Workshop on Applied Research for CO_2 Transport

Sponsored by the U.S. Department of Energy, Office of Fossil Energy and Carbon Management

and held

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Disclaimer

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Acronyms and Key Terms

AI: Artificial Intelligence
API: American Petroleum Institute
BIL: Bipartisan Infrastructure Law
BTCM: Battelle Two-Curve Method
CCT: Corrosion in CO_2 Transmission Pipelines
CCUS: Carbon Capture, Utilization, and Storage
CDR: Carbon Dioxide Removal
CFR: Code of Federal Regulations
CRADA: Cooperative Research and Development Agreement
DAC: Direct Air Capture
DNV: Det Norske Veritas
DOE: U.S. Department of Energy
DOT: U.S. Department of Transportation
EDX: Energy Data eXchange platform
EOR: Enhanced Oil Recovery
EPA: U.S. Environmental Protection Agency
FECM: Office of Fossil Energy and Carbon Management
FEED: Front-End Engineering Design
FOA: Funding Opportunity Announcement
ICMT: Institute for Corrosion and Multiphase Technology
JIP: Joint Industry Partnership
LCA: Life Cycle Analysis
LNG: Liquified Natural Gas
LPG: Liquified Petroleum Gas
ML: Machine Learning
MT/yr: Metric Tonnes per year
NGO: Nongovernmental Organization
NIST: National Institute of Standards and Technology
PRCI: Pipeline Research Council International
PHMSA: Pipeline and Hazardous Materials Safety Administration
R&D: Research and Development
RD&D: Research, Development, and Demonstration
TCF: Technology Commercialization Fund
TEA: Techno-Economic Analysis

Overview

Summary

The Long-Term Strategy, Pathways to Net-Zero Greenhouse Gas Emissions by 2050 report[1] advised that the United States will require significant carbon capture, utilization, and storage (CCUS) infrastructure to realize a carbon-free electricity sector by 2035 and a net-zero carbon emissions economy by 2050. [2] The most recent synthesis report from the Intergovernmental Panel on Climate Change indicates the current rates of CCUS deployment worldwide fall far short of restricting global warming to important 1.5 to 2 degree Celsius thresholds. [3] Achieving the 2050 net-zero target will require mobilization of research, development, demonstration, and deployment efforts to launch CCUS technologies over the next two decades.

CCUS technologies encompass carbon dioxide (CO_2) capture from a range of sources, including from industrial processes, power plants, and directly from the atmosphere (direct air capture, or DAC). Carbon capture and storage technologies are important for attaining near to medium-term reductions in greenhouse gas emissions from energy and industry while development of DAC and other carbon dioxide removal (CDR) capabilities will counterbalance emissions from sectors that are difficult to decarbonize. [4] Once captured, CO_2 may be transferred via pipeline, truck, rail, barge, or ship for 1) use as a feedstock in subsequent chemical and manufacturing processes; or 2) injection into saline formations or hydrocarbon reservoirs for permanent geologic storage.

To meet CCUS targets, rapid growth of the U.S.'s CO_2 transport infrastructure will be necessary. Since the 1970s, the U.S. has operated CO_2 transport pipelines for enhanced oil recovery (EOR) and, in some instances, associated geologic storage. Approximately 5,300 miles of CO_2 pipelines are in operation today within 13 states, and about 90% of this infrastructure supports the EOR industry. [5] In 2019, over 20 million metric tons (MT) of CO_2 were captured from industrial sources for supply into the economy, of which approximately 15 million MT of CO_2 were supplied for enhanced oil recovery. This is only a portion of the total amount of CO_2 that is supplied for enhanced oil recovery operations which totaled to approximately 52 million MT in 2019. Experience in geologic storage has been built over decades through the DOE R&D programs such as in Decatur, Illinois where more than 2 million MT of CO_2 have been injected and stored since 2017. [6] Looking to the future, the 2022 Strategic Vision developed by the U.S. Department of Energy's (DOE's) Office of Fossil Energy and Carbon Management (FECM) sets a steep trajectory for additional commercial CO_2 storage capacity over the next few decades based on the Princeton Net Zero America studies: from 2,000 million MT storage capacity by 2030, 7,500 million MT storage capacity by 2035, and 13,000 million MT storage capacity by 2040 (Figure 1). The studies additionally projected new or converted pipelines must expand to an estimated 11,800+ miles by 2030 and 65,800+ miles by 2050 to accommodate stated storage capacities. [7]

Compared to other CO_2 transport systems, pipelines typically offer greater economies of scale. However, infrastructure to transport and store smaller volumes of CO_2 by truck, rail, barge, or ship may be developed to capture CO_2 and transport it in regions where pipeline construction is not possible or to manage smaller CO_2 capture volumes where pipeline construction is not economical. Alternative modes of CO_2 transport may also support early CCUS adopters due to the time required to secure permits and construct pipelines.

The Pipeline and Hazardous Materials Safety Administration (PHMSA) within the Department of Transportation (DOT) develops and enforces regulations for the safe, reliable, and environmentally sound operation of the nation's 3.3 million-mile pipeline infrastructure network, including CO_2 pipelines. [8] CO_2 pipeline operations have a strong safety record, with no attributed fatalities since large-scale transport began in 1972. PHMSA records[9] from the period of 2003 to 2022 document 102 reported accidents and one in-patient hospitalization for the approximately 5,300 miles of CO_2 pipeline in the U.S. As a basis of comparison, during this same time period, there were 2,299 reported incidents resulting in 38 fatalities and 158 in-patient hospitalizations for the approximately 300,000 miles of natural gas transmission pipelines in the U.S.

		5 Year Goal 2030 ACTIVATION	10 Year Goal 2035 EXPANSION	15 Year Goal 2040 AT SCALE
Carbon-SAFE	Commercial Storage Capacity	2,000 Million MT over 30 years	7,500 Million MT over 30 years	13,500 Million MT over 30 years
	Injectivity	Injection of 65 Million MT/yr	Injection of 250 Million MT/yr	Injection of 450 Million MT/yr
Contingent Storage Resource		Identify 5,500 Million MT	Identify 6,000 Million MT	Identify 7,500 Million MT
Repurposing Storage Infrastructure		FEED studies for repurposing onshore and offshore infrastructure (depleted oil/gas fields, wells, pipelines, etc.)		
CO_2 Transport Infrastructure		Support design studies of regional infrastructure; feasibility studies of national network	Support pre-FEED studies of trunk lines to interconnect regional hubs	Support development of trunk lines and feeder lines
Advanced R&D		Develop tools for basin-scale management of storage resources Develop and deploy tools to reduce cost, risk and uncertainty in storage projects Establish CarbonSTORE facilities in multiple different geologic settings Integration of Science-informed Machine learning to Accelerate Real Time decisions for Carbon Storage (SMART-CS) and National Risk Assessment Partnership (NRAP) tools into commercial storage applications		
Crosscutting Synergies		Develop programs to provide technical assistance and make information readily available to agencies and stakeholders		

Figure replicated with permission from the 2022 FECM Strategic Vision. (FEED refers to Front-End Engineering Design).

Figure 1. Strategies and research priorities to support CO_2 storage and transport infrastructure.

The definition for reportable incidents and accidents is codified in Title 49 of the Code of Federal Regulations (CFR) Parts 191[10] and 195. [11] Following investigation of a CO_2 pipeline failure in Satartia, Mississippi in 2020, PHMSA announced new safety measures for CO_2 pipelines in May 2022. [12] DOE FECM continues to work in partnership across all government, including with DOT PHMSA and other federal agencies, in support of these safety measures. [13]

Several cross-sector research, development, and demonstration (RD&D) efforts for CO_2 transport are already in progress, and there is potential overlap among these initiatives. A coordinated approach among domestic and international initiatives can support the prioritization of research activities and avoid unnecessary duplication. The pace of these activities should also be accelerated to match the pace of CO_2 transport systems that are currently in development. Capturing lessons learned from CO_2 pipeline systems currently in operation may provide additional data for future modeling efforts and enable refinement of potential RD&D objectives.

Based on workshop findings, future RD&D activities should consider areas of interest including 1) further reducing the risk of pipeline corrosion, fracture, and potential failure; 2) improving monitoring technologies and emergency protocols to proactively address pipeline integrity challenges; and 3) developing tools, metering, and intermodal designs to enable multimodal transport of CO_2. The insights gained can further inform industry standards and best practices as well as the development of supporting regulations when necessary.

The role of CO_2 transport should also be considered in the context of DOE FECM's broad strategic portfolio to ensure optimal integration with other large-scale DOE initiatives, such as H2@Scale. [14] From an economic standpoint, strategies pursued should maximize benefits in the form of a robust CO_2 transport and storage industry offering high-paying jobs that are accessible to all communities. Integrating life cycle analyses (LCAs) with techno-economic analyses (TEAs) will support the optimization of community, environmental, and economic benefits. A coordinated and proactive two-way communications initiative to engage the public will be fundamental to investigating and addressing public concerns related to carbon transport technology, its ongoing development, and its future deployment.

The 2021 Bipartisan Infrastructure Law (BIL) and 2022 Inflation Reduction Act fund and incentivize the build out of the CCUS value chain with select funding opportunities administered through DOE FECM. [15] To meet DOE FECM decarbonization targets, extensive engagement and discussion is needed across stakeholders to accelerate carbon transport deployment and effectiveness. This DOE FECM-hosted workshop brought together diverse stakeholders to 1) listen and capture a broad range of input and perspectives; 2) identify applied RD&D areas of interest in CO_2 transport; and 3) identify whether a CO_2 transport research consortium would advance CCUS technology development, deployment, and overall success. Workshop discussions uncovered areas of interest that may lead to the removal of technical barriers but did not lead to specific recommendations for DOE FECM.

Workshop Objectives

In line with the goal of broad stakeholder engagement and its 2022 Strategic Vision, [16] DOE FECM hosted a Workshop for Applied Research in CO_2 Transport[17] from February 21-22, 2023. (The workshop's initial name — "Roadmap for CO_2 Transport Fundamental Research" — was changed after the meeting). Approximately 100 individuals from federal agencies, industry, academia, nongovernmental organizations (NGOs), national laboratories, and other stakeholders gathered in Dublin, Ohio to share individual perspectives and input with regards to the following objectives:

- Identify near-term challenges and RD&D areas of interest;
- Identify lab- and pilot-scale research areas of interest;
- Identify potential participants in ongoing and future RD&D efforts; and
- Identify whether a CO_2 transport research consortium would advance CCUS deployment and potential barriers to future success.

