Pipeline Research Council International

Research Exchange REX 2024

CO2 Pipelines – Deep Dive Session

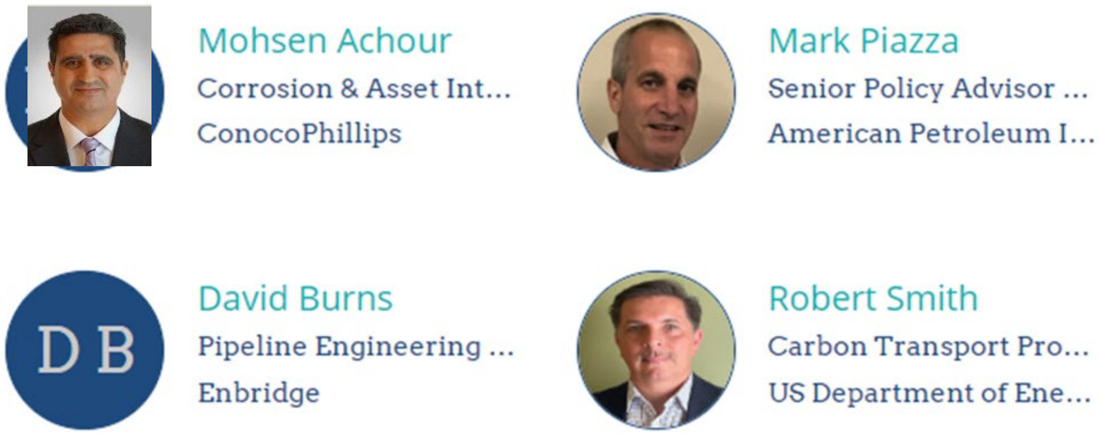
Mohsen Achour

ConocoPhillips

Feb. 28, 2024

LEADING PIPELINE RESEARCH

CO2 Pipelines Deep Dive Session … Agenda



1:00 – 1:05	Introductions & Agenda – Mohsen Achour, session facilitator
1:05 – 1:20	Development of CO2 Pipeline Design Standards for Carbon Hubs – David Burn, Enbridge
1:20 – 1:35	DOE Carbon Transport RD&D – Robert Smith, US Department of Energy
1:35 – 1:50	Standards – Mark Piazza, API
1:50 – 2:05	Inventory of CCS Research in Industry & Academia – Mohsen Achour, ConocoPhillips
2:05 – 2:30	Q&A

Development of CO2 Pipeline Design Standards for Carbon Hubs

David Burn, Enbridge

Development of CO2 Pipeline Design Standards for Carbon Hubs

PRCI, Research Exchange

San Diego, CA

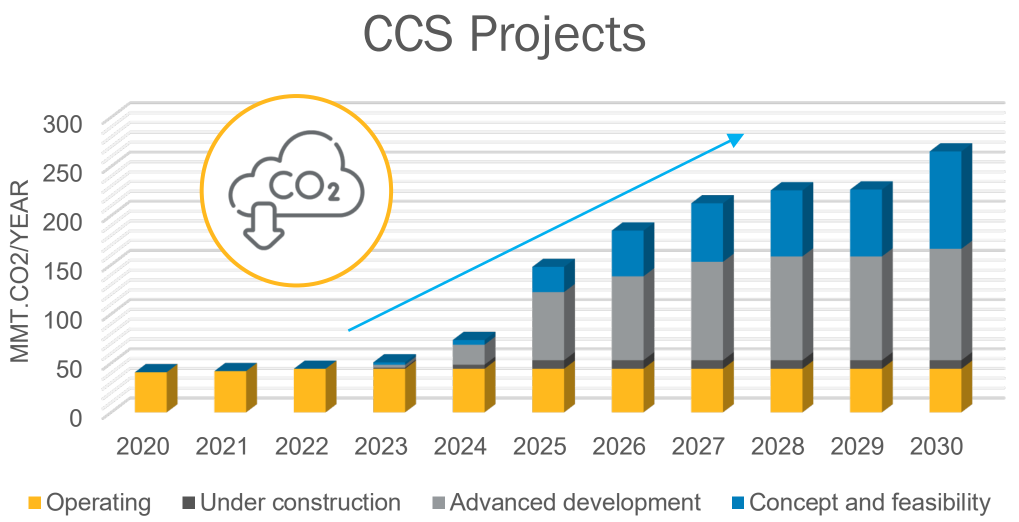
ENBRIDGE®

Agenda

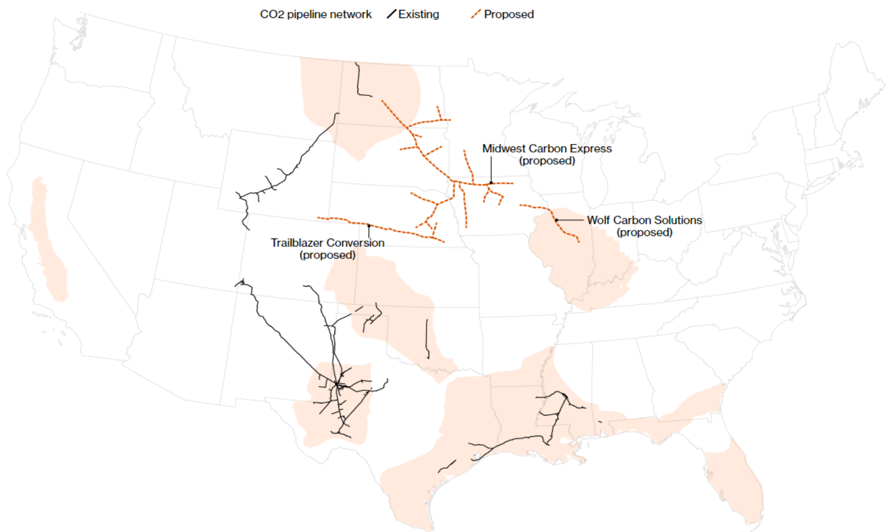
- Background of CCS
- Safety Facts on CO2
- Objective of Developing CO2
  - Challenges with developing Multi-emitter hubs
- Impact of Impurities
- Other Technical Considerations
  - Hydraulic Modelling
  - Material Selection
  - Control Philosophy
- Balancing Risks
- Conclusions

