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DEVELOPING DESIGN AND WELDING REQUIREMENTS INCLUDING MATERIAL TESTING AND QUALIFICATION OF NEW AND EXISTING PIPELINES FOR TRANSPORTING CO_2

Research Contract #693JK32210007POTA

US Department of Transportation (US DOT)
Pipeline and Hazardous Materials Safety Administration (PHMSA)
Pembina Pipeline Corporation

Project Overview Agenda

- Project Team
- Project Background and Objectives
- Project Scope of Work

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Project Team - Execution Involves Input From

- US Department of Transportation (US DOT)
  Pipeline and Hazardous Materials Safety Administration (PHMSA)

- Pembina Pipeline Corporation

- BMT Project Team

- Technical Advisory Panel
  - With representatives for API, PRCI, Operating Companies, Universities and Technical specialists

Background

- Recognizing the need to develop CO_2 pipeline regulations to support expansion of CO_2 sequestration endeavours, PHMSA called for proposals to support this work
- The BMT proposal identified gaps in process regulation and industry knowledge base
  - Relevance of existing pipeline practice
    - Operations, maintenance and FFP
  - CO_2 decompression process
    - Effect of impurities and implications on operations (blow down) and ductile fracture
  - Moisture response and limits
    - In service and failure effects
  - Dispersion risk
    - Effects of environment (natural and man-made) and response
  - Non metallic performance
    - Inspection and fitting components
  - Leak detection
    - Odorants or other monitoring tools

Project Objective

- Objective of this project is to identify unique aspects of CO_2 pipeline design, integrity, and operational considerations that are not well supported by existing knowledge and to define processes and procedures to fill these safety gaps.
- Work to identify performance-based safety targets for CO_2 pipelines by
  - Define CO_2 pipeline state-of-knowledge (pipeline design, integrity, and operations)
  - Identify technical challenge groups and which are supported by proven theory, trials, and data
  - Compare and contrast conventional and CO_2 design, integrity, and operational regulatory requirements and industry best practices
  - Define and demonstrate gap filling procedures or data, and identify future research needs
- Results to support development of best practices, regulations, and research requirements for design and conversion of pipelines for CO_2 service with proven demonstrable levels of safety.

Project Scope of Work

1. State of Knowledge Information Collection & Review
2. Layer of Protection Analysis (LOPA)
3. Demonstration of Identified Design & Operational Issues
   a. Line Pipe Material Properties . . . . Long running facture control
   b. Release Event Cooling and CO_2 Equations of State
   c. Release Event CO_2 Dispersion
   d. Management of Non-Metallic Components
   e. Other Operational Concerns . . . . Leak detection / odorization

Task 2. State of Knowledge, Information Collection, & Review (Part 1)

- Build on previous literature and gap analyses focused on pipeline lifecycle

Design & Construction

- Material challenges and requirements
- Welding challenges and requirements
- CO_2's potential impact on High Consequence Areas or sensitive location factor locations, and design factors (e.g., outcomes of dispersion modelling/valve spacing, etc.)
- Fracture control (Line pipe toughness, External mitigation measures (arrestors))
- Global codes & standards for design and construction of CO_2 pipelines
- CO_2 decompression behavior and effect of impurities (equations of state)
- Selection of non-metallic components to withstand effect of CO_2

Integrity & Maintenance

- CO_2's impact on pipeline damage mechanisms (e.g., internal corrosion)
- Fracture behavior of line pipe steel
- In-service repairs (e.g., in-service welding of hot-taps or Type B sleeves)
- In-line inspection tool performance / longevity in CO_2 environments (e.g., tool wear on pipe surface)
- Global codes & standards for integrity and maintenance activities on CO_2 pipelines
- Pipeline depressurization strategies

Operations

- Estimation of release volumes and associated potential asphyxiation areas
- Strategies for minimizing or eliminating CO_2 release for maintenance in highly populated areas
- Requirements for valve spacing
- Effect of impurities and moisture levels on damage mechanisms / operations
- Odorization options
- Blowdown and depressurization event requirements (Emergency Response)
- Post-rupture safe distances
- Personal protective equipment (PPE) requirements
- Separation distances from blowdown locations (protection from freezing)
- Conversion of existing oil & gas pipelines to CO_2 service including minimum pipe material mechanical properties to support conversion considering operating pressure and product
- Requirement for fracture arrestors (e.g., required spacing for older lower toughness lines, requirements for HCA's, etc.)