The workshop agenda (Appendix A) outlines the meeting sessions. These sessions were derived by reviewing and organizing carbon transport challenges previously identified in published strategic reports. The session topics were established for the purpose of workshop organization and provided a basis for individual idea generation and comment but do not represent an all-encompassing list. Each session included presentations from an expert panel. Except for the first session (during which representatives from DOE FECM, labor, industry, and academia offered their perspectives to set the stage for future workshop topics), expert presentations were followed by attendee discussion during which individuals shared perspectives. Through articulation of individuals' perspectives, all sessions identified technical and non-technical challenges and barriers that, if removed, would advance emission reduction goals. In the second session, representatives of ongoing initiatives presented partnership objectives and project status updates. Subsequent sessions addressed four RD&D topics:

1) Impact of CO_2 impurities on asset integrity;
2) CO_2-specific leak detection and emergency response protocols;
3) Repurposing of existing infrastructure for CO_2 service; and
4) Developing and connecting with other modes of CO_2 transport/intermodal hubs.

Following the presentation of ongoing initiatives and each RD&D topic, workshop participants — who were seated at tables of 10 — discussed a series of prepared questions that were circulated prior to the workshop. Questions for the Ongoing Initiatives Session (Appendix B) differed from those asked for sessions addressing Topics 1-4 (Appendix C). Selected speakers from corresponding sessions served as moderators and floated among tables to guide conversation. During discussion, one or more individuals per table submitted anonymous high-level feedback through Mentimeter interactive software[18] (Appendix D). Discussion periods for Topics 1-4 concluded with two-minute verbal reports from each workshop table; one individual per table was nominated to summarize table discussion of individual perspectives. Session moderators met separately with conveners to identify and compile common themes from each topic. Whole-meeting input on the draft areas of interest, organized by topic, was elicited by moderators (Appendix E) during a final discussion session.

This workshop captured the wide-ranging breadth and depth of participants' perspectives regarding different areas of interest for applied research in CO_2 transport over the next five years. A five-year outlook was chosen as a reasonable period to possibly initiate future RD&D programs to address areas of interest identified during the workshop. A summary of each topic is presented later in this document, with draft actions summarized in Figures 3-6. Organizations listed as potential leads were suggested by workshop participants; leading and participating parties may evolve as efforts are refined. Findings will support the development of a future CO_2 transport roadmap.

On February 23, 2023, workshop attendees had the option to tour the Det Norske Veritas (DNV) Laboratory in Dublin, Ohio and the Institute for Corrosion and Multiphase Technology (ICMT) in Athens, Ohio. Facility tours covered research, testing, and analytical capabilities.

Key Takeaways

After considering all individual perspectives, DOE FECM identified the following five key takeaways from the meeting. Topic-specific insights are presented in the subsequent subsections.

KEY TAKEAWAY #1

Develop a CO_2 Transport Consortium to coordinate RD&D efforts and facilitate communication among stakeholders.

Deploying CO_2 infrastructure at scale will require cross-sector coordination. DOE FECM was encouraged to support formation of a consortium and to coordinate supporting activities with other federal agencies. The consortium should include a range of organizations not limited to:

- Federal agencies (e.g., DOE FECM, DOT, Department of the Interior, Environmental Protection Agency (EPA), Occupational Safety and Health Administration)
- State agencies (e.g., public utility commissions, departments of natural resources, environmental agencies, departments of transportation)
- National laboratories
- Academia
- NGOs
- Standards bodies (e.g., Association for Materials Protection and Performance, American Society of Mechanical Engineers, American Petroleum Institute (API), Process Industry Practices, International Organization for Standardization)
- Industry owners and facility operators
- Service providers and equipment vendors
- Trade associations
- Manufacturing entities (e.g., pipe fabricators)
- Labor unions
- International entities

KEY TAKEAWAY #2

Compile and curate information in an open access platform to facilitate gap analyses.

A large body of CO_2 transport data, models, and industry knowledge already exists. Several ongoing Joint Industry Partnerships (JIPs) and other initiatives are conducting literature reviews and technical gap analyses with complementary objectives. The facilitation of an open-access central platform to organize existing information and share new information will enable efficient use of resources and avoid unnecessary duplication of efforts. For example, DOE's Energy Data eXchange (EDX) platform[19] offers a public forum for compiling, curating, and analyzing information and may be suitable for future use.

KEY TAKEAWAY #3

Accelerate experimental and modeling RD&D efforts to keep pace with the timeline for CO_2 transport demonstration projects and at-scale deployment.

Global deployment of CCUS infrastructure falls significantly short of targets recommended by modeled strategies to restrict warming to important climate thresholds. [3] Achieving a net-zero carbon U.S. economy by 2050 necessitates rapid construction of CO_2 transport infrastructure over the next two-and-a-half decades. [16] Deployment strategies should be supported by LCA and TEA, compatible with the entire CCUS infrastructure value chain, and optimally aligned with other national decarbonization strategies. The integration of experimental and modeling efforts that capture evolving streams of CO_2

quality and transportation modes will close potential RD&D gaps and inform design standards and best practices. RD&D efforts should track the pace of demonstration projects and subsequent at-scale infrastructure build out.

KEY TAKEAWAY #4

Create pathways to engage and grow the workforce in an equitable, inclusive, and accessible manner.

Building an extensive CO_2 transport network will require a large workforce. Recruitment and training initiatives should consider the needs and opportunities across local to national scales. To meet the future skilled labor demand, it is imperative that training and work opportunities are accessible and welcoming to all potential participants.

KEY TAKEAWAY #5

Engage the public in two-way communication.

Educational materials and a two-way communications plan should be developed and implemented to promote public awareness and provide venues for robust community consultation and engagement. Effective public engagement is the responsibility of all future consortium parties and will require constructive coordination (see Key Takeaway 1 for potential parties). Future communication efforts may leverage and build upon existing resources, including those from industry (e.g., API's recommended practice 1185 titled "Advancing Stakeholder Engagement through Two-Way Communication" and FECM's Societal Considerations and Impacts materials[20]).

RD&D Opportunities

After considering individually shared perspectives presented during the workshop, DOE FECM identified common themes of feedback and topic-specific RD&D opportunities. Figure 2 presents common workshop themes as a set of foundational RD&D efforts that span engineering and sciences, governance, and project development and operation scenarios. DOE FECM observed that applied RD&D activities in addition to labor and community engagement should progress simultaneously, and a framework supporting knowledge sharing and the concurrent communication of needs across efforts is foundational to carbon transport deployment and emission reduction goals.

Figure 2. CO_2 Transport Workshop RD&D themes over the next five years.

Topic-specific RD&D areas of interest were either shared vocally or through Mentimeter submissions. These RD&D areas of interest are summarized below by topic session and may be repeated across topic areas based on the input received.

Topic #1 RD&D Areas of Interest: Impact of CO_2 Impurities on Asset Integrity

- Relevant existing research and models, as well as lessons learned from industry, should be compiled in a centralized open repository to encourage the sharing of knowledge and best practices.
- CO_2 streams from diverse industry sources and capture technologies will contain varying amounts and types of impurities, including but not limited to H_2O, H_2S, CO, CH_4, O_2, N_2, Ar, H_2, SO_x, and NO_x. Impurities content in these streams should be determined to guide future experimental testing and improve modeling capabilities. Impacts of odorant should also be considered.
- Round-robin experimental testing integrated with modeling is desired to further understand how impurities interact with each other and how they affect various physical phenomena, including phase behavior, flow rates and behavior, heat transfer, corrosion, and material properties and associated material performance. Analogous studies are needed to understand the impact of impurities and other system conditions on non-metallic/polymeric pipeline components. A coherent and comprehensive program is needed to distribute efforts across laboratories according to capabilities and interests.
- Large-scale and long-term testing are needed to validate small-scale laboratory findings.
- An annual forum engaging industry participants will support updating existing standards or creating new standards.
- Supply chain models and constraints for typically selected materials should be considered.

Topic #2 RD&D Areas of Interest: CO_2-Specific Leak Detection and Emergency Response Protocols

- Relevant existing research and models, as well as lessons learned from industry, should be compiled in a centralized open repository.
- Laboratory- to full-scale field tests are needed to update models evaluating the factors that could contribute to increased risk of pipeline fracture during CO_2 transport.
- Deployment of CO_2 infrastructure at scale will require an advanced sensor system with remote, distributed, and real-time monitoring capabilities. Further development of sensing capabilities for small leak detection and impurities is desired. Sensor commercialization and supply chains should be developed in parallel.
- Comprehensive dispersion modeling is needed to understand how CO_2 and impurities will disperse from the point of release and to guide the development of emergency response protocols. Full-scale tests are needed to validate dispersion models.
- Health risks from acute and chronic exposure to a potential CO_2 stream should be further assessed for stakeholders (e.g., emergency responders, repair crews, the public, etc.).
- Best practices for design to prevent and manage leaks and for fracture control should be further developed and refined.

Topic #3 RD&D Areas of Interest: Repurposing of Existing Infrastructure for CO_2 Service

- Coordination with industry is needed to develop a database of repurposed infrastructure for CO_2 transport. Compiled information should include relevant research, models, and lessons learned.
- Whether natural gas pipelines and other systems can be converted for CO_2 transport alone or used for transporting more than one type of fluid depends on materials compatibility, design temperature and pressure, and other factors. Likewise, the compatibility of end-use infrastructure should be evaluated. Gap analyses are needed to catalog common metallic and non-metallic materials used in existing transportation infrastructure and to determine compatibility with CO_2 service. Efforts should consider the re-use of existing offshore platforms.
- Existing systems are currently being repurposed for CO_2 transport. A reference/checklist specifying appropriate materials and required data should be developed for use until existing standards and regulations are updated.
- TEA tools incorporating compression costs, retrofit costs, and risk analyses should be developed. Tools may guide when to prioritize retrofit of natural gas pipelines for CO_2 service or blended hydrogen (H_2) service.

Topic #4 RD&D Areas of Interest: Developing and Connecting with Other Modes of CO_2 Transport/Intermodal Hubs

- TEA tools incorporating LCA and risk are needed to address optimal integration of CO_2 transport modes with other decarbonization strategies across scales. Tools should also consider source and sink usage patterns and the potential for intermittent operations.
- Costs and project timelines for offshore CO_2 infrastructure should be refined.
- When pipeline construction is not economical or practical, infrastructure to enable CO_2 transport by truck, rail, barge, or ship should be evaluated as alternatives.
- Developing and certifying intermodal carriers compatible with transportation by truck, rail, barge, and/or ship can facilitate system integration.
- Accurate processes and equipment to meter CO_2 are needed for carbon accounting and monitoring, reporting, and verification purposes.

Workshop Review

The following content presents DOE FECM's summary of the individual perspectives provided during the sessions. RD&D areas of interest are further refined into draft action plans by topic session to logically sequence potential future efforts. Note, draft action plans are nonbinding but provide a basis for knowledge sharing and future consideration.