CCUS in North America

- As of 2023, there were approx. 5,200 mi of CO_2 pipelines in North America. To enable forecasted growth in Carbon Capture and Sequestration (CCS) more pipelines are required.
- Most CO_2 pipelines, in operation and proposed, transport the gas in 'dense phase', which is a liquid-like state.
- The first large-scale pipeline was the Canyon Reef Pipeline built in the 1970s and the industry has decades of experience operating CO_2 pipelines.
- Shell Quest in Alberta Canada (2015) and Sleipner in Norway (1995) (and several others) are full scale projects that sequester CO2.



[1]



[2]

[1] EA, Capacity of large-scale CO2 capture projects, current and planned vs. the Net Zero Scenario, 2020-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/capacity-of-large-scale-co2-capture-projects-current-and-planned-vs-the-net-zero-scenario-2020-2030, IEA. Licence: CC BY 4.0

[2] https://www.bloomberg.com/graphics/2023-green-revolution-needs-96000-miles-of-new-pipeline/

CO_2 Safety Facts

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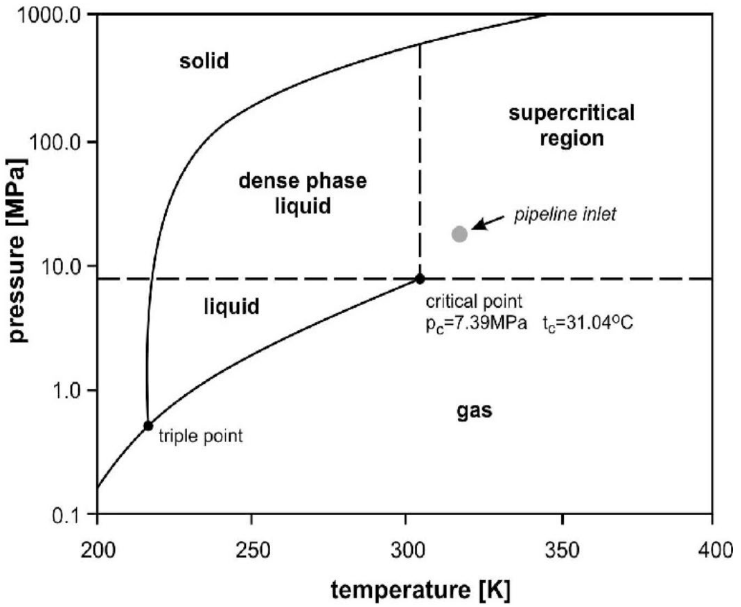
- Unlike natural gas, CO_2 is heavier than air. In the event of a release, CO_2 will dissipate slower than natural gas & accumulate in low-lying areas, displacing oxygen in the affected area.
- Symptoms of mild CO_2 exposure may include headache and drowsiness, and higher CO_2 levels will cause rapid breathing, confusion, increased cardiac output, elevated blood pressure, and increased arrhythmias may occur.
- CO_2 release from liquid form inside of a pipeline will transform into gas/solids due to temperature & pressure changes.
- CO_2 may accumulate static electricity, even when being filled into properly grounded containers, and reacts with water to form carbonic acid (H_2CO_3).
- Most CO_2 pipelines operate in dense phase

Rupture of a carbon dioxide pipeline near Satartia, MS in February 2020



CO2 Pipeline Standards Development

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- Objective
  - Develop a suite of fit for purpose standards to support engineering and construction of new CO2 pipelines for Multi-Emitter Hubs at Enbridge
- Challenges
  - Anthropogenic emissions contain various impurities of concern
  - Research gaps leave a degree of certainty for setting design limits
  - Carbon Hubs need to operate flexibly to allow access for emitters of various differing operating conditions and process streams
- PRCI SOTA Prioritized Gaps

1. Impacts of Impurities
2. Fracture Control
3. Re-Purposing Pipelines
4. Safety and Dispersion Modeling

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CO2 Composition

Pathway to Corrosion (CO2 + presence of SO_2, NO_2, H_2S, O_2)

- $H_2O + CO_2 \rightarrow H_2CO_3$ (Carbonic acid)
- $H_2O + SO_2 \rightarrow H_2SO_4$ (Sulfuric acid)
- $H_2O + NO_2 \rightarrow HNO_3$ (Nitric acid)

Acidic formation leads to corrosion of steel, oxygen accelerates corrosion process

- $H_2O + H_2S \rightarrow HS^- + H^+$
- $H_2O + H_2S \rightarrow S^{2-} + H^+$

Weak acids, atomic hydrogen and Sulphur leads to Hydrogen and sulfide induced cracking