Task 2. State of Knowledge, Information Collection, & Review (Part 2)

- The focus of this effort is on differences between conventional oil and gas pipelines and CO_2 pipelines
- Build upon previous literature and gap analyses to produce
  - A reference bibliography
  - A summary of current knowledge and challenges for CO_2 pipelines
  - A basis to guide the LOPA and future work.

Task 3. Layer of Protection Analysis (LOPA) - Part 1

- Complete a CO_2 pipeline LOPA followed by an industry stakeholder workshop to systematically
  - Identify hazards considering ASME B31.4 operations and maintenance threats to pipeline integrity
  - Organized by life cycle concerns
  - Consider what can go wrong and what protections (or controls) exist.
- Identified hazards will be matched to controls including:
  - Conventional pipeline regulations
  - Industry standards
  - Available research
- Recommendations will be given to support development of regulations and standards
  - Fracture control
  - Release volume and dispersion
  - Nuances associated with the properties of CO_2 (including trace elements) and its phase behavior

Task 3. Layer of Protection Analysis (LOPA) - Part 2

- The LOPA will be completed with a report defining:
  - Range of CO_2 pipeline applications that have been considered to-date
  - Strength of the technical basis for each hazard control
  - Weaknesses or gaps in knowledge and challenges for CO_2 pipeline design, maintenance, and operation
  - Listing of future research or concept demonstration projects

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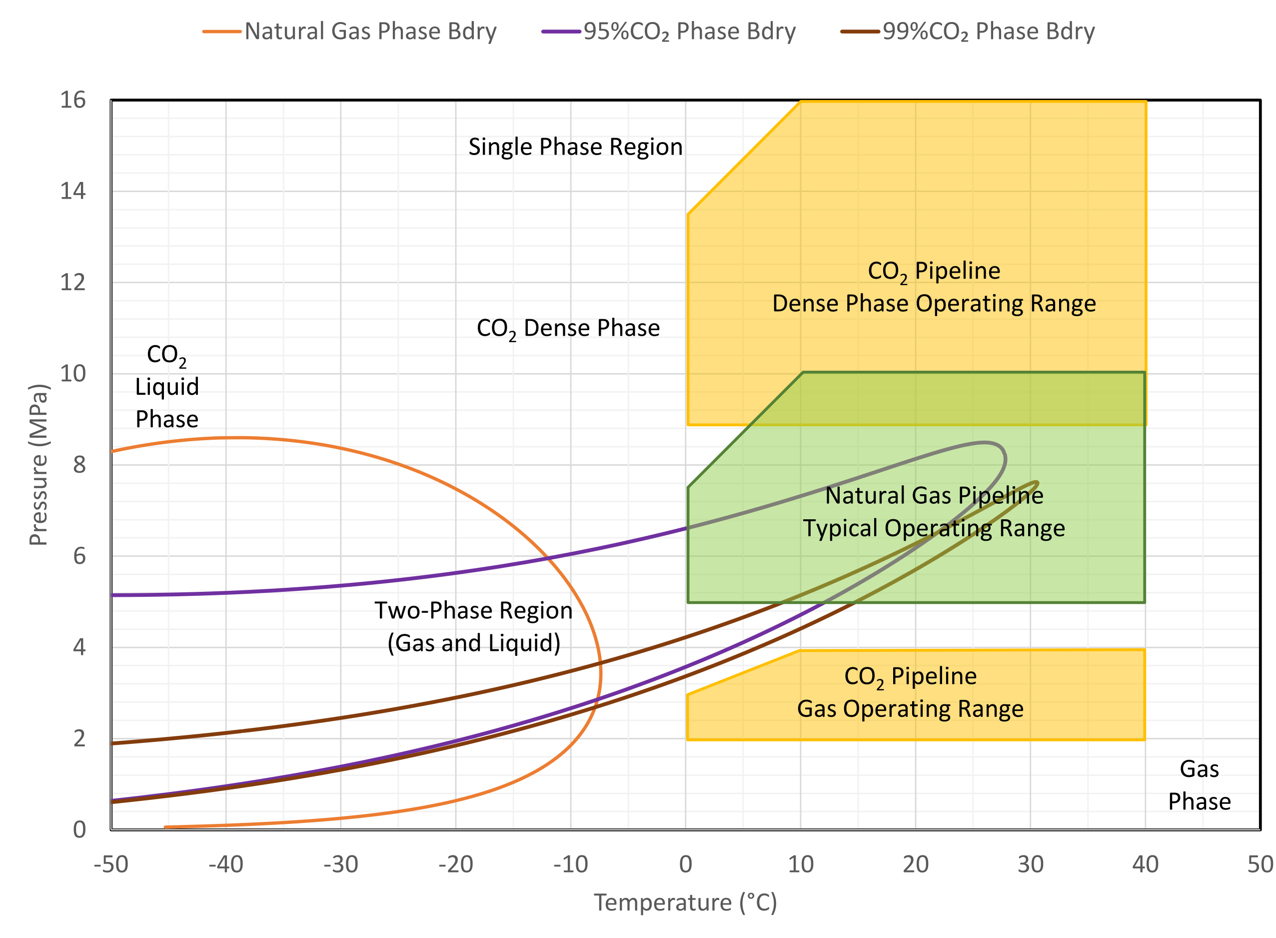
Task 4. Demonstration of Identified Design & Operational Issues