Ongoing Initiatives

Session presentations reviewed the objectives and status of four CO_2 transport partnerships described below. Complementary objectives among these projects present opportunities for future knowledge sharing and create a strong foundation for future RD&D efforts. [21,22]

Pipeline Research Council International (PRCI): The PRCI CO_2 Taskforce was formed in April 2022 by Shell, Williams Companies, API, and ExxonMobil to support research and technology challenges towards meeting the 2050 net-zero target. After its formation, the CO_2 Taskforce funded the CO_2 Pipeline Transportation State of the Art Review, Gap Analysis, and Future Roadmap (ALT-1-6) project.

CSM-Rina has been contracted to map current CO_2 projects worldwide and conduct a literature review and gap analysis of existing information regarding pipeline corrosion, fracture, safety/dispersion, and re-purposing. Products will be delivered between March and August of 2023 and will include: 1) a map of CO_2 pipelines; 2) a literature review; 3) a gap analysis; 4) a roadmap to address experimental and analytical gaps; and 5) a final report. Progress and findings will be presented at PRCI symposia in March and June of 2023.

Corrosion in CO_2 Transmission Pipelines (CCT) JIP: Initiated in January 2023, the CCT JIP led by Ohio University's ICMT is currently sponsored by ten industry partners. The JIP has funding through December 2025 to:

1. Understand the effect of a wide range of impurities (O_2, SO_2, NO_2, H_2S, etc.) in the presence of water on the physical properties of dense phase[*] CO_2 streams;
2. Develop a thermodynamic model for predicting water solubility in the presence of impurities in dense phase CO_2 streams;
3. Determine the impact of environmental parameters (pressure, temperature, flow, and impurity types and concentrations) individually and synergistically on steel corrosion in dense phase CO_2 in the presence of impurities; and
4. Develop a mechanistic model to predict corrosion processes to estimate facility lifetime.

JIP experimental capabilities (glass cell, autoclave, and flow loop experiments) will enable thermodynamic and long-term corrosion studies which will guide corrosion modeling. Future steps will address corrosion mitigation, the effect of other impurities and low temperature, and the effect of upset conditions towards establishing safe CO_2 specifications.

CO_2 Safe and Sour JIP: The DNV-led CO_2 Safe and Sour JIP was formed in March 2022 with work to conclude in the summer of 2024. The JIP is updating the recommended practice DNV-RP-F104 "Design and operation of carbon dioxide pipelines" which defines the allowable concentration of H_2S in CO_2

[*] Dense phase CO_2 refers to CO_2 at conditions above its critical pressure.

pipelines. This recommended practice was not created for CCUS pipeline applications where the comingling of impurities and significantly higher levels of H_2S are anticipated. Determining the extent to which H_2S service design and restrictions are applicable to CCUS and can be potentially adjusted to meet current and future CCUS demand may increase industry eligibility for participation in the emerging industry.

The project is progressing in two phases supported by various industry partners. The first phase will: 1) generate a roadmap report detailing background information (e.g., H_2S integrity risks, relevant standards, pipeline environment) and guiding experimentation rational; 2) define the new H_2S limit with water present to avoid sulfide stress cracking; 3) determine if corrosion rates within the increased H_2S limit are acceptable; and 4) evaluate the cost of H_2S removal from CO_2 streams. The second project phase will examine the effect of other impurities and upset conditions on sulfide stress cracking. Results will be used to update DNV-RP-F104 and guide specifications for the European-based Northern Lights pipeline project. [23]

BMT Global-DOT PHMSA, Developing Design and Welding Requirements Including Material Testing and Qualification of New and Existing Pipelines for Transporting CO_2: This PHMSA research contract broadly seeks to evaluate and, as appropriate, strengthen safety regulations for low-pressure gas or high-pressure dense phase CO_2 pipelines. Project activities began in 2022 and will carry through 2024. Tasks are as follows:

1) Review the current state of knowledge of pipeline design, construction, maintenance, integrity, and operations with a focus on the difference between conventional oil and gas pipelines and CO_2 pipelines.
2) Conduct a layer of protection analysis and deliver a report evaluating the range of CO_2 pipelines considered to date, the strength of the technical basis for each hazard control, knowledge gaps and challenges, and future recommended research or concept demonstration projects.
3) Demonstrate materials properties and performance under operational conditions that contribute to hazards during blowdown or failure events. Identify techniques and recommendations suitable for pipeline design, maintenance, and operation to mitigate hazards as well as remaining gaps. Studies will address: long running fracture control, release event cooling and associated CO_2 equations of state, CO_2 dispersion during release events, performance of non-metallic materials, leak detection, and CO_2 odorization.

Topic 1 Summary: Impact of CO_2 Impurities on Asset Integrity

The existing U.S. network of CO_2 pipelines, primarily used for EOR, is regulated by PHMSA. These pipelines transport high purity CO_2 with a low tolerance for impurities including water, the presence of which promotes corrosion. However, CO_2 transport for CCUS will lead to the comingling of CO_2 streams from industrial processes, power generation sources, other industrial sources, and DAC Hubs. These CO_2 streams are likely to contain varying types and concentrations of impurities, including H_2O, H_2S, CO, CH_4, O_2, N_2, Ar, H_2, SO_x, NO_x, and others. These impurities can act individually and synergistically to undermine the integrity of both metallic and nonmetallic pipeline materials. For example, impurities impact water solubility. When water and impurities are present within the CO_2 stream, there is an increased risk of integrity threats (e.g., corrosion and sulfide stress cracking). Polymeric materials (e.g., elastomers or plastics for gaskets and other components) may be highly permeable to CO_2 itself and are subject to other forms of degradation and failure (e.g., swelling). Potential odorants added to CO_2 streams may also behave similar to an impurity component and further interact with system factors to affect materials performance requirements.

A better understanding of integrity threats and their evolution over temporal periods corresponding to pipeline operational lifetime (i.e., decades) is needed to guide materials selection, standards, and regulations for pipeline construction. Specifically, experimental and modeling approaches are needed to clarify how and which concentrations of impurities impact pipeline integrity across a wide range of operating conditions. Studies should also consider the performance of potentially more durable alloys and polymers with results guiding future supply chain analyses. Going forward, a program to coordinate round-robin materials testing among existing and new research facilities is needed. These efforts should be closely coordinated with complementary fluid characterization, transport, and corrosion modeling research.

Meeting discussion and individual perspectives centered on 1) compiling and efficiently leveraging existing information to identify gaps; 2) ramping up the number of laboratories supporting materials testing and modeling and ensuring coordination among these efforts; and 3) scaling up the size and duration of tests. Results, paired with supply chain models, will inform materials standards for pipeline construction. An annual forum engaging domestic and international industry standards participants will further support standards development and utilization. Figure 3 reflects the timeline for draft RD&D activities estimated by DOE FECM after considering individual perspectives.

Participants also emphasized the importance of bounding future test and model parameters, especially those related to impurities, to applicable operating conditions. Defining the types and levels of impurities in CO_2 streams from major industry sources and DAC Hubs will be an important prelude to strategically focusing limited research capacity. The order in which different types of industries connect to CO_2 pipelines will likely correlate with the difficulty in dehydrating (drying) and separating impurities from CO_2 feed streams. Industry sources related to natural gas, ethanol, and ammonia processing will likely be the first to connect to CO_2 transport pipelines. These sources generate CO_2 streams that may only require drying due to the relative high purity of the CO_2 they produce. Expanded industrial sources of captured CO_2 may require additional purification and drying processing due to the production of CO_2 with higher impurity content. Thus, CO_2 transport technical challenges related to typical product quality specifications, such as water content specification (i.e., dryness), should be addressed in the near term. Broader product quality specifications incorporating wider ranges of impurities and synergistic behavior challenges originating from more diverse capture sources should be addressed in the longer term.

Topic 1: Impact of CO_2 Impurities on Asset Integrity

Year 1

Consolidate existing research to an open repository for CO_2 transport R&D data and models in EDX.
(Led by DOE, DOT, and the consortium)

- Compile existing materials performance/corrosion data and models, including from ongoing efforts and EOR research. Conduct literature surveys/gap analyses as needed.
- Engage pipeline owners and operators to leverage lessons learned from materials degradation to inform LCA and TEA.
- Survey impurity levels in CO_2 streams from different industries and capture technologies to guide future experiments.
- Create a centralized list of laboratories and research capabilities to develop an integrated testing and modeling ecosystem.
- Request relevant available data be shared with industry standards bodies.

Create a testing protocol to complement ongoing work and coordinate experimental and modeling efforts.
(Led by national laboratories and the consortium)

- Assess the impact of impurities, including potential odorant additives, on the performance of metallic and nonmetallic materials. Bound impurity levels using EDX data on impurity concentrations in industry and capture technology streams (e.g, 10% impurities/90% CO_2 per Title 49 CFR Part 195.2). Incorporate effects of temperature, pressure, CO_2 flow rate, and other system considerations. Characterize CO_2 fluid properties and behaviors that support the prediction of conditions resulting in corrosion, fracture control, and other modes of failure.
- Conduct tests in pre-corroded pipe systems and old service pipe.
- Conduct performance tests with new steel alloys and polymers in the presence of impurities.
- Use results to determine acceptable levels of impurities. Determine impurity thresholds that are compatible with the properties and performance of other CO_2 transportation and storage

Years 2-3

Conduct longer-term testing to evaluate the impact of impurities at pilot scale.
(Led by the consortium)

- Consider creation of a National Test Loop Center similar to the National Carbon Capture Center.
- Interface with industry standards bodies to map work for standards development.

Hold an annual forum with industry standards participants and leverage international efforts.
(Led by the consortium)

Identify supply chain models and constraints for required construction materials.
(Led by the consortium)

Years 4-5

Continue longer-term testing to measure the impact of impurities.
(Led by the consortium)

Propagate consortium research into new standards or modify existing standards.
(Led by standards organizations)

Figure 3. Draft actions for Topic 1 areas of interest.

Topic 2 Summary: CO_2-Specific Leak Detection and Emergency Response Protocols

The footprint of today's 5,300-mile CO_2 pipeline network is anticipated to expand rapidly over the next two decades to meet emission reduction targets. The continued safe deployment and operation of CO_2 pipeline infrastructure at even larger scales requires: 1) understanding factors contributing to pipeline leaks and fracture to inform materials design standards and regulations directing pipeline design, construction, and operation; 2) advancing the capabilities of monitoring technology; and 3) developing robust emergency response protocols.

CO_2 pipelines are typically constructed to operate at pressures around 1,450 to 2,175 pounds per square inch and 60 to 85 degrees Fahrenheit during normal operations. [24] Under these conditions, CO_2 generally remains in the dense phase. However, typical operating pressures and temperatures vary along the transport system and for different modes of operations, leading to the presence of various phases of CO_2. For example, during standard operations that reduce pipeline pressure (e.g., blowdown) or when there is a leak, the decompression of CO_2 to atmospheric pressure causes a rapid drop in fluid temperature due to Joule-Thompson expansion effects and fluid phase change from liquid to vapor. Low temperatures and associated pressure-temperature cycling of the system can cause asset integrity challenges for both nonmetallic and metallic components, including but not limited to brittle fracture, ductile fracture, and a general degradation in material performance properties. Materials need to be suitable for the wide range of temperatures and pressures, the associated rate of change of conditions during transient operations, and impurities encountered throughout operations.