- Key Effects of Impurities
  - Reservoir- formation of acids and hydrates downhole can lead to plugging/corrosion
  - CO2 equations of state are sensitive to impurities which impacts system hydraulics
  - Integrity risks
    - H2S cracking and avoiding dealing with sour gas during operations
    - Corrosion fatigue
    - Hydrogen embrittlement
    - Water solubility impacts from NOx and SOx levels
    - Water drop out during operation leading to corrosion

Multi-Emitter Carbon Hub System Planning

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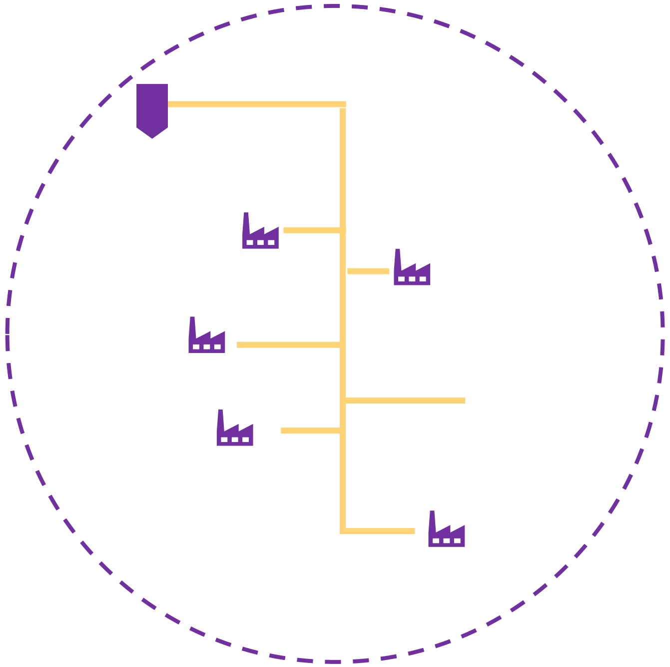
- Systems thinking approach
  - CO2 Composition Standard and how it can impact subsurface, pipeline and facilities
  - Metering and Control at custody transfers
  - Well injectivity and system hydraulics response
  - Lifecycle MMV Plans
  - Optimization- pipe diameter, intermediate pumps, MOP
- Issues to tackle
  - Avoid multi-phase flow (safety critical)
  - Perform Scenario analysis
    - Low flow
    - Variability in emitter operations
    - Transient analysis (e.g. impact on pipeline stress)
    - Blowdown (Joule-Thomson effect greater than natural gas)



Multi-emitter Carbon Hubs are complex and early engagement on these issues will benefit future Operations

CO2 Safety: Dispersion Modeling

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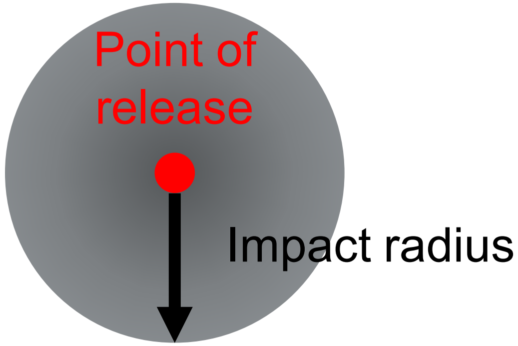
- ‘Potential impact radius’ for CO_2 is non-linear
- Simplified plume vs. complex computation model depending on:
  - Pipeline operating characteristics (size, pressure)
  - Surrounding topography & land uses
  - Atmospheric conditions
  - Fluid components that could affect vapor dispersion

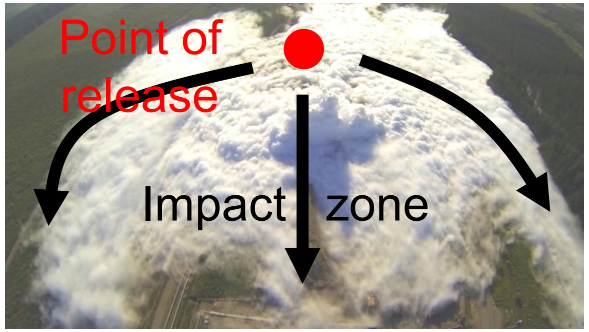
Risk assessment inputs affecting design/operations

(valve spacing, vent design, pipeline routing, pipe toughness, etc.)

Conventional Model



Dispersion Model



High Reliability Systems

- Pipelines reliability targets suggested to be 1x10-5 by Hassanien et al [1] – perhaps suitable for CO2 pipeline but need to consider Human health impacts.

- CO2 Projects perform Quantitative Risk Assessment- options to mitigate risk:
  - Enhanced Pipeline Monitoring and leak detection (e.g.Hifi Monitoring System)
  - Heavier wall thickness
  - Re-routes
  - Gas phase CO2 (lower pressure)

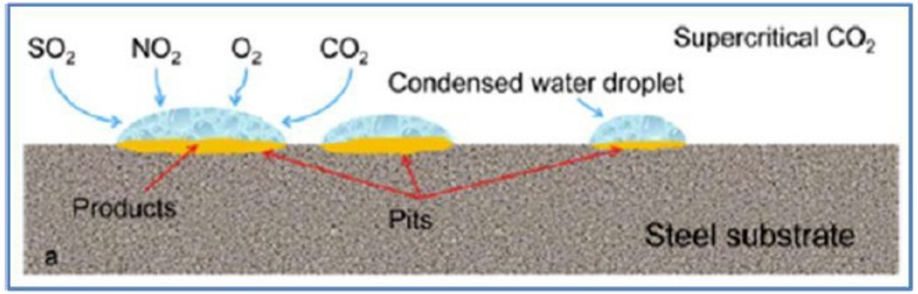
With gaps in knowledge how can we sure that the reliability targets can be met?