- Demonstrate and discuss processes that contribute to hazards, and the strategies and procedures that can be used to mitigate hazards
  - Task will not completely resolve or fill technical gaps
  - Provide recommendations for future work
  - Define performance based requirements
    - Demonstrate techniques suitable for CO_2 pipeline design, maintenance and operational condition evaluation
  - Highlight areas where existing regulations can be strengthened to guard against design and operational issues

Task 4a. Line Pipe Material Properties – Long running facture control (Part 1)

- Design and operational differences between natural gas pipelines and CO_2 pipelines are driven by the differences in properties of the two gases — in this case the differences in phase behaviour
- The two-phase region of CO_2 intrudes into the normal operating range of conventional oil and gas pipelines forcing CO_2 pipelines to operate
  - At high pressure in the dense phase above phase boundary—typically above 9 MPa (1300 psi)
  - At low pressure in the gas phase below the phase boundary—typically below 4 MPa (600 psi)
- When CO_2 pipelines depressurize for any reason
  - Dense phase CO_2 decompresses into the two-phase region creating design & operational issues
  - Gas phase CO_2 decompresses mostly in the single phase and is relatively free of design and operational issues due to phase behavior (except for its low operating pressure)



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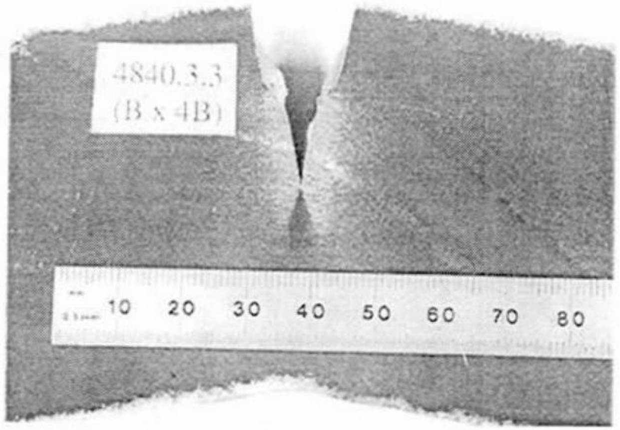
Task 4a. Line Pipe Material Properties – Long running facture control (Part 2)

- Control of longitudinal running ductile fractures in pipelines uses two basic strategies
  - Prevent fracture initiation by keeping flaws from critical size (construction QA/QC or IM in-service)
  - Prevent fractures propagation after initiation - fracture resistant pipe (grade, thickness and toughness)
- The strategies are the same for both natural gas and CO_2 pipelines, except for one major unresolved difference—how to design fracture resistant pipe for dense phase CO_2 pipelines
- The BTCM has been developed for pipeline industry based on natural gas pipe burst tests
- The BTCM will not work for dense phase CO_2 pipelines without significant modification