Models describing materials performance properties and fracture propagation (Battelle Two-Curve Method, BTCM) are well characterized for natural gas pipelines. Limited data from CO_2 pipelines indicate different system properties and the need for model correction factors. Large-scale field tests are needed to validate updated models generated in a laboratory setting with small physical specimens. Once developed, models can inform methods to prevent and arrest fractures, including the addition of crack arrestors (rings which encircle and reinforce pipelines at regular intervals). Findings may prevent overly conservative design and thus reduce the cost of asset integrity management.

Structural monitoring and leak detection, especially detection of small leaks, can present costly challenges to pipeline companies. As described during the workshop, current monitoring practices, such as those employed by natural gas companies, are complex and time and labor intensive. Deployment of CO_2 infrastructure at scale will require an advanced sensor system with remote, distributed, and real-time monitoring capabilities. Integration of continuous monitoring data with artificial intelligence (AI) methods can further improve the reliability, safety, and operational efficiency of CO_2 pipelines. Pipeline sensor technologies currently being advanced include distributed optical fiber sensors, passive wireless sensors, and advanced electrochemical sensors. As a suite, these technologies complement each other's functions (detection of temperature, pressure, flow rate, pipe strain, gas chemistry, humidity, corrosion onset and rate of progression, vibration/seismic events, etc.) and geospatial sensing ranges. As noted during the workshop, sensor costs range from moderate to low. AI can be trained to recognize patterns in monitoring data to anticipate and identify adverse events (deformation, corrosion, leak, fire, etc.) and rapidly target resources to the affected location.

In addition to monitoring technology, assessment tools are needed to anticipate the consequences of accidental CO_2 dispersion from high-pressure pipelines and determine the potential impact radius. Such tools can guide development of emergency response and public evacuation plans. CO_2 is heavier than air, and it is important to understand circumstances that could lead to asphyxiation due to oxygen displacement by released CO_2. Modeling the release and dispersion of CO_2 from a high-pressure pipeline, however, is complex; pipeline attributes, operating pressure, local terrain, and weather, among other factors, can affect CO_2 dispersion. Computational fluid dynamics models predicting the dispersion behavior of CO_2 are under development and can be paired with experimental data to generate a database of outcomes under different dispersion scenarios. Machine learning (ML) can assist in understanding public health risks and provide guidance for CO_2 release in varying consequence areas based on population and other environmental factors. Full-scale experiments are important for the development and validation of such predictive tools.

Meeting discussion and individual perspectives focused on 1) compiling and efficiently leveraging existing information; 2) gathering data needed to revise the BTCM; 3) advancing sensor technologies specific to CO_2 service; 4) advancing CO_2 dispersion modeling capabilities to inform emergency responses; 5) expanding understanding of CO_2 exposure health risks; and 6) leveraging existing organizational models for pipeline safety (e.g., the Center for Hydrogen Safety, the National Center of Excellence for Liquified Natural Gas (LNG) Safety) as templates for founding a Center for CO_2 Safety. Figure 4 reflects the timeline for draft RD&D activities estimated by DOE FECM after considering individual perspectives.

Topic 2: CO_2-Specific Leak Detection and Emergency Response Protocols

Year 1

Consolidate existing research to an open repository for CO_2 transport R&D data and models in EDX.
(Led by DOE and the consortium)

- Compile existing information for pipeline fracture/failure; pipeline sensors; and CO_2 dispersion data and models, including from ongoing efforts. Conduct literature surveys/gap analyses as needed.

Develop sensing capabilities for impurities and small leak detection. Continuously monitor performance and integrate data with ongoing modeling efforts.
(Led by national laboratories and the consortium)

- Consider sensor interaction with integrity management system (e.g., cathodic protection).

Generate additional experimental data across scales to revise the BTCM for fracture propagation and inform other relevant models with consideration given to the impact of impurities.
(Led by research institutions)

Determine human exposure risk to CO_2 with impurities (e.g., first responders, repair crews, and the public).
(Led by the consortium)

- Leverage knowledge from existing hazardous materials frameworks for managing emergency response, containment and clean-up, and public safety.

Use existing organizational models for CO_2 Safety (e.g., Center for Hydrogen Safety and National Center of Excellence for LNG Safety).
(Led by the consortium)

Years 2-3

Continue the development of sensor technologies to detect impurities and small leaks.
(Led by the consortium)

- Consider threat detection capabilities by evaluating dispersion modeling, risk, and impact.
- Update best practices for implementing detection technologies.

Utilize the revised BTCM and other models for modifying or creating new standards for fracture control.
(Led by standards organizations)

Use dispersion modeling and ML to generate recommendations for varying areas of concern and emergency response in case of a CO_2 release event. *(Led by the consortium framework)*

Years 4-5

Advance commercialization and strengthen supply chains for sensor development.
(Led by the consortium and industry)

- Engage industry with lead time for development.

Refine dispersion modeling and ML to generate recommendations for varying areas of concern and emergency response in case of a CO_2 release event.
(Led by the consortium)

Figure 4. Draft actions for Topic 2 areas of interest.

Topic 3 Summary: Repurposing of Existing Infrastructure for CO_2 Service

Repurposing existing infrastructure for CO_2 service requires 1) determining whether systems designed for transporting other products are compatible with CO_2 service; and 2) completing LCAs and TEAs to optimize the economic, environmental, and societal returns of repurposing activities in the context of other national decarbonization strategies. Ultimately, repurposing infrastructure will likely occur on a case-by-case and asset-by-asset basis. Standards and regulations for transporting gaseous and liquid CO_2 and for repurposing existing infrastructure for CO_2 service need to be developed.

Existing natural gas pipelines in the U.S. have the potential to be repurposed for H_2, CO_2, and ammonia transportation. Associated infrastructure (liquefication equipment, storage tanks, vaporizers, etc.) for LNG, liquified petroleum gas, and ammonia may also be modified to support CO_2 transportation. Whether systems can be converted for CO_2 transport alone or used for more than one type of fluid depends on materials compatibility, design temperature and pressure, and other factors. For example, flow meters designed for natural gas may not accurately track CO_2 flow, and several steel grades and non-ferrous metal types present in compressor stations for other service grades are not suitable for CO_2 service. Furthermore, using the same infrastructure to transport more than one type of product will lead to new profiles of intermingled impurities. Similar to Topic 2, corrosion, calibration of the BTCM for fracture arrest, and testing materials (both metallic and non-metallic) at different scales were discussed. Precise material information is important for designing experiments to test materials performance. However, obtaining this information from manufacturers can be difficult. Characterizing the performance of new alloys and polymers is as important as assessing the properties of vintage lines, which may have changed ownership multiple times and have limited available records.

LCA and TEA tools for CO_2 transport infrastructure should integrate with other national decarbonization strategies, such as H2@Scale. For instance, there is an opportunity to use both H_2 and CO_2 in the production and delivery of synthetic fuels for transportation. Current H_2 models assess costs of the H2@Scale strategy by region, materials, labor, and other parameters, and these models may be adapted for CO_2 service. Specifically, tools integrating the costs and risks of retrofitting existing infrastructure for CO_2 service or pursuing other strategies (e.g., flowing blended natural gas with H_2) will aid in identification of scenarios where retrofitting is beneficial from economic, environmental, and societal vantage points.

Meeting discussion and individual perspectives (Figure 5) addressed: 1) compiling and efficiently leveraging existing information, especially component materials and lessons learned from industry; 2) creating a checklist of considerations to guide repurposing infrastructure while formal regulations and standards are developed; 3) generating data needed to revise the BTCM; 4) developing LCA and TEA tools; and 5) conducting gap analyses and related RD&D to address materials standards. Figure 5 reflects the timeline for draft RD&D activities estimated by DOE FECM after considering individual perspectives.

Topic 3: Repurposing of Existing Infrastructure for CO_2 service

Year 1

Consolidate existing research to an open repository for CO_2 transport R&D data and models in EDX.
(Led by DOE, the consortium, and international entities)

- Coordinate with industry to develop a database of repurposed infrastructure for CO_2 transport, including methods used, lessons learned, etc.

Create a reference, guidance, and/or checklist for materials for repurposing infrastructure.
(Led by research institutions)

Continue development of regulations for CO_2 transport, including gas phase and other transport modes.
(Led by federal agencies)

Develop new dynamic material fracture resistance testing for the BTCM. Conduct high-energy full-scale testing to validate findings from small-scale testing.
(Led by the consortium)

Consider the reuse of existing offshore platforms.
(Led by the consortium and partners)

Years 2-3

Develop TEA tools.
(Led by national laboratories and the consortium)

- Tools should incorporate compression costs (gas/liquid phase); retrofit costs; and risk analyses.
- Approaches may include updating existing TEA models with industry data.
- Develop a decision tree to guide when to prioritize the retrofitting of natural gas pipelines for blended H_2 or for CO_2 service.

Perform a gap analysis of common metallic and non-metallic materials used in existing transportation infrastructure. Determine acceptability of materials for CO_2 service and/or recommend testing necessary to verify compatibility with CO_2 service.
(Led by the consortium)

Years 4-5

Share lessons learned from retrofit and repurposing activities.
(Led by industry)

Amend existing standards for testing criteria to qualify materials for CO_2 service.
(Led by standards organizations)

Figure 5. Draft actions for Topic 3 areas of interest.

Topic 4 Summary: Developing and Connecting with other Modes of CO_2 Transport/Intermodal Hubs

Optimally integrating CO_2 transport infrastructure with national decarbonization strategies will require assessing risks and costs across systems and scales. Studies have projected the need for CO_2 infrastructure under several future scenarios (e.g., limited availability of technologies to support geological storage of CO_2 and variable costs for natural gas) while accounting for energy use patterns and periods of peak energy demand. Insights offered by these scenarios can guide strategies for 1) when and where building CO_2 pipelines, or 2) retrofitting existing infrastructure, makes economic and environmental sense versus transporting CO_2 by other modes (e.g., truck, rail, barge, or ship).

Although pipelines present an economical solution for transporting large quantities of CO_2, the current U.S. CO_2 pipeline network is limited in size and is not yet connected to many sources. Building pipelines in some areas, such as major metropolitan centers or conserved lands, may be met with societal and environmental concern. In addition, there are many U.S. sources that produce small amounts of CO_2 at the individual level (<100,000 MT of CO_2/year) but collectively produce approximately 128 million MT of CO_2/year. Building pipelines to transport small CO_2 amounts may not be economically viable, yet capturing the net CO_2 produced by these sources is environmentally important and aligned with U.S. long-term decarbonization goals. When building pipelines for small sources is too costly, smaller companies are unable to take advantage of the 45Q tax credit for CCUS (or CDR), placing them at a financial disadvantage relative to larger companies. In these instances, transport of CO_2 by truck, rail, barge, or ship may offer a solution and be particularly important for early CCUS adopters. Enabling these transportation capabilities will require development of alternative infrastructure (intermodal containers, storage facilities, liquefaction and reconditioning equipment, marine terminals, etc.). Developing alternative materials for storage containers, such as fiber-reinforced polymer for dense phase CO_2, may aid in bridging container and pipeline transport and potentially reduce transportation costs.