How to provide guidance to projects in development with the uncertainty in the research?

[1] Hassanien et al, Towards an Acceptable Pipeline Integrity Target Reliability, IPC 2016

Conservatism and Consensus Engineering

Literature Review and SOTA

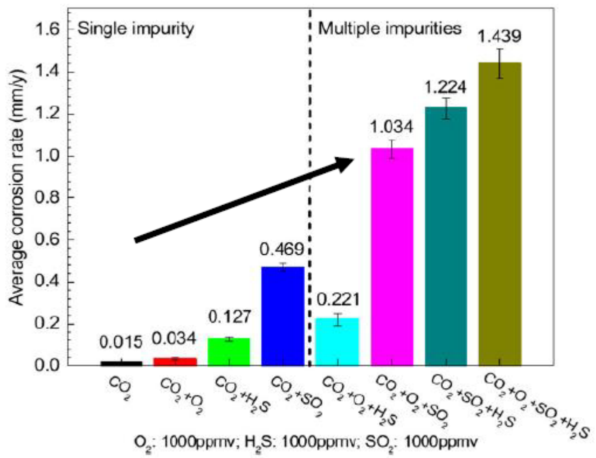


Internal and External subject matter expertise

Ongoing Research

Table 4: Draft Composition Impurity Limit [3] [6] [7] [8]

Constituent	Limit	
Carbon Dioxide, CO_2	> 95 mol%	
Water, H_2O	< 50-100 ppmv	
Sulphur Oxides, SO_x	< 10 ppmv	
Nitrous Oxides, NO_x	< 2.5-10 ppmv	
Hydrogen Sulphide, H_2S	< 5-10 ppmv	
Carbon Monoxide, CO	< 1000 ppmv	
Hydrogen, H_2	< 1 mol%	Total < 4 mol%
Argon, Ar	< 1 mol%	
Nitrogen, N_2	< 4 mol%	
Oxygen, O_2	< 10-20 ppmv	
Methane, CH_4	< 2 mol%	
Other Hydrocarbons	< 1 mol%	
Total Sulphur	< 35 ppmw	
Glycol, $(CH_2OH)_2$	< 0.3 US gal/MMSCF	
Ethanol, C_2H_6O	< 20 ppmv	
Methanol, CH_3OH	< 500 ppmv	
Ammonia, NH_3	< 125 ppmv	
Amines, $-NH_2$	< 1 ppmv	
Particulates	< 1 ppmw	
Mercury, Hg	< 5 mg/sm^3	



Summary

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- System thinking provides better insight in the design decisions that impact the overall system reliability and costs.
- Conservative Consensus Engineering was the chosen methodology because:
  - Pipeline permitting and construction is complex and increasing opposition to CO_2 pipelines.
  - Reputational risks of pipeline failure would impede the ability to permit new projects
  - Outsized risk to the pipeline corrosion vs the cost to process the gas to meet pipeline specification
- Be flexible to change and anticipate direction of R&D

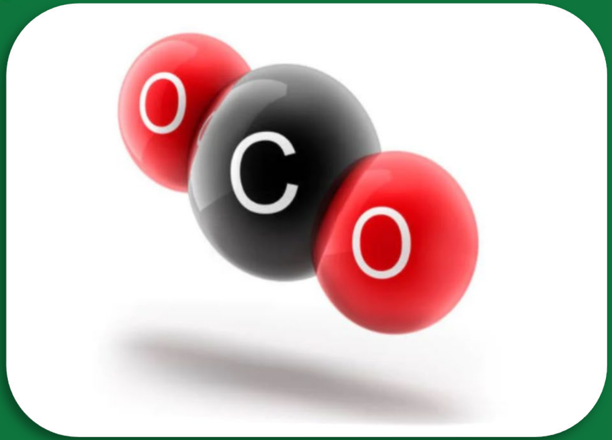
Rupture of a carbon dioxide pipeline near Satartia, MS in February 2020

U.S. DEPARTMENT OF
ENERGY
Fossil Energy and
Carbon Management

DOE Carbon Transport RD&D: 2024 Update

Robert Smith
Carbon Transport and Storage (CTS) Program
Office of Fossil Energy and Carbon Management

February 27, 2024



“The following PowerPoint was created for the PRCI 2024 Research Exchange Meeting.

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Lab Work Addressing Feb 2023 DOE Applied R&D Workshop

Thermodynamic study of the effect of impurities on phase behavior of dense phase CO_2

- Investigate effect of impurities (e.g., CO, O_2, H_2, NOx, SOx) on the phase boundaries of CO_2.
- Review impact of impurities on water solubility limits (water dropout) in dense and vapor phase CO_2.
- Understand speciation pathways for acid formation and solubility due to interaction of various impurities with water.
- Develop thermodynamic models to predict fluid (CO_2 + impurities) behavior in pipelines.

Evaluation of the risk of corrosion with presence of aqueous/acid phase (continuous or droplets) in CO_2 with impurities

- Review literature for corrosion, stress corrosion cracking (SCC), and depressurization related fracture in CO_2 transport.
- Establish test methodologies to investigate general corrosion and pitting corrosion in CO_2 containing impurities.
- Determine general corrosion mechanisms, behavior and rates on pipeline steels in the presence of water dissolved in dense phase CO_2.

