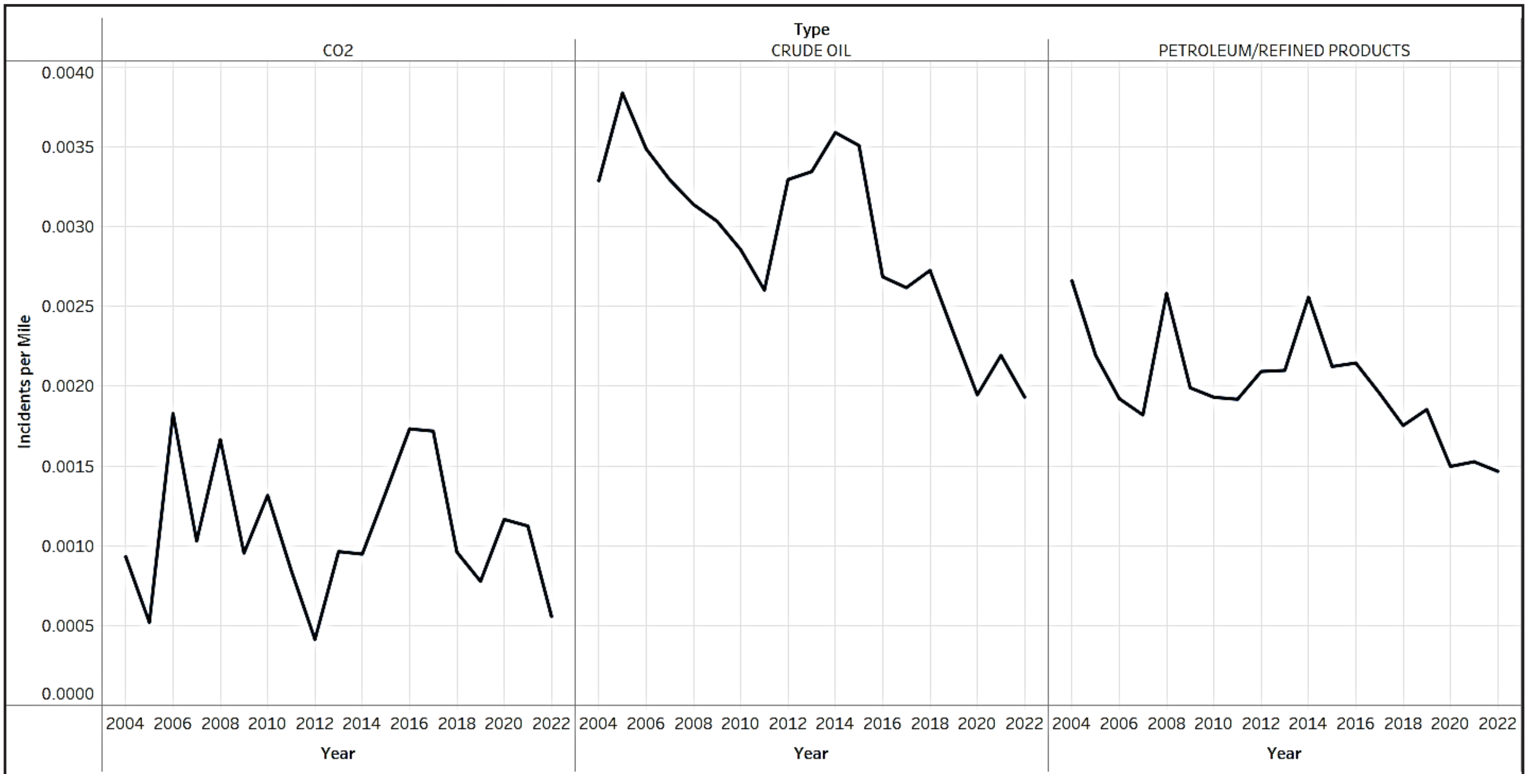
APPENDIX III

GEOLOGIC RISKS	CAUSES	RESOLUTION
SOIL COMPOSITION	The type of soil the pipeline is buried in can affect its stability. Different soils have varying load-bearing capacities, settlement behaviors, and drainage characteristics.	• If the soil is clay-rich and prone to swelling, design the pipeline with flexible joints to accommodate soil movement without causing structural damage.
TERRAIN AND TOPOGRAPHY	The pipeline route may cross varying terrains, including slopes, valleys, and hills. Steep slopes can lead to soil erosion, while valleys may be prone to landslides.	• In areas with steep slopes, install erosion control measures such as retaining walls or vegetation to prevent soil erosion that could expose the pipeline.
GROUNDWATER LEVELS	Elevated groundwater levels can lead to soil instability, erosion, and corrosion of the pipeline. Changes in groundwater levels due to seasonal variations or nearby water bodies can impact soil behavior.	• Install drainage systems around the pipeline to help manage excess groundwater and prevent soil instability and corrosion risks.
SOIL EROSION AND LANDSLIDES	Erosion can expose the pipeline, increasing the risk of external damage. Landslides in hilly or mountainous areas can cause soil movement and impact pipeline integrity.	• Implement erosion control techniques such as slope stabilization, rock protection, and vegetation to prevent soil erosion and landslides. • Install erosion control mats or blankets along slopes to provide soil stability and prevent erosion that could undermine the pipeline's support.
SEISMIC ACTIVITY	Regions prone to earthquakes can experience ground shaking that affects the pipeline's structural integrity. Seismic activity can induce ground movement and potentially lead to pipeline failure.	• Conduct seismic hazard assessments to determine potential risks. Design pipelines to withstand anticipated seismic forces. • Reinforce pipeline supports in earthquake-prone regions and incorporate flexible joints to absorb seismic movements without damaging the pipeline.

APPENDIX IV