Meeting discussion and individual perspectives focused on 1) development of TEA and LCA tools across scales and systems; 2) review and refinement of welding methods for CO_2 service; 3) RD&D to support development of intermodal CO_2 carriers compatible with transportation via truck, rail, barge, or ship; and 4) RD&D to improve metering of CO_2 for monitoring, reporting, and verification purposes to accurately track CO_2 storage levels. Figure 6 reflects the timeline for draft RD&D activities estimated by DOE FECM after considering individual perspectives.

Topic 4: Developing and Connecting with Other Modes of CO_2 Transport/ Intermodal Hubs

Year 1

Develop TEA tools.
(Led by national laboratories and the consortium)

- Incorporate LCA and risk analyses.
- Address optimization within and across systems at a national level and finer levels of granularity throughout the entire decarbonization value chain.
- Consider CO_2 end use requirements and the required pressure and temperature at the end use location. Consider source and sink usage patterns and potential for intermittent operations.
- Identify where building pipeline versus investing in other modes of CO_2 transport (rail, truck, barge, or ship) offers the greatest environmental, economic, and social benefits.

Refine cost estimates and project timelines for offshore CO_2 transport infrastructure.
(Led by the consortium)

Evaluate the economic feasibility and U.S.-specific use cases of the design of CO_2 ships and barges.
(Led by the consortium and classification partners)

- Leverage related international work (e.g., projects in Japan, Netherlands, and Norway).

Years 2-3

Conduct R&D necessary to support the design and inspection of intermodal CO_2 carriers compatible with transportation by truck, rail, and/or ship.
(Led by the consortium)

- Consider the development and certification of fiberglass reinforced plastic tanks.

Improve metering of CO_2 for monitoring, reporting, and verification.
(Led by the consortium)

Years 4-5

Future steps to be determined by the consortium.

Figure 6. Draft actions for Topic 4 areas of interest.

Conclusions and Next Steps

Overcoming RD&D, economic, and public acceptance barriers to deploying CO_2 transport infrastructure at scale will require coordination among diverse stakeholders to deliver RD&D solutions, a trained workforce, and effective two-way public communication and community engagement. DOE FECM was strongly encouraged by participants to support formation of a consortium to focus and share research and accelerate the development of transport infrastructure. DOE FECM and other agencies are also encouraged to coordinate efforts and consider the recommended RD&D actions across topics as part of future research and road-mapping activities. Several funding mechanisms are available to support RD&D efforts for the development of CO_2 transport infrastructure. Examples follow:

- **DOE FECM Cooperative Agreements advertised through Funding Opportunity Announcements (FOAs)** enable transfer of DOE FECM funds to grant recipients. The Carbon Capture Technology Program, FEED for CO_2 Transport (DE-FOA-0002730) is an example FOA funded by the BIL. [25] DOE FECM has also posted a Notice of Intent to issue an FOA (DE-FOA-0002614, Round 3) for Carbon Management. [26] Funding is available to support pre-feasibility studies for intermodal hubs incorporating at least two modes of transport for CO_2.
- **DOE FECM Cooperative Research and Development Agreements (CRADAs)** enable the DOE FECM national laboratories and one or more parties (e.g., industry) to collaborate on RD&D efforts in the DOE FECM mission space. An example call is the 2021 H2@Scale Laboratory CRADA Call. [27] The Hydrogen Materials Compatibility Consortium (H-MAT) [28] is the product of a CRADA.
- **DOE FECM Laboratory Calls/Field Work Proposals** enable DOE FECM to directly allocate funds to DOE FECM national laboratories and facilities, including when the laboratory applicant is a partner on a DOE FECM proposal submitted by a different entity.
- **DOE FECM's Technology Commercialization Fund (TCF)** [29] is managed by the Office of Technology Transitions. The TCF annually appropriates approximately $30M to support maturation and commercial application of promising technologies in DOE FECM's mission space. The BIL has provided an additional $62M in TCF funds for BIL activities enabling commercialization, replication, and scaling of demonstration projects.

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Appendix A. Workshop and Facility Tour Agenda

Copies of all workshop presentations are available online.[17]

Roadmap for CO_2 Transport Fundamental Research Workshop

DoubleTree by Hilton Columbus Dublin
600 Metro Place North
Dublin, OH 43017
February 21-23, 2023

Tuesday, February 21, 2023

11:00 am Registration Open

11:30 – 12:30 pm DOE FECM Program Introductory Remarks / Lunch Provided

- Overview of DOE FECM's Office of Fossil Energy and Carbon Management (FECM) (15 minutes) - **John Litynski, Director, DOE FECM Carbon Transport and Storage Program**
- Overview of the Carbon Transport RD&D Program at DOE FECM (15 minutes) - **Sarah Leung, Carbon Transport Program Manager, DOE FECM**
- Perspectives from Labor (United Association of Journeymen and Apprentices of the Plumbing and Pipefitting Industry of the United States and Canada) (5-10 minutes) – **Jeremy Moddrell, UA**
- Perspectives from Industry (API) (5-10 minutes) – **Mark Piazza, API**
- Perspectives from Academia and Steel Producers (Colorado School of Mines) (5-10 minutes) - **Lawrence Cho, Colorado School of Mines,** Advanced Steel Processing and Products Research Center (ASPPRC)

12:30 – 2:00 pm Ongoing Initiatives: Building a consortium to complement partnerships that exist today (1.5 hours)

Session Moderators: Shawn Bennett, Battelle and Matthew White, EWI

- PRCI CO_2 Task Force (15 minutes) – **Rick Noecker, ExxonMobil**
- Ohio University CO_2 Impurities Joint Industry Partnership (JIP) (15 minutes) – **Yoon-Seok Choi, Ohio University**
- DNV Safe and Sour CO_2 Pipeline JIP (15 minutes) – **Ramgopal Thodla, DNV**
- BMT Global – DOT PHMSA R&D Material Testing and Qualification for CO_2 Pipelines (15 minutes) – **Aaron Dinovitzer, BMT Global**
- Discussion (30 minutes)

2:00 – 2:30 pm Networking Break

2:30 – 4:30 pm Topic 1: CO_2 Impurities and Impact to Integrity (2 hours)

Session Moderators: Rick Noecker, ExxonMobil and Srdjan Nesic, Ohio University

- 1A. First principles thermodynamic modeling of phase change in dense phase CO_2 environment in the presence of impurities (15 minutes) – **Sumit Sharma, Ohio University**
- 1B. Lab-based corrosion determination of impurities on dense-phase and supercritical CO_2 (15 minutes) - **May Martin, National Institute of Standards and Technology (NIST)**
- 1C. Impact of impurities on non-metallic seals (15 minutes) – **Bonnie Antoun, Sandia National Laboratories**
- Discussion (1 hour 15 minutes)

Wednesday, February 22, 2023

8:30 – 10:00 am Topic 2: CO_2-Specific Leak Detection and Emergency Response Protocol (1.5 hours)

Session Moderators: Bill Caram, Pipeline Safety Trust and Ruth Ivory-Moore, Global CCS Institute

- 2A. Dispersion modeling and Potential Impact Radius (PIR) for CO_2 / Odorant Additives R&D (10 minutes) – **Bob Smith, DOT Pipeline and Hazardous Materials Safety Administration (PHMSA)**
- 2B. Sensors Development and Integrity considerations for CO_2-pipelines, multi-modal monitoring, and leak detection (10 minutes) – **Jagan Devkota, National Energy Technology Laboratory (NETL)**
- 2C. Low temperature brittleness and ductile propagation testing in CO_2 depressurizing scenarios (10 minutes) – **Benjamin Hanna, DNV**
- 2D. Overview of Emergency Response Workgroup (API-LEPA) (10 minutes) – **Mark Piazza, American Petroleum Institute (API)**
- Discussion (50 minutes)

10:00 - 10:30 am Networking Break

10:30 -12:00 pm Topic 3: Repurposing of Existing Infrastructure for CO_2 Service (1.5 hours)

Session Moderators: Darshan Sachde, Trimeric and Florent Bocher, SWRI

- 3A&B. Databasing information for existing pipeline infrastructure / Dual-use infrastructure – technical considerations for dual-use transport of LPG/LNG/H2/CO2/Ammonia (15 minutes) – **Mike Kass, Oak Ridge National Laboratory (ORNL)**
- 3C. Lab-testing capabilities to determine integrity for repurposing (15 minutes) – **Yunior Hioe, Engineering Mechanics Corp. of Columbus**
- 3D. Leveraging ongoing Hydrogen pipeline R&D for CO_2 (H2 @ Scale / HyBlend / HyMaRC) / Co-location considerations with Hydrogen Hubs (15 minutes) – **Amgad Elgowainy, Argonne National Laboratory**
- Discussion (45 minutes)

12:00 – 1:00 pm Lunch Provided

1:00 - 2:30 pm Topic 4: Developing and Connecting with Other Modes of CO_2 Transport/Intermodal Hubs (1.5 hours)
Session Moderators: Richard Middleton, Carbon Solutions LLC and Erick Danyi, BP

- 4A. The Role of CO_2 Infrastructure in Achieving US Economy-Wide Net-Zero Emissions (15 minutes) – **Derek Wissmiller, GTI Energy**
- 4B. Considerations for offshore pipelines / pipelines that cross navigable waterways and water bodies (15 minutes) – **Yong-Yi Wang, Center for Reliable Energy Systems (CRES)**
- 4C. Multi-modal modeling for decarbonization scenarios and industrial decarbonization, CDR, CO_2 conversion (15 minutes) – **Corey Myers and Wenqin Li, Lawrence Livermore National Laboratory**
- Discussion (45 minutes)

2:30 – 3:00 pm Networking Break

3:00 - 4:00 pm Key Takeaways and Next Steps (1 hour)
Session Moderators: Neeraj Thirumalai, ExxonMobil and Edgar Lara-Curzio, ORNL

4:00 pm ADJOURN

Thursday, February 23, 2023

9:00am– 12:00 pm DNV Lab Visit (Optional for Attendees)
POC: Ramgopal Thodla, DNV

Det Norske Veritas (DNV) Lab
5777 Frantz Rd.
Dublin, OH

- Material Testing Capabilities
- Harsh Environment Testing (H_2/CO_2)
- Flow, Corrosion, and Stress Corrosion Cracking Capabilities
- Failure Analysis Laboratory for Pipelines

12:00 – 2:30 pm Travel from Dublin, OH to Athens, OH (Travel is on your Own)
Estimated drive time is 1.5 hours.