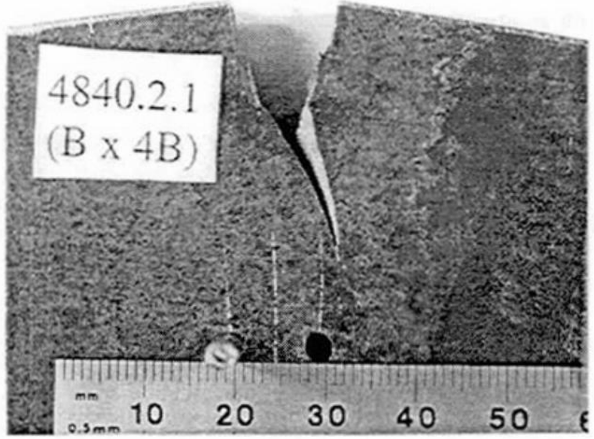
- There has not been enough testing with dense phase CO_2 to gain a basic understanding of why it doesn't work for dense phase CO_2 pipelines, and there has been no testing with gas phase CO_2 pipelines

Task 4a. Line Pipe Material Properties – Long running facture control (Part 3)

- Scope of Work for this Project
  - Review previous work
  - Analyse burst test results reported in the open literature
  - Test vintage and modern steels to identify differences in transition curves
    - Up to 15 materials . . . . Input from TAP will be sought
    - Consider effects of temperature and strain rate on initiation and propagation resistance
    - Include material characterization, CVN for all materials and modern arrest energy methods for select materials
  - Define role of girth, long seam and spiral welds in fracture control



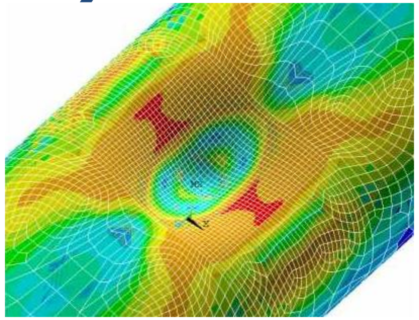
Higher CTOA or Fracture Strain

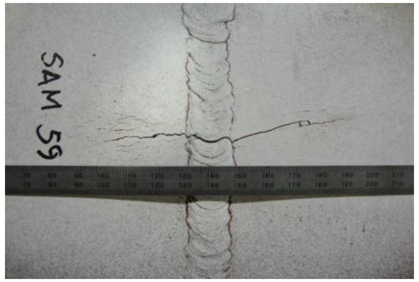


Lower CTOA or Fracture Strain

Task 4a. Demonstration of Identified Design & Operational Issues – Material Properties (Part 4)