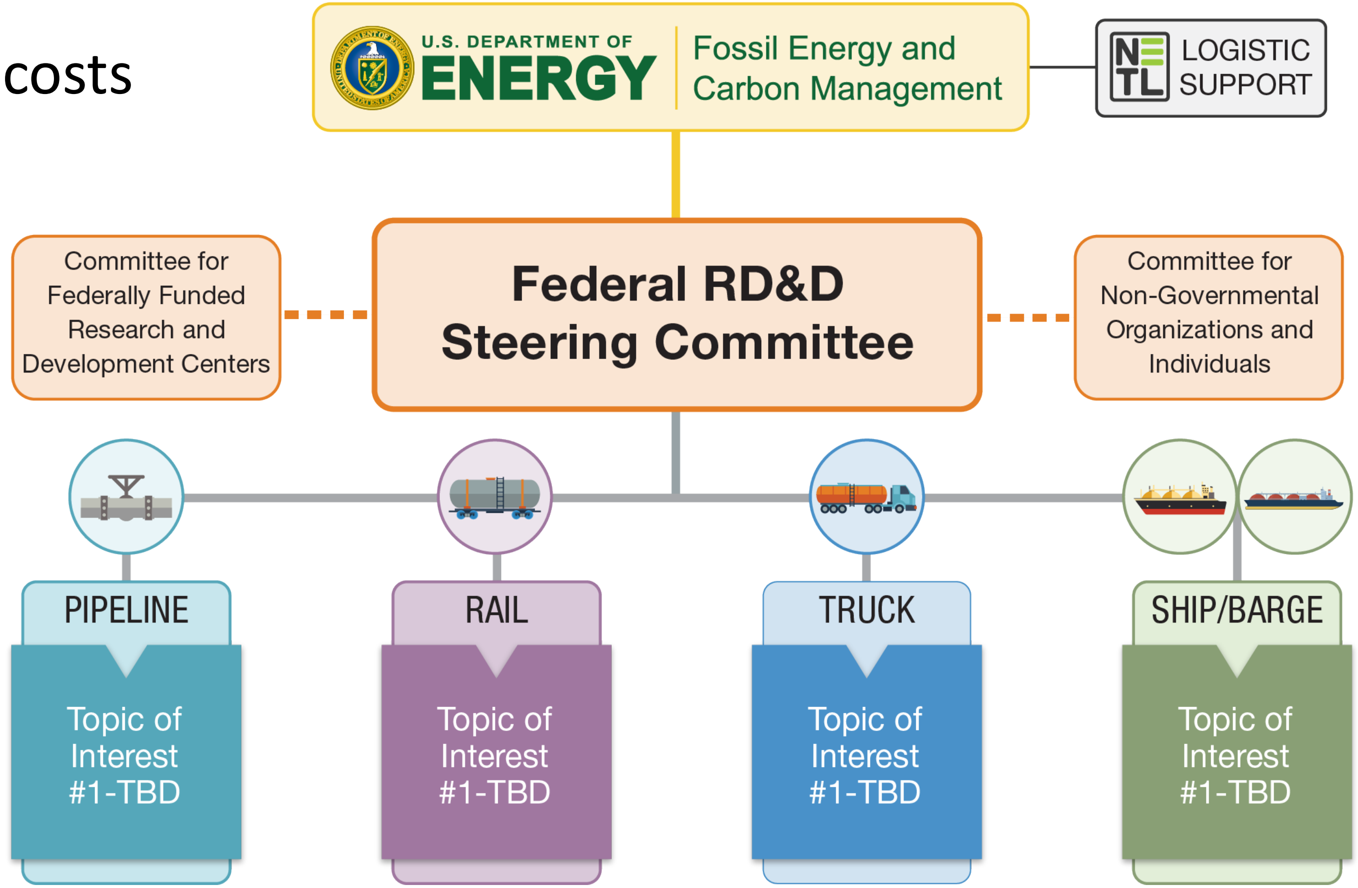
Stress Corrosion Cracking of carbon steels under CO_2/CO/H_2O environments in process piping before water treatment or CO_2 pipeline with water dropout due to upset.

- Establish test methodologies to investigate stress corrosion cracking in CO_2 pipeline steels in the presence of impurities.
- Determine SCC behavior on steels under CO_2/CO/H_2O environments.
- Develop a predictive model for SCC of pipeline steels and validate it using experimental data.

Carbon Transport RD&D Consortium

Benefits

1. Awareness, work sharing and reduced costs
2. Increased credibility
3. Improve chances to achieve goals
4. Growing network of knowledge
    - Increased access to experts
    - Increased access to organizations
    - Increased access to peer reviewed knowledge
    - Increased access to intermodal transport companies
5. Access to federally funded R&D laboratory resources



Carbon Transport RD&D Consortium – Next Steps

- **Release Request for Information (RFI)**
  - What the consortium is, what are our goals, how can you get involved, etc.
- **Review RFI Responses**
  - Register those who want to get involved into relevant committee
- **Inaugural Committee Meetings**
  - Develop/finalize committee governance
- **Launch Consortium Portal/Webpage**
- **DOE Funding Announcements – Future**

Leave no knowledge behind! Collaborate, coordinate, co-fund, categorize & collate consortium tracked research in an open access public portal.

Thank You!