2:30 – 5:00 pm ICMT Lab Visit (Optional for Attendees)
POC: Marc Singer, Ohio University

Institute for Corrosion and Multiphase Technology
342 West State Street
Athens, OH

- Large Scale Multiphase Flow Loop Capabilities
- High Pressure Systems Dedicated to CO_2 transport with Impurities
- Wide Variety of Small-Scale Corrosion Setups
- Comprehensive Analytical Capabilities (Solubility, Impurity Monitoring)
- More information at (https://www.ohio.edu/engineering/corrosion/facilities-instruments/facilities)

Appendix B. Mentimeter questions and instructions to moderators for the Ongoing Initiatives Session

10 minutes: Discuss questions amongst tables, develop answers, and submit onto Mentimeter portal as a group through the designated synthesizer. If desired, any one at the table can submit additional responses to Mentimeter to share differing perspectives within the table, in addition to the collated table answer.

1. (Icebreaker): Dogs or Cats? (Multiple Choice)
   1) Dog 2) Cat
2. What are lab and pilot-scale research needs to inform CO_2 transport infrastructure deployment? (Free response)
3. Prioritize the lab and pilot-scale research identified in the previous question in order of importance. (Virtual whiteboard)
4. How can a new research consortium address these research needs without duplicating work from existing JIPs and collaborations? Who is involved? (Free response)

20-30 minutes: 2-3 minutes for each of the 10 tables to report out on their answers, focusing on high level points.

10-20 minutes: Remainder of allotted time for group discussion on key themes and answers that emerge from the responses.

Appendix C. Mentimeter questions and instructions to moderators for Topics 1-4

10 minutes: Discuss questions amongst tables, develop answers, and submit onto Mentimeter portal as a group through the designated synthesizer. If desired, any one at the table can submit additional responses to Mentimeter to share differing perspectives within the table, in addition to the collated table answer.

1. Based on the Key Takeaways and Next Steps from each presentation, what does your table propose as 2-3 further challenge(s) that need to be addressed? (Free response)
2. What needs to be done in the now, in the next 2-3 years, and in the next 4-5 years to address the top challenge? (Free response)
3. Who is the best party to lead the completion of these actions, and how? (Virtual whiteboard, rank)

20-30 minutes: 2-3 minutes for each of the 10 tables to report out on their answers, focusing on high level points.

10-20 minutes: Remainder of allotted time for group discussion on key themes and answers that emerge from the responses.

Proposed moderator question pulling key themes: Are there any additional technical challenges above and beyond what was raised earlier?

Appendix D. Mentimeter responses

Responses from Mentimeter, edited for spelling, are included below. Selected changes are marked with "[ ]" to denote an edit for clarity.

Ongoing initiatives

Question 2. What are lab and pilot-scale research needs to inform CO_2 transport infrastructure deployment?

Impurity impacts to internal corrosion and fracture
Impurities impacts to valves, flow components, compressors, instrumentation
Transport mode other than pipelines
Public acceptance and communicating the benefits (doing machine learning to get lessons learned)
Understanding the acceptable impurities for the entire value chain (capture, transport, and storage), not just the pipeline
Corrosion testing in all steels to determine size of defects. Early testing is showing very small pin holes that can't be seen by ILI tools. Then perform burst test to see fracture behavior - do all weld types.
Minimum
Effect of impurities in alternative transport method
Impact of interacting threats - e.g. corrosion + geohazards + mechanical damage
Impacts of physical characteristics and parameters (pressure, temperature) of CO_2 streams on various equipment
Standardization of interconnection for CO_2 alternative transport methods and pipelines
- gas decompression behavior / impurities - avoid repetition of R&D - CO_2 effects on corrosion / impurities - leak detection - dispersion analysis - non-metallic response. - fracture control - std to limit impurities/ moisture… measurement
More Dispersion Modeling - with computational flow dynamics (ALOHA) with what CO_2 concentration could be - a lack of understanding of exposure limits for the general public - with concern for people, livestock. (More Exposure guidance limits)
RISK Failure rates, repurposing , non metallics issues, examples of non metallics on pipelines. Lining or coating on existing pipelines. Operating lower pressures - gas phase. Framework for gas phase transport. Polymer damage on CO_2 decompression.
Scale up of lab scale systems to mid scale and pilot scale studies.
Smaller diameter pipes, 8 inch and smaller. Test.
Odorant additives - olfactory suggestions for chemicals that can be used and what concentrations for adding to the pipelines for emergency response and leak detection.
Limits on operations, damage mechanism
Evaluate influence of: 1) Odorants on fracture control and corrosion? 2) Composition and microstructure of the steel on CO_2 corrosion and fracture control (including welding)? System considerations from emitter to well.
Impurities: does it really matter beyond corrosive? What extra cost to minimize the impurities?

Literature review of impurities within existing CO_2 pipeline network moved today - doing a literature review of impurities impact.
Consistent standard for equipment design
Effect of CO_2 and impurities on existing anomalies of vintage pipelines.
Communication and education of the public on research results and safety aspect of CO_2 transport
We need better understanding of preferential corrosion, for example at seam weld and girth weld
Research groups talk in the same language and interact with each other
- Continuous feeding of impurities for corrosion testing. Generate data from more labs/ lab capability - Cross- contamination - Studies including 3-5 impurities are important - Standardization of corrosion and fracture control testing
Process flow characteristics, from the source what will be deliver to the pipeline
impurities effects on material and driving force for fracture control (BTCM gas decompression)
monitoring of infrastructure, maybe odorization at this scale is too much?
There has been work done in UK on equation of state.
- Identify research needs to use existing infrastructure clearly from needs for new infrastructure - Take out all the impurities at the capture site vs allowing more impurities in pipelines
- Techno economic analysis tools for repurposing vs new build pipelines - Life cycle costs gas phase vs dense phase - Use of composite pipelines/slip line inside existing pipelines infrastructure. Compatibility with CO_2 need to be established
Canada has experience composite pipes with EOR applications. - There is benefit to using existing right of ways to enable CO_2 transportation
- Public education needs to be led by DOE labs by generating data complementing industry JIPs, API and PRCI efforts
Effect of phase behavior and outside environmental temperatures on pipeline operations.
Need one gatekeeper of the data either through an association etc.
Effect of impurities on materials composition, microstructure, and structure
Identification of candidate materials
Analysis of supply chains

Question 3. Prioritize the lab and pilot-scale research identified in the previous question in order of importance.

1. Impurities (thermodynamic model) which influences future work 2. Exposure limits for people and livestock
Potential rate of impurities, Concentrations, Definition of “dirty” CO_2 Definition of Dry CO_2
1. Impurities levels 2. physical parameters influencing pipe condition such as P, T, and flowrate 3. Scaling up to pilot scale
1. Impurities 2. Dispersion including emergency response when do you use CFD, Gaussian type models 3. Fracture mitigation
1. Impurities 2. Dispersion 3. Existing analogies for vintage pipe

Optimizing metallurgy of steel for CO_2 performance: chemistry, processing, microstructure
#1 - Agreed upon level of impurities (min/max) in the entire value chain (capture, transport, and storage) #2 - Monitoring and leak detection to ensure that the quality specification is being met #3 - Geohazards, slip mitigation (sinkholes, landslide
1. Focus on figuring out the effects and exposure limits on people 2. Materials sourcing (in general as a need)
1. Scale up testing of all flow component 2. Impurity phase behavior 3. Decompression behavior
Understanding clearly "what is the saturation pressure" for booth ductile fracture propagation and corrosion understanding. Running more testing
1-effect of impurities 2-standardization 3-risk communication. … public education 4-repurposing pipelines 5- dispersion modelling 6-leak detection.
1. Fully address the topic of impurities which segways into the other research topics.
Influence of CO_2 specification on materials, construction and operation of CO_2 pipelines.
Testing to improve EoS = improve fracture understanding and liquid dropout corrosion
Ensure sufficient SME review structure of system.
1. Impurities and the effect of Corrosion and cracking 2. Scale up from lab to pilot scale and critical for full scale transition
different transportation modes
impurities problem but specifically for pipeline
1. Scale up to get to the 1 gigaton
1. Validation of air dispersion modeling through destructive testing of pipelines
leakage detection, measurement, audit, standard
Prioritize, define maintenance programs for CO_2 pipelines
1. Lessons learned from EOR and do impurities cause issues on current transport infrastructure. (Impact on tubulars with H2S) - even with pipelines and for decades and small amounts - can demonstrate from ILI runs on existing CO_2 pipelines
1-standardization of interconnection 2-developing a value chain for point source at small scale
impurities, repurposing current pipeline.
impurities and specification problem is the most important question, different transportation modes, MRV impacts

Question 4. How can a new research consortium address these research needs without duplicating work from existing JIPs and collaborations? Who is involved?

Create a "Center for CO_2 Safety"
A new consortium including Industrial Gas Shipping Companies with expertise in alternative transport methods
DOT Center for CO_2 Safety
Love the idea of a center for CO_2 safety
Include capture technology experts to devise cost effective strategies to minimize impurities at the source

Take lead from the gap analysis from PRCI. Broadening since impurities pose an enormous problem and in various concentrations, so broadening existing efforts to cover more impurities ranges. DOE to bring the consortia together - funding and initiatives
Event like this annual, with check in steps quarterly. Standards bodies should be a part of the conversation with revisions to 318S on integrity management. Not enough time to reproduce what's been done so mechanisms for two phase flow. DOE to lead
benchmarking to the current H2 – HyBlend [initiative]. involving research value chain. gov, academia and commercial.
Example for NASA wasn't collaborating enough, so workshops like these with timelines to get together more often to cross pollinate these learnings
Have DOE take a leading role to facilitate collaboration (act as a convenor) between existing efforts, to include standard organizations and other Federal agencies, and fund closure of gaps: e.g. Fuel Cells summit, Manhattan Project.
Gap analysis between existing regulatory PHMSA DOT expectations and current expectation
- A modest amount of repetition is not bad. Pooling expert opinion. - DOE oversight with national lab expert review/contribution - need to hold information sharing events. - need industry, standards and experts invited to support
Current event brings different input.
Government sponsor an entity/organization to collectively identify, collect, and host the R&D information in publicly available medium
Opportunity with regional initiatives to pull in on the scale up question - a lot of synergies with scale up with consortium.
Centralized depository of research data maintained by DOE labs
Government industry partnership is needed in CO_2 transportation - e.g. US Drive, HyBlend, 21st century truck partnership
Center for CO_2 safety will be a curator for open source data, experiments and results for tests and results
There's no holistic view for ongoing research. PRCI has a Wikipedia so started capturing the research going on and DOE being part owner of that and start looking at that research and where the overlaps and the gaps we need to fill, to go in parallel.
DOE reaching out to international - Australia and EU on their ongoing research.
connecting the consortium among truck, rail, marine, pipeline transportation.
Generate new data from DOE/NIST labs that support and complement the data generated by current JIPs to generate public support for CO_2 transportation
1. Identify the gaps 2. Build a workgroup as a way to start and to identify how to look ahead
public page for others to keep up to date so they don't have to duplicate work.
Geohazards and landslide: Other aspects of operating a pipeline that would have an accepted level of protection - towards the state of the art approach - fiber optics
Interact with other consortium (H_2, biomass industry, gas industry etc.) who is solving similar questions to share learnings.
- Data generated by JIPs is generally not publicly available. Therefore, DOE/NIST labs data is needed for public availability of data Encourage JIPs to contribute data to a DOE public database
Copy the model currently in place by DOE's hydrogen and fuel cells program