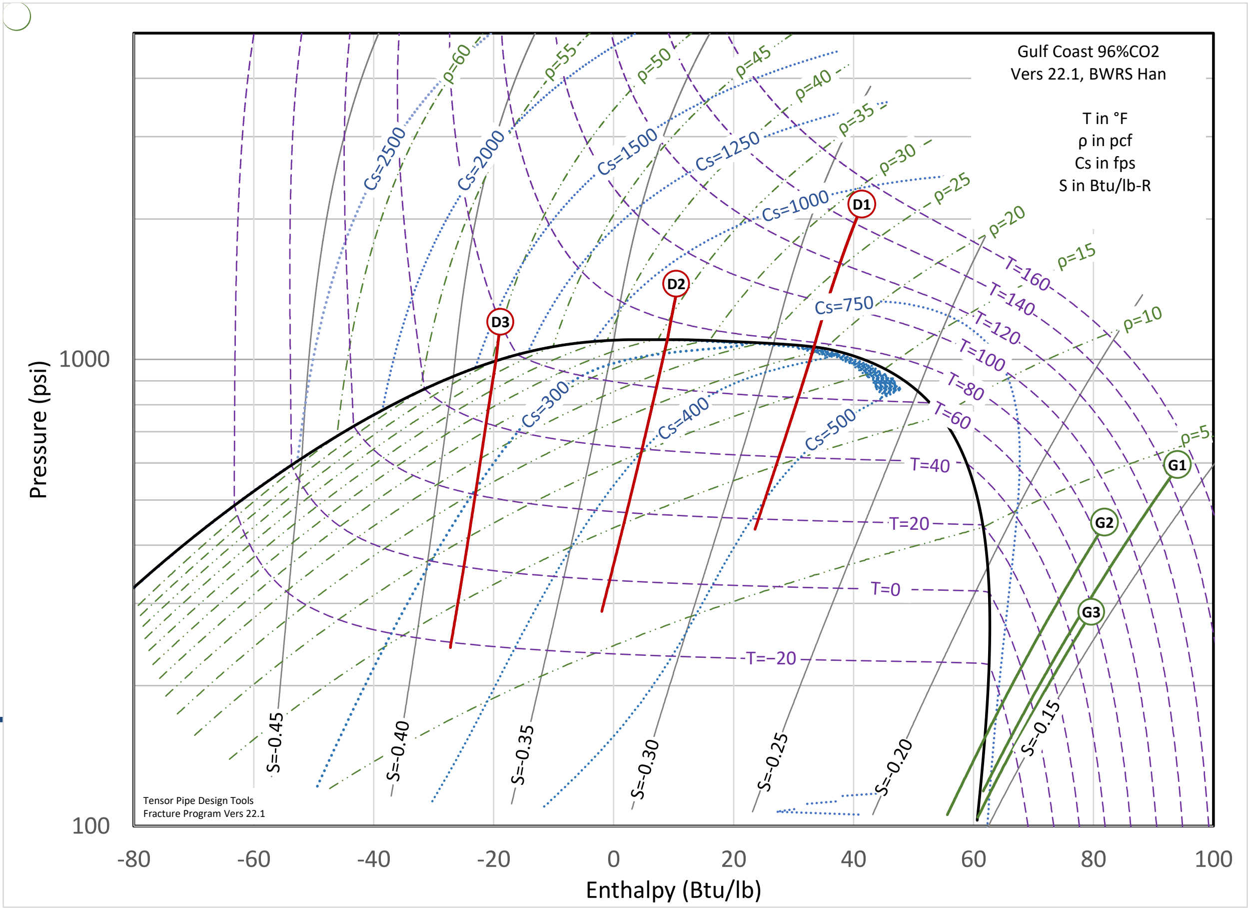
- Collect and consider operational data from SCADA data
  - Maximum operating pressure
  - Cyclic pressure data
  - Frequency of depressurization
- Consider, safety drivers associated with pipeline and operations:
  - Rate of damage accumulation for a range of features
    - Dents, corrosion, cracks
  - Identify expected frequency of CO_2 pipeline depressurization and its impact on safety
  - Present relative sensitivity to feature types for conventional liquid and gas versus CO_2 pipelines





Task 4b. Release Event Cooling and CO_2 Equations of State (Part 1)

- When dense phase CO_2 decompresses into the two-phase region after a burst (or in a blowdown stack) it first forms an homogeneous mixture of heterogeneous components (liquid clusters and gas), which has properties that may not be as well understood as they could be
- After its pressure has fallen to 500 psi, the hoop stress is low (about 15%SMYS) and its temperature is still quite high, e.g. +20°F (-7°C), so that longitudinal brittle fracture is not a problem
- Towards the end of the depressurization when internal pressure and hoop stress are both very low, wall temperature can also be very low e.g.−110°F(−80°C) and axial tension at the girth welds can cause brittle fracture issues



Task 4b. Release Event Cooling and CO_2 Equations of State (Part 2)