U.S. DEPARTMENT OF
ENERGY
Fossil Energy and
Carbon Management

https://www.energy.gov/fe/office-fossil-energy

Sign up to receive DOE FECM's email updates here.

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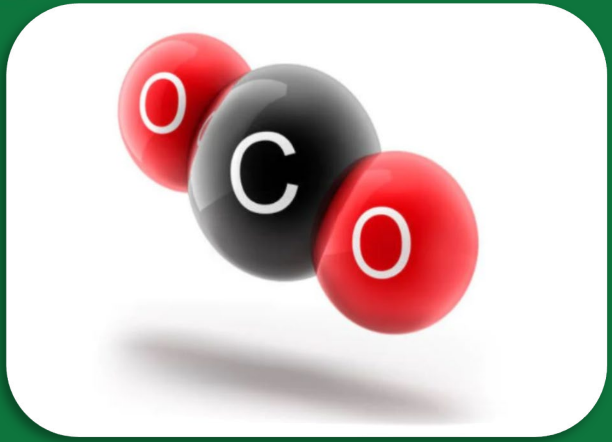


Standards – Mark Piazza, API

CCS Research in Industry & Academia – Mohsen Achour, ConocoPhillips

- DNV
- IFE/OLI – Norway
- Ohio University ICMT

WHEN TRUST MATTERS

DNV Led CO_2 / CCUS JIPs

Summary of DNV Led CO2 Pipeline JIPs

Title	Topic	Timeline
CO_2 Safe & Sour	Integrity of pipelines subjected to H_2S from CCS. Sulfide stress cracking/hydrogen embrittlement. Corrosion	2022 – 2024
CO_2SafePipe	Update of DNV-RP-F104 "Design and Operation of Carbon Dioxide Pipelines"	2023 - 2024
Materials Performance in CCS Storage Wells	Damage mechanisms of Corrosion Resistant Alloys in CCS well applications. Materials selection, operational windows, and assess long term performance of materials in CCS storage wells.	2023 - 2025
CO/CO_2 SCC	Chemistry and metallurgical limits of CO and other impurities to prevent CO/CO2 cracking. Develop a simplified qualification methodology for screening	2024 – 2026
SubCO_2 Phase 3	Subsurface and atmospheric dispersion and dynamics of underwater CO_2 pipe leaks in deeper, more representative water than before.	2024 – 2025
CO_2GASMET Flow Metering	Development of a traceable CO_2 flow standard for medium & low pressure and low temperatures enabling performance assessment and calibration of flow meter technologies along the CO_2 value chain.	2023 - 2024
CO_2LIQMET Flow Metering	Development of a CO_2 flow reference system for high to extreme high pressure and low temperature applications, liquid and dense phase CO_2.	2023 - 2024
KFX-CO_2	Development of CO_2 dispersion simulation technology for 3D industrial analyses, which considers important effects of CO_2 thermodynamics, geometries, topography and atmospheric conditions.	2019 - 2024
Skylark (CO_2Dispersion)	Address challenges related to the dispersion behavior of CO_2 that are important for pipeline risk assessment, operational practice and emergency response	2024 - 2027

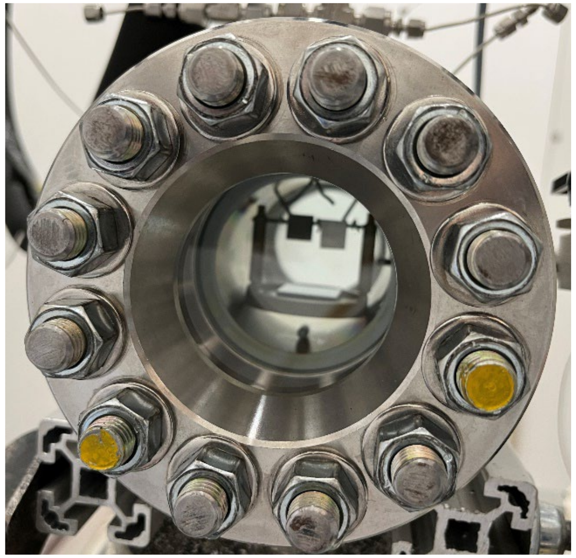
Norway IFE (Institute For Energy) Dense Phase JIPs

JIP #1: Kjeller Dense Phase CO_2 Corrosion IV (KDC-IV) - Objective

- Provide a tool for simulation of solubilities and chemical reactions in dense phase CO_2 by extending the capabilities of the OLI thermodynamic model to include reactions in dense phase CO_2.
- Provide experimental results that can be used by the CCS industry to prevent negative effects of impurities with respect to chemical reactions, corrosion and formation of solids in the CO_2 transportation system.