Topic 1: Impact of CO_2 Impurities on Asset Integrity

Question 1. Based on the Key Takeaways and Next Steps from each presentation, what does your table propose as 2-3 further challenge(s) that need to be addressed?

impurities on material such has corrosion but also on equation of state in BTC[M] (gas decompression). Developing sensors for monitoring. dispersion modeling, UK, impurities on shipping on saturation and density, structural, construction, and maritime.
- Direct air capture, they get impurities from the air, they should address how that affect the pipeline transportation.
Lots of information provided, but no overarching program for how to use information/curate it
seals and gasket material for testing but also for operation. Round robin for data qualification
Need prioritization on what scopes need to be included in the research
Multi-lab corrosion testing with various impurity combinations
Would like more information on the details of corrosion mechanisms
Would like test/experimental data correlated/validated with larger scale
understanding weld materials after base metal. Too many variables that still need to be explore.
Relaying test parameter scenarios with real-world application and operations
System wide optimization to handle impurities before it goes into the transport network
Develop more lab capabilities and have those labs communicate and collaborate.
Focus on non-metallic materials
Need to better understand the capabilities of testing (which is currently ongoing)
need test data to support the analytical tools.
Develop practical guidelines to support the safe design and construction of pipelines.
- Take the data and translate the data to what would happen in the field, lay out what has been done, what needs to be done.
High-throughput data collection to support the development of models
Taking Lessons learned from ADM pipeline conditions and OK Chapparal field
- Compatibility of elastomers/non-metallics in existing infrastructures for CO_2 transportation Effect of impurities on elastomers/non-metallics for new CO_2 pipelines
Define impurities and impacts as well as maximum limit of impurities is tolerable
Corrosion testing in realistic conditions
Stop using super-critical CO_2 terminology, instead use dense phase for branding of CO_2 pipelines for public acceptance.
Corrosion in welds and joints
Understanding degradation mechanisms in non-metallic materials, such as polymers
A lot of studies have been done for CO_2, how can we leverage the existing learnings and knowledge to solve this CO_2 transportation problem?
#1 - Repurposing and retiring infrastructure. How do we quantify the design life? #2 - When looking at impurities and phase behavior, we need to look at all components in the pipeline (welds, metals, and non-metallics).
Stress corrosion cracking (SCC) subjected to stress below material's yield strength and at high strain beyond yield strength.
Central prioritization activity to ensure/support testing is consistently progressing (ref: Sandia work) given the expedient real-life delivery expectations
Continued focus on non-metallic testing to understand the impacts to critical materials / components

Standardization for testing and data reporting
Develop consensus on limited range of test conditions that testing labs will use when evaluating impurity effects to facilitate comparisons among labs
how to use all this information for design criteria
Take in count fluctuating operating conditions on the testing environment
Database of CO_2 stream composition from different capture and CO_2 sources is needed to guide research as well as for pipeline design and operations
Establish a prioritization mechanism to ensure work takes place in a systematic, built upon way, with the appropriate funding accessible
Don't know what the impurities are sometimes - gathering from 4-5 sources. That's one of the first steps and then prioritize the approach based on that "fingerprinting"
Identify, honestly, the things we don't know
Need a total characterization on the CO_2 stream after capture
National and global statistical analysis of chemical compositions of all potential CO2 streams, or those most viable for CCUS, and model what the CO_2 compositions might be when these varied sources are mixed.
Research and development of impurity removal techniques and technologies, such as scrubbers and sacrificial pipeline parts
Now: do the corrosion testing on pipe (metallic) and components (non-metallic) - Identify a method to simulate long-term testing
Building a lesson learned from operating assets - such as ADM Decatur ethanol (oxygen) - pump seals, valve history, corrosion coupons
- what impurities to expect and their effect - need to consider stress conditions on behavior - in situ testing of material to consider degradation - maintenance activities causing decompression and thus damage to non metallics.

Question 2. What needs to be done in the now, in the next 2-3 years, and in the next 4-5 years to address the top challenge?

short term design parameter / guideline based on what currently know, such as detection.
Identify, honestly, what we don't know
Establish standard corrosion test procedures for dense phase CO_2 +impurities in the next 1-2 years
Use actual operating experience within the discussions
Develop the framework for the connecting the ongoing independent efforts to support focused development of initiatives
Ensure the deliverables are targeted at supporting operations
Develop strategies for building CO_2 pipelines now while working on research to expand the operational envelopes and addressing gaps
Start with the activities that will take the longest time to achieve, such as data collection to support modeling
Consider AI/Data Analytics to accelerate progress
- Data on Rate of corrosion -Guidelines on CO_2 purity levels for commercial large-scale infrastructure
Find a low hanging fruit, for example if humidity is the issue, then get that solve first. Economic consideration, balance between R&D vs. regulation.
Prioritize and focus the initiatives
Next 2-3 years: What impurities likely to be seen from different sources? Can some of the impurities be removed economically before transportation? This would set the likely impurities in CO_2 being transported by pipelines.
Need to identify affiliated system failures (like oil or gas pipelines) to understand potential

Top challenge: what's the new about this problem based on what has been learnt. Field test is the missing component.
Lack of economic incentive in funding or tax credits expire. It needs to become a profitable industry,
4-5 years: doing corrosion and thermodynamics of CO_2 with likely impurities in pipelines.
Establish whether the lines will be cycled in pressure when going to a hub model from bespoke lines from source to EOR.
Closely monitor small anthropogenic pipeline projects to learn from experience before large projects are built
Impurity effects to enable a CO_2 hub model
1. Gap analysis on research efforts (DOE) 2-3 years: Identifying scope on funding projects (DOT/DOE/Industry) 4-5 years: using this information for specifications and standards (DNV, API)
How to avoid damage caused by maintenance decompression. - identify alternate materials that can support depressurization. - need to introduce materials researchers to operators to understand operational requirements

Topic 2: CO_2-Specific Leak Detection and Emergency Response Protocol

Question 1. Based on the Key Takeaways and Next Steps from each presentation, what does your table propose as 2-3 further challenge(s) that need to be addressed?

Need more full-scale testing with CO_2 compositions with impurities to understand running ductile fracture behavior to update BTCM parameters
Odorant impacts on equations of state, water drop out, and decompression behavior of CO_2 pipelines.
better understanding human asphyxiation factors in the presence of CO_2
linking model/ testing to sensor technology
How to better simulate CO_2 release in valleys? Is the tent method conservative for such scenarios?
better source model to input into release model
Confirm the link between small scale testing with large scale behavior with respect to fracture control.
Can the optical sensors determine contaminants and levels or are there other tools available for detection and measurement?
Corrosion sensors, CO_2 leak sensors, temperature sensors, strain sensors would be helpful to monitor CO_2 pipelines in real time.
Define the requirements for bolts and fasteners consider realistic leak scenarios at fixtures and fittings.
big difference between impact release from ductile fracture and small release because of small leaks on flanges
For small leak scenarios additional testing of burst pressure at low temperatures is needed
Continuous monitoring/Sensing for water, acid drop out, NOX, SOX in the pipelines
Sensing for small leaks
Establish a continuous process of dispersion analyses
establish shut off points needed based on a COs gas quality spec
Create or update Battelle or create new ductile fracture model
How much sensing do we need to get an accurate detection and protection? what is the extra investment?
Getting a model or web-based that takes into consideration topography, and being able to validate it
Link dispersion and detection tools
There is a gap between what science suggest to be safe and what's public feel safe, how do we bridge the gap?
Emergency response standards need to be updated for CO_2
Need more ductile fracture testing across materials.
- understanding crack arrest - monitoring/leak detection technology improvements (currently underway) - motivating operators to monitor/detect leaks
Integrating Physics based and data-driven modeling and validating with sensor devices and monitoring
Using CFD with Gaussian models for dispersion modeling
What health effects, acute or long term, can be expected from a large CO_2 leak that includes more toxic trace contaminants?
Gas decompression process needs fundamental research for all compositions
Address the effect of impurities on emergency response. For example, the presence of H_2S
Leakage detection, how to find the cracks earlier and do something about it before it gets bigger and worse
Development of sensors to detect leaks
PIR - Is there consideration for the impurities in the PIR calculation? Gather additional real world data on ductile and brittle fracture during depressurization. Is there a disconnect between lab and real world?
For temperature depressurization scenarios, if there can be fatigue and cycling analysis that can be done

Adapting fiber optic technology to create continuous comprehensive pipeline CO_2 monitoring
Detection and measurement tools and equipment and methodologies
acute or chronic effect from the impurities aside from CO_2
Dispersion test
issue with current analytical tool /BTCM need upgrading to new data
public engagement on effect and procedures on CO_2 exposures
what happened with leak vs a running failure that easily spotted.

Question 2. What needs to be done in the now, in the next 2-3 years, and in the next 4-5 years to address the top challenge?

enhancing dispersion models
Now: more dispersion modeling; tune the models with validation experiments.
assessment of failure model scenarios. Better understanding of each failure model characteristic
Next 2-3 years: define potential odorant chemicals and begin to understand their effects on CO2 stream thermodynamics.
from the existing 5000 miles of existing pipelines, what are the main failure mechanisms?
Need more full-scale testing with CO_2 compositions with impurities to understand running ductile fracture behavior to update BTCM parameters
Now: finalize emergency response guidelines and deploy.
Increasing TRL level of sensing and commercialization of monitoring technologies for CO_2 pipelines
Developing frameworks for fusing sensing data with integrity management systems
2-3 years: additional CO_2 testing using homes located a ground level.
4-5 years: update regulations based upon research conducted over the next several years.
Public education and education to close the gap between science and public perception.
Continuously Improve standards.
Short term emergency response guidelines.
Short term. - link small:lab scale testing to full scale fracture tests
Medium term - develop a suit of distributed co2 leak detection tools.
Now: Human body toxicity exposure limits related to the interface for CO_2 and O_2 and various impurities, and how that affects depressurization behavior
2-3 years: integration with modeling and sensors detections
Top challenge: How to define leakage detection, define the standard and limit, and detect the small leakage earlier not only through standard tools.
2-3 years: Have a equation to define PIR, leakage detection, 4-5 years: inspection and mitigation.
- testing to determine optimal pipeline design (toughness and stress/strain response)
Short term - can areal patrol or satellites be used for leak detection
Improve sensor development on pipelines. What potential problems do we need to detect? Do regulations need to be revised to address this additional monitoring using risk based methodology?
Battelle Two Curve - a better model for fracture control, there are areas where they haven't been tested
How do you detect small leaks, fiber optics, are these deployable? Devices are difficult to make
How to enter the commercial space and bring that into the R&D process
public engagement can start as soon as possible.
updating to the BTCM analysis with more test data need to be done soon
next gen sensor for the 4-5 years
Deployment for next gen sensor for the long term

Topic 3: Repurposing of Existing Infrastructure for CO_2 Service

Question 1. Based on the Key Takeaways and Next Steps from each presentation, what does your table propose as 2-3 further challenge(s) that need to be addressed?