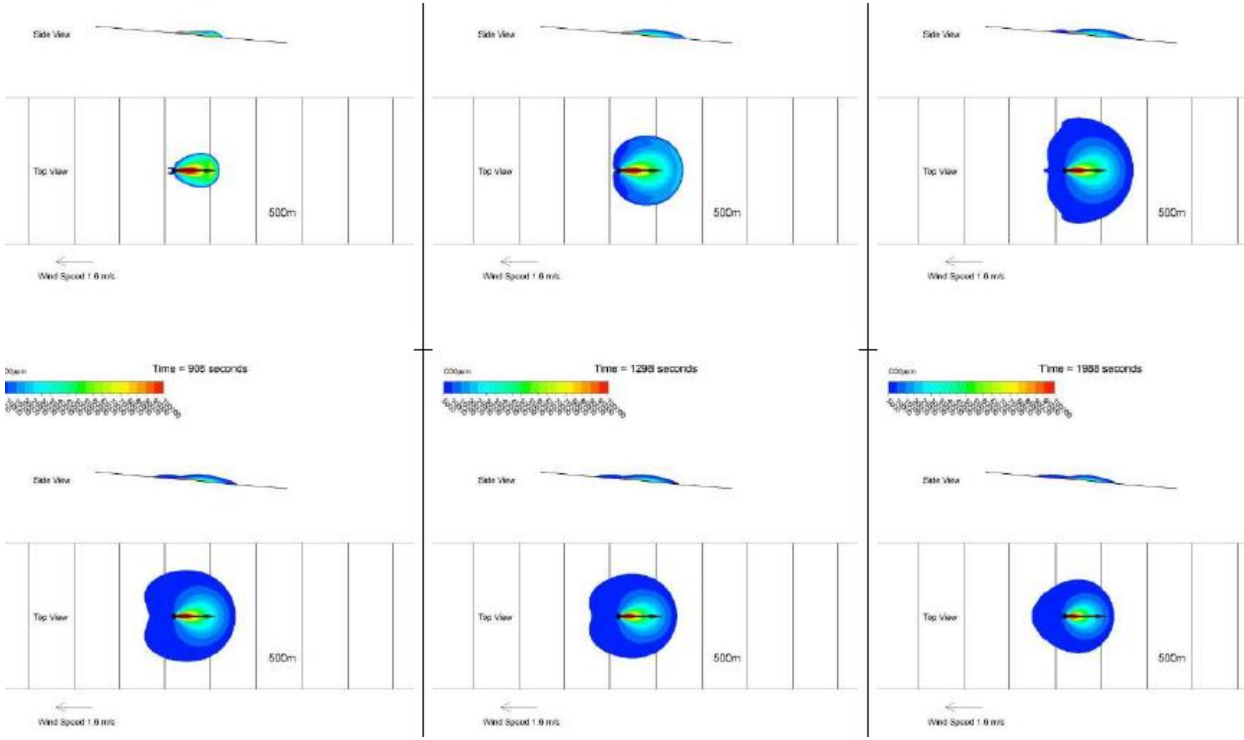
- To help understand the decompression process, collect and analyze data from up to ten sets of decompression data available in the open literature or from other sources
  - Apply analytic and CFD modelling to predict CO_2 pressures and temperatures, and pipe wall temperatures during planned and unplanned release events using gas properties from equations of state and compare with available measured data
  - Because natural gas has potential to cool to lower temperatures than CO_2 during rapid decompression, compare natural gas and CO_2 pipe wall temperatures during decompression following a burst, and during
  - Determine the extent to which conventional design practices for natural gas pipelines can be leveraged for CO_2 pipeline design, and recommend areas of special concern that need to be considered in design and operation of CO_2 pipelines

Task 4b. Release Event Cooling and CO_2 Equations of State (Part 3)

- While experimental gas decompression trials are not included in the scope of work
  - Available detailed data measurements from shock tube tests will be analyzed and compared with predictions using existing theories of two-phase decompression and equations of state
  - A testing process and plan will be developed to look for systematic differences between measured and predicted data that may
    - Indicate overlooked principles at work during rapid decompression of dense phase CO_2
    - Explain faster crack propagation and higher required toughness than the BTCM predicts
  - The testing process and plan may be used
    - To support a program to validate equations of state by investigating the impact of different CO_2 compositions and impurities such as nitrogen, SOx, NOx, CO
    - In future research to further validate the CO_2 equations of state and physical principles used in decompression event evaluation, including poorly understood mechanisms such as the speed of liquid nucleation in CO_2 mixtures, and the effects of heat transfer and friction

Task 4c. Demonstration of Identified Design & Operational Issues – Release Dispersion (Part 1)