Year	Type	Miles of Pipeline	Number of Incidents	Incidents per Mile
2004	PETROLEUM/REFINED PRODUCTS	62,391	166	0.0027
2004	CRUDE OIL	49,264	162	0.0033
2004	CO_2	3,221	3	0.0009
2005	PETROLEUM/REFINED PRODUCTS	62,899	138	0.0022
2005	CRUDE OIL	48,732	187	0.0038
2005	CO_2	3,846	2	0.0005
2006	PETROLEUM/REFINED PRODUCTS	61,905	119	0.0019
2006	CRUDE OIL	48,453	169	0.0035
2006	CO_2	3,827	7	0.0018
2007	PETROLEUM/REFINED PRODUCTS	62,091	113	0.0018
2007	CRUDE OIL	49,488	163	0.0033
2007	CO_2	3,884	4	0.0010
2008	PETROLEUM/REFINED PRODUCTS	61,599	159	0.0026
2008	CRUDE OIL	50,963	160	0.0031
2008	CO_2	4,203	7	0.0017
2009	PETROLEUM/REFINED PRODUCTS	61,803	123	0.0020
2009	CRUDE OIL	52,737	160	0.0030
2009	CO_2	4,192	4	0.0010
2010	PETROLEUM/REFINED PRODUCTS	64,742	125	0.0019
2010	CRUDE OIL	54,631	156	0.0029
2010	CO_2	4,560	6	0.0013
2011	PETROLEUM/REFINED PRODUCTS	64,122	123	0.0019
2011	CRUDE OIL	56,100	146	0.0026
2011	CO_2	4,735	4	0.0008
2012	PETROLEUM/REFINED PRODUCTS	64,040	134	0.0021
2012	CRUDE OIL	57,653	190	0.0033
2012	CO_2	4,840	2	0.0004
2013	PETROLEUM/REFINED PRODUCTS	63,349	133	0.0021
2013	CRUDE OIL	61,277	205	0.0033
2013	CO_2	5,190	5	0.0010
2014	PETROLEUM/REFINED PRODUCTS	61,766	158	0.0026
2014	CRUDE OIL	67,133	241	0.0036
2014	CO_2	5,276	5	0.0009
2015	PETROLEUM/REFINED PRODUCTS	62,632	133	0.0021
2015	CRUDE OIL	73,247	257	0.0035
2015	CO_2	5,241	7	0.0013
2016	PETROLEUM/REFINED PRODUCTS	62,459	134	0.0021
2016	CRUDE OIL	75,954	204	0.0027
2016	CO_2	5,195	9	0.0017
2017	PETROLEUM/REFINED PRODUCTS	62,362	122	0.0020
2017	CRUDE OIL	79,458	208	0.0026
2017	CO_2	5,237	9	0.0017
2018	PETROLEUM/REFINED PRODUCTS	62,719	110	0.0017
2018	CRUDE OIL	81,079	221	0.0027
2018	CO_2	5,206	5	0.0010
2019	PETROLEUM/REFINED PRODUCTS	63,107	117	0.0019
2019	CRUDE OIL	84,475	197	0.0023
2019	CO_2	5,147	4	0.0008
2020	PETROLEUM/REFINED PRODUCTS	64,111	96	0.0015
2020	CRUDE OIL	85,293	166	0.0019
2020	CO_2	5,150	6	0.0012
2021	PETROLEUM/REFINED PRODUCTS	64,200	98	0.0015
2021	CRUDE OIL	84,819	186	0.0022
2021	CO_2	5,339	6	0.0011
2022	PETROLEUM/REFINED PRODUCTS	64,082	94	0.0015
2022	CRUDE OIL	84,363	163	0.0019
2022	CO_2	5,385	3	0.0006