More test data linking lab to full scale performance
translating properties from small scale to real scale test
translate from small scale to full scale performance
Sharing of data to support design is a challenge
Define an improved fracture arrest specimen: e.g. PRCI MAT-8-6 "A new definition of the resistance to ductile fracture propagation "
Repurposing pipelines is challenged by lack knowledge on the properties of pipe in the ground.
Update of regulations requiring more accurate impact testing than Charpy
Compare new round of CO_2 pipeline burst tests to modified DWTT specimens.
- testing at scale (for each fluid) - under what circumstances are higher cost materials appropriate (for impure gas streams)
Need research on assessing dynamic materials properties for line pipes to improve on DWTT and CVN for modeling using BTCM
Repurposing may work to make a whole CO_2 pipeline project financially feasible but may not be the easiest to operate and monitor and represent a higher safety risk than a new pipeline
What residual component exists in the previous, SCO2 could be a super solvent, what come out of the pipeline would be interesting.
How to use it/re-purpose the pipeline safely?
develop new testing methodology in between DWTT and full scale . Maybe a " expansion ring test"?
It I felt that integrity assessment tools for features that are not through wall remain valid. Need to demonstrate what inputs need update. E.g. corrosion rate or pressure cycling
The Battelle Two Curve Method needs to be revised If an operator has unused, reusable infrastructure, does the original documentation still exist? What is the remaining design life? Pipeline hydraulics need to be considered for pipeline reuse
For repurposing, need to better understand the pedigree of existing pipelines. Complete US DOT PHMSA Traceable, Verifiable Complete actions for pipelines to be repurposed.
small scale test to predict better full scale behavior
Make a public database of both technical, cost and mitigation cost data for CO2 pipelines
Have a checklist you need from data wise, and identify the gaps and research needs
Again the issue of CO_2 gas quality/impurities impacts on the existing infrastructure
To combine efforts in establishing material databases considering environmental and product impact.
In situ testing for in service CO_2 lines needs to be developed
Getting a better idea of relevant pipelines near probable storage formations (as pipelines were routed without regard to environmental justice considerations) with ties to public engagement and outreach
Defining the limits and parameters for repurposing such as impurities level, mechanical considerations
Consider use for hydrogen in the future when you build a new CO_2 pipeline
A lot of natural gas will be moved around today so limitations to availability: how many pipelines will be capable to repurposed
Setting the pipeline pressure to maintaining the single phase flow to avoid two-phase flow
Use of coatings and liners for repurposing the existing pipelines
Extensive blending testing on large scale systems to determine viability of different mixes
- Comparing self-arrest vs crack arrestors system and spacing and standards

- Getting a better idea of relevant pipelines near probable storage formations (as pipelines were routed without regard to environmental justice considerations) with ties to public engagement and outreach
- A lot of natural gas will be moved around today so limitations to availability: how many pipelines will be capable to repurposed
how real is repurposing, there is the pipe / vessel but also the soft goods such as the seals and gaskets. there is even issue with Teflon seal for thread that might have issue with CO_2
certification "stamp" for CO_2 item
cost benefit analysis is currently custom made for each projects with no clear guidance.

Question 2. What needs to be done in the now, in the next 2-3 years, and in the next 4-5 years to address the top challenge?

Make a public database of both technical, cost and mitigation cost data for CO_2 pipelines as soon as possible
understand limitations of BTCM in 2-3 years. What will be the correct safety factors
Encourage data sharing
Now: assess fracture techniques and technologies to define what is needed to update pipeline fracture control requirements.
develop alternative testing methods
Now: replace DWTT with suitable lab scale test with burst test validation.
Many NG pipelines can only be repurposed for CO_2 transportation in gas phase. Need regulations for gas phase CO_2 pipelines.
assess what levels of Safety factors are adequate based on the information now. if more information becomes available , we can revisit those safety factors
Next 2-3 years: central repository for pipeline material performance characteristics.
Short term - collection and integrating data sets from multiple sources.
First evaluate what are the applicable tests for CO_2 pipelines and see what needs update especially for the service temperatures
Do we understand risk enough to setup necessary safety factors
Next 2-3 years: understand what is driving variations in cost, and work to identify ways to reduce cost per inch-mile. Economics of CO_2 transport need to be broadly attractive.
Don't know enough for a full LCA
steel manufacturers need to deliver product base material design specifically for this application
Run regional analysis, expand the retrofit process step by step, re-purpose for H2 first, then can expand to see how to re-purpose it for CO_2.
Now - Develop a guideline/flowchart/checklist to assist operators with understanding conversion to CO2 pipeline Verify there is a uniform set of codes/regulations for CO_2 pipeline operation
Short term - standards for repurposing for CO_2.
developing better testing target to specific types of steel to be used in CO_2
Now Full scale high energy testing
for existing lines needs to better understand the limitations
Take inventory of all the potential sources of various gasses that may be transported or co-transported, do extensive statistical study of their impurity makeup, and follow up with studies of how mixing/blending effects overall chemistry
develop safety mechanisms to arrest cracks. (carbon fiber field joint crack arrestor)?
2-3 year guidance from conversion to service (DOT) and API/DNV for recommended practice
Now Full scale high energy testing (DOE funded) 2-3 year guidance from conversion to service (DOT) and API/DNV for recommended practice

Conduct regional analysis or testing, have more research and exchange program, share best practices, share experiences/failures. Generate Standard to inform next steps.
Capture economics of CO_2 compressions costs of liquid vs gas transport in TEA as well as risk models.
gaps in regulation for 2-3 years for materials and construction

Topic 4: Developing and Connecting with Other Modes of CO_2 Transport/ Intermodal Hubs

Question 1. Based on the Key Takeaways and Next Steps from each presentation, what does your table propose as 2-3 further challenge(s) that need to be addressed?

Understanding geohazards/other pipeline strain and rupture risks
where to put the intermodal. how about urbanized area where land cost is astronomical top put on
Demand and economics will have to drive intermodal transportation - limited opportunity
Initial design considerations to get into the systems could be less rigorous for short-term expectations on shorter/smaller runs while the key transmission lines have more substantial (with known industry experience) requirements
Integrity of girth welds and associated risk implications in new high strength pipelines (X65 higher grades)
optimization tools for determining locations
For intermodal transport, regional variation and capture cost variation need to be considered to determine how systemwide economics will play out
Focus on welding specifications to understand why failures are occurring
Steel making process for the tighter ranges for yield strength, so your weld don't become stress concentration
Interior waterway (e.g. Mississippi River) and coastal transport by barge needs examination relative to truck, rail, pipeline
Tying in other modes of transportation as near term solutions
Incorporating and identifying risks with the other modes of transportation
Lifecycle analysis for truck vs rail vs barge vs pipeline
Do existing codes/regulations adequately address geohazards (earth movement), specifically with respect to pipe stress and welding integrity? If not, are they being addressed?
Use existing technology/practice in higher risk/more managed technology (like subsea p/ls)
Holistic assessment of threats to pipelines with reference to real-world experience
Potential that welding codes can be looked at to reduce allowable defects
Safety aspects of mode change: loading and unloading of trucks, containers, rail cars, barges
- Identify research questions based on transportation modes and size scale e.g. trucking vs short pipelines vs long distance trunk lines Identify the risks of trucking CO_2 on highways with respect to accidents.
Understand risks and challenges with respect to loading and unloading CO_2
Guidelines for retrofitting considerations - including fracture control and crack arrestors. and updating codes and standards as needed.
Adding shipping to the analysis ad dual transport or seasonality related to shipping
Don't use super sophisticated p/l metallurgy. Use material that we know the behavior of/risks already.
Spec changes between modes: consistency or bridging of standards gaps between different transport types
Understand economics, risks and challenges with respect to loading and unloading CO_2 from trucks and rails
Carbon storage will be necessary for NZE cost effective scenarios

Question 2. What needs to be done in the now, in the next 2-3 years, and in the next 4-5 years to address the top challenge?

2-3: optimization tools for intermodal locations, type of transports. 4-5: built the infrastructure and safety.

2-3 years: holistic review of codes and standards to identify gaps, starting with natural gas and hazardous liquid service, moving to CO_2 pipelines
4-5 years: model development and large-scale testing and validation of pipeline integrity against realistic threats
Now: For intermodal transports, what are the impacts of impurities, if any, that are not covered in current CO_2 transport space
DOT needs to study trucking and rail related technical and economic challenges
Tracking fugitive emissions of CO_2
Medium/Long Term: How do we account for CO_2 from multiple small sources?
Remote sensing of pipeline route and measuring strain
Standards alignment, updates and/or development. Research to fill any gaps (a lot being done on GW failures and land movement hazards)
Further studies on feasibility of small source aggregation - balance the approach with the realities of economics and public safety and acceptance
New pipelines need models to incorporate geohazard analyses to verify pipeline and weld integrity. Any infrastructure intended to be repurposed also needs to consider the risks of geohazards. Public perception of truck/train transport of haz liquids
Business case and TEA analyses
Steel making process for the tighter ranges for yield strength, so your weld don't become stress concentration Tying in other modes of transportation as near term solutions
Acceptable limits for CO_2 end uses Adding shipping to the analysis and dual transport or seasonality related to shipping
Developing intermodal hubs and buffer storage Geohazard threats (seismic, karst, desktop) - would be good with accumulated strain capacity cross weld tensile test
Now Incorporating and identifying risks with the other modes of transportation Lifecycle analysis for truck vs rail vs barge vs pipeline

Appendix E. Instructions for moderators leading the Key Takeaways and Next Steps session

By this time, we will have a schematic of the Roadmap within the 4 topical areas across Year 1, Years 2-3, and Years 4-5. Present the areas of interest for each topic and invite questions and comments from all participants. Allocate approximately 15 minutes per topic. Sample prompts to elicit feedback are listed below:

1. What would you change about the roadmap displayed? (Free response)
2. For a potential CO_2 Transport consortia, describe the challenges and next steps. (Free response)
3. What is the single biggest technical barrier to the successful creation of a national CO_2 transport network? (in 1-2 sentences) (Free response)