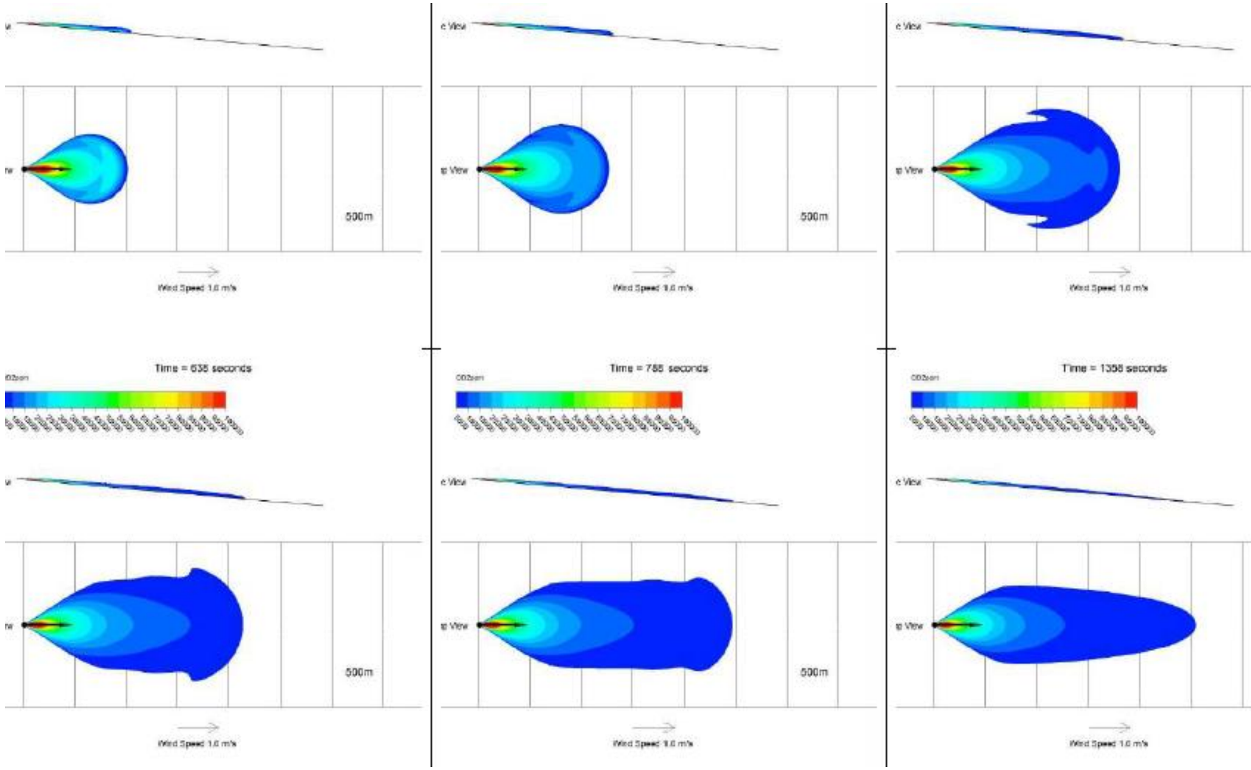
- Employ previous testing and observations to demonstrate CFD dispersion process
  - Both failure and operational (blowdown) events
  - Complete up to twenty analyses to discuss release rate impact on public/first responders and risk of asphyxiation considering
    - Through wall feature size and pipeline pressure
    - Operational response and valve spacing
    - Local topology and wind speed



Full bore CO_2 release / 5 degree slope / low wind uphill / release downhill

Task 4c. Demonstration of Identified Design & Operational Issues – Release Dispersion (Part 2)

- Define high consequence zone and safe response distance in the absence of SCBA
  - Definitions will be demonstrated based on position/concentration/time history data
- Consider training for public on right of ways and safe-proofing houses and buildings
  - Development of an outline of the requirements for public information, training and safety.
- The scenarios being considered will be discussed with the TAP before proceeding



Full bore CO_2 release / 5 degree slope / low wind downhill / release downhill

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Task 4d. Demonstration of Identified Design & Operational Issues – Non-Metallic Materials

- Impact of CO_2 on non-metallic components and equipment vital to pipeline operation will be described
  - CO_2 does not behave as a lubricant and can promote premature wear (e.g. valve seats, gaskets, ILI tool components)
  - Known problems will be defined
    - Explosive decompression of certain plastics
    - Loss of function to pressure-bearing components
  - Causes and cures associated with these issues will be documented.
  - No testing is expected, however, an outline test plan to demonstrate these issues will be defined.

Task 4e. Demonstration of Identified Design & Operational Issues – Leak Detection and Odorization

- To ensure the safety of CO_2 transportation, concerns related to
  - Gas/leak detection
    - Odorization
    - Mass balance
    - CO_2 detection in low areas and communities adjacent to ROW
    - Fiber optic leak detection
  - Impact of impurities and moisture in the CO_2 product stream will be discussed
    - Effect on gas behavior
    - Precipitation of dissociated acids in the pipeline or at release sites
  - The task will produce a listing of
    - Existing knowledge and solutions
    - Techniques for evaluating these concerns
    - Suggested research programs to fill gaps that are identified.

Thank you for your attention

Questions?