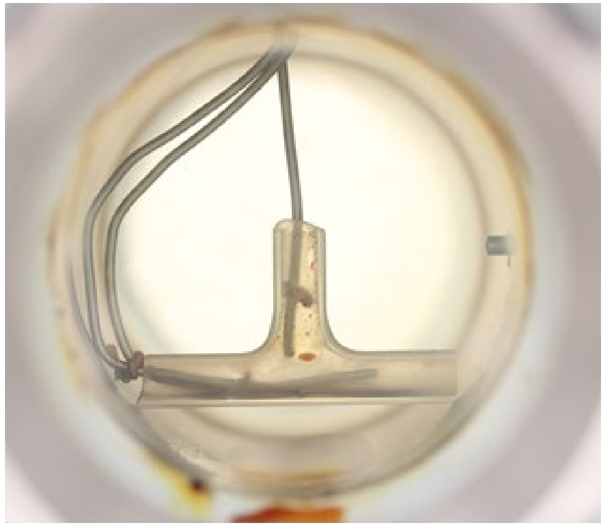
JIP #1: KDC-IV … Scope

1. Effect of low (but not zero) impurity concentrations, e.g. low ppm NO_2, and 10 ppm of H_2S, SO_2, O_2
2. Low pressure or low temperature conditions (including gas phase CO_2)
3. Practical consequences of liquid phases (corrosive phases, including acids)
4. Partitioning of impurities (in two-phase situations)
5. Thermodynamic modelling (OLI): Experimental results from the JIP will be used to improve the dense phase CO_2 prediction capabilities in the OLI model



Extensive laboratory capabilities with close control of impurities in dense phase CO_2

(a) 20 hours: SO_2 /O_2



(e) 102 hours: All impurities

*Morland, Tjelta, Norby, Svenningsen, *International Journal of Greenhouse Gas Control, 87, (2019) pp. 246-255.*
**Morland, Dugstad, Svenningsen, *International Journal of Greenhouse Gas Control, 119, (2022) p. 103697.*

JIP # 1: KDC-IV … Participation & Timeline

Participants

Shell	Neptune Energy
TotalEnergies	Gassco
Equinor	EBN
BP	ArcelorMittal
Chevron	Vallourec
ExxonMobil	AirProducts
Saudi Aramco	Fluxys
Wintershall Dea	Gasunie

Possible to join for new companies against an entrance fee giving access to previous JIP results

Duration

Four years, Sept 2023 – June 2027

IFE JIP #2: CO2WellMat-II … Objective

- Determine the maximum acceptable concentrations of impurities in CO2 when they are present in various combinations in a CO2 injection well

- Determine critical conditions (temperature and CO2/water ratio) for pitting and cracking of 13% Cr steel exposed in brine and condensed water equilibrated with the specification

- Determine critical conditions (temperature and CO2/water ratio) for pitting and cracking of 22%Cr and 25%Cr steel (or other alternatives to 13% Cr) exposed in brine and condensed water equilibrated with various CO2 blends

- Develop guidelines for downhole corrosion in CO2 injection wells based on experimental data generated in the CO2WellMat and KDC projects

IFE JIP #2: CO2WellMat-II … Scope

- High temperature testing, up to 120 °C
- Other impurities; effects on partitioning and corrosion
  - Determine acceptable limits for NO_2, SO_2, CO and H_2S for different materials
- Test materials: Super 13Cr, 22Cr (Duplex), 25Cr (Superduplex), Alloy 625 and/or others
  - Selection of materials to be included is still under discussion
- More targeted crevice tests (critical size, critical temperature)
- More accurate determination of O_2 partitioning
  - Expand the temperature range
  - Explore the pressure dependence
- Look into the consequence of large O_2 concentrations in the aqueous phase. What does it take to bring Cr-steels out of the passive range and into a pitting range?
  - Electrochemistry (potential sweeps)
  - Interplay between pH, chloride and O_2

JIP # 2: KDC-IV … Participation & Timeline

Participants

Shell
ExxonMobil
Cohillips
WinnocoPtershall Dea
Neptune Energy
Vallourec
Tenaris
JFE
Halliburton
Tubacex
Nippon Steel
Repsol

Duration

2 ½ years, Sept 2023 – June 2026

Possible to join for new companies against an entrance fee giving access to previous JIP results

Corrosion in CO_2 Transmission Pipelines (CCT) JIP

Yoon-Seok Choi

Associate Director for Research
Institute for Corrosion and Multiphase Technology
Ohio University

Create for Good.

February 2024

RUSS COLLEGE OF ENGINEERING AND TECHNOLOGY

OHIO UNIVERSITY

CCT JIP Objective and Goals

Objective: Identify and quantify the key issues which impact corrosion of materials specifically relating to the integrity of structures for the CO_2 transport pipelines.

Goals:

- To understand the effect of a wide range of impurities (O_2, SO_2, NO_2, H_2S, etc.) on **the water/acid solubility and the speciation** in dense phase CO_2.
- To develop a **thermodynamic model** for predicting the water/acid solubility and the speciation in dense phase CO_2 in the presence of impurities.
- To determine impact of **environmental parameters (pressure, temperature, flow, and impurity types and concentrations)**, both individually and synergistically, on **steel corrosion** in both dense phase CO_2 and aqueous phase in the presence of impurities.
- To develop a **mechanistic model** to predict the corrosion processes in order to help determine facility lifetime.

Duration: 3 years (Jan. 2023 ~ Dec. 2025)

CCT JIP Scope of Work and Deliverables

Scope of work

- **Part 1. Thermodynamic study:** Develop a thermodynamic model of solubility of water/acid and speciation in dense phase CO_2 in the presence of impurities like SO_2, NO_2, H_2S and O_2.
- **Part 2. Corrosion study:** Evaluate long-term corrosion behavior under water unsaturated dense phase CO_2 in the presence of various impurities.
- **Part 3. Model development:** Develop a mechanistic model, which can predict the rate and mechanism of corrosion of steel in dense phase CO_2 with impurities.

Deliverables

- Biannual reports
- Thermodynamic and corrosion prediction models
- Guideline for impurity concentrations in corrosion mitigation

Sponsors: Baker Hughes, BP, Chevron, ConocoPhillips, Enbridge, Equinor, EVRAZ North America, ExxonMobil, Occidental Oil Company, Petrobras, Saudi Aramco, Shell, Slb, Tenaris, TotalEnergies.