INCIDENT RATE COMPARISON (2004-2022)



The trend of sum of Incidents per Mile for Year broken down by Type.

FOOTNOTES

[1] See, PHMSA's Annual Report Mileage for Hazardous Liquid or Carbon Dioxide Systems. This report provides details of the existing pipeline network in the US of liquids categorized as Petroleum, HVL's, Crude Oil, CO2, and Fuel grade ethanol. https://www.phmsa.dot.gov/data-and-statistics/pipeline/annual-report-mileage-hazardous-liquid-or-carbon-dioxide-systems.

[2], [3], [4], [6] -See, The Report | Net-Zero America Project (Nov. 2021), published by Princeton University. The study anticipates an investment of $13 billion is estimated for stakeholder engagement plus characterization, appraisal and permitting across multiple storage basins and sites before 2035 to enable rapid expansion thereafter. https://netzeroamerica.princeton.edu/the-report.

[5]- See, CO2 Pipeline Map, provided by National Pipeline Mapping System, PHMSA, which provides the latest network of CO2 present in the US. https://www.npms.phmsa.dot.gov/GeneralPublic.aspx

[7]- See, Carbon Dioxide Capture and Storage (2005)— IPCC. This report analysis the CO2 storage process and details factors influencing the methodology. Detailed report found at https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/.

[8]- See, IEA GHG Weyburn CO2 monitoring and storage project. International Energy Agency. IEA summaries geological storage, and injection of CO2 and its role in EOR by taking The Weyburn project as a reference. https://ieaghg.org/docs/general_publications/weyburn.pdf.

[9]- See, Failure Investigation Report - Denbury Gulf Coast Pipelines, LLC – Pipeline Rupture/ Natural Force Damage (May 2022). U.S DOT, PHMSA. The report details the complete failure analysis and the Denbury pipeline incident at Satartia, MS. https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf.

[10]- See, Notice of Probable Violation, Proposed Civil Penalty, and Proposed Compliance Order (May 2022). U.S DOT, PHMSA.
https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf.

[11]- See, Pipeline Incident 20 Year Trends. U.S DOT, PHMSA. PHMSA maintains a database to record and store incident information for years starting from 2003. https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends.

[12]- See, Navigator CO2. Heartland Greenway. Estimated employment opportunity announced by Navigator Ventures. https://heartlandgreenway.com/wp-content/uploads/HG-Fact-Sheet.pdf.

[13]- See, Summit benefits. Summit Carbon Solutions. Projected benefits due to the construction of the proposed pipeline network by Summit. https://summitcarbonfacts.com/public-benefits/.

[14]- See, Dakota-Institue-Economic-Impacts-of-CO2-Pipelines-Final-Report.pdf (dakotainstitute.org).

[15]- See, Texas A & M Engineering Extension Services - https://teex.org/

ABOUT UH ENERGY

UH Energy is an umbrella for efforts across the University of Houston to position the university as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, research and development for needed innovations and new technologies.

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