PRCI Gap Analysis Results

CO2 Gap Summary

Area	Idea	Project Code	Proposed Project Idea Title	Rank	Sub area	GAP	Ideas	Work type
Corrosion	3647	ALT-1-8	Corrosive Impact of Trace Components in Transport of C02	1	A - Effect of impurities on corrosion of Transportation and Storage Pipeline Assets	Corrosion mechanisms not completely know. Need to better model corrosion rate. Lack of experimental results. Acid drop out scenarios and consequences not covered in standards	Lab work e.g. electrochemical methods, autoclave testing, to improve understanding of mechanisms	Lab Testing
Corrosion	3648	ALT-1-8a	Validation for water and acid solubility in CO2 with impurities	1	B - Thermodynamic models	Need more validation for water and acid solubility in CO2 with impurities	Lab tests to measure water and acid solubility in CO2 stream with impurities. Compare to existing thermodynamic models	Desk Study/Lab Testing
Corrosion	3649	SSC-02-16	Cracking and corrosion fatigue in CO2-H2O-CO. H2 gas embrittlement	2	C - Stress Corrosion, Fatigue and Cracking	SSC and HIC due to H2S. Cracking and corrosion fatigue in CO2-H2O-CO. H2 gas embrittlement	Lab SSC crack initiation (e.g. four point),fracture mechanics+ HIC tests different CO2+H2S+H2O levels+ pipe grades, age, sour/non (phase I)	Lab Testing
Corrosion	3650	ALT-1-7	Guideance for CO2 Specifications for Pipeline Transport & Storage	3	F - CO2 specifications	Lack of detailed guidance to a CO2 specification (limits for minor components)	Create a 1st guideline/RP with threshold ranges for key impurities based on this review. Can incorporate advice on scenarios where impurity levels can be relaxed, reporting the limited experimental dataset where no corrosion occurs, show tentative limits for cracking etc.	Desk study
Corrosion	3651	NDE-X-X	Inline Inspection Tools for Dense Phase		G - Any Other Gap	Corrosion inline inspection tools for dense phase CO2 service		
Fracture	3653	MAT-8-6a	Review and Refine EOS for CO2 Transport	2	A - EOS	A reference equation of state	Compare different EOS and define the better to use	Desk Study/Modelling
Fracture	3652	MAT-8-7	Full Scale Fracture Propagation Test with Gas Phase C02	1	B - Fracture Propagation	Extend the range of applicability of the empirical methods (cf. DNV-RP-F104). Need improved prediction models (BTCM, FEA). Need experimental verification for gas CO2	Lab and full scale testing in different conditions to extend the range of applicability of the empirical methods (cf. DNV-RP-F104)	Lab/Full Scale Testing
Fracture	3654	MAT-8-8	Effects of C02 on the ductile to brittle fracture initiation transition temperature	3	C - Fracture Initiation	Warm Pre-stressing to be investigated	(Additional) Experimental validation of Warm Pre-stressing	Lab/Full Scale Testing
Fracture	3655	MAT-8-9	Guidelines for Crack Arrest Design for CO2 Pipelines	3	D - Crack Arrestor	No established guidelines for CA design for CO2. Limited full scale tests results available	Develop CA design guidelines for CO2	Desk study/Modelling

CO2 Treating / Quality
EOS
Fracture Propagation
Odorants
Dispersion

CO2 Gap Summary

Safety / Dispersion	**3658**		**Building CO2 Transmission Pipelines: A Primer**	**3**	**A - Social acceptance**	Bad perception about CO2 pipelines safety	Proving that CO2 pipelines are as safe as NG pipelines by performing comparative risk analysis in different scenarios	Desk study
Safety / Dispersion	**3657**		**Evaluation of Odorants fo C02 Service**	**2**	**B - Leak identification**	CO2 is odourless and can not be detected during leakage	Investigation of potential costs and benefits (in terms of social acceptance) of adding odorant in CO2 pipelines	Desk study
Safety / Dispersion	**3656**	**ALT-1-9**	**Decompression Radius Modelling of CO2 Pipeline Rupture**	**1**	**E - Release**	Poor release modelling. Models does not describe CO2-fluid interaction (H2O acidification) for offshore. Impact of running ductile failure length on consequence modelling setup and results	Develop better release modelling (3-phase) and testing	Modelling
Re-purposing	**3661**	**API-2-3**	**Literature Review of Technical Stamdards applicable to CO2**	**2**	**B - Standards**	Not all technical items properly covered in the current standards, update needed	Sistematic review of technical items in pre-standardization form	Desk study
Re-purposing	**3660**	**EC-02-14**	**Comprehensive Metal-Loss Assessment Criterion for CO2 Pipelines**	**1**	**C - Pipeline status**	How to deal with aged pipeline materials and/or poor material data	Develop criteria and testing for assessing aged materials	Desk study/Lab Testing
Re-purposing	**3662**	**MAT-7-1a**	**Non-Metallic Material Components for CO2 Pipelines**	**3**	**D - Non-metallic materials**	Material compatibility need to be assessed for components, i.e Flange Gaskets, seals, etc.	Develop testing procedure and criteria for non-metallic materials	Lab Testing

CO2 Treating / Quality
EOS
Fracture Propagation
Odorants
Dispersion