Low Temperature Brittleness and Ductile Propagation Testing in CO₂ Depressurizing Scenarios

Roadmap for CO₂ Transport Fundamental Research Workshop

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CO₂ Phase Diagrams

Typical operating range for pipelines spans multiple CO₂ phases.

Two options:
- Low pressure gas phase
- High pressure dense phase

As dense phase CO₂ decompresses to atmospheric pressure, the pipe gets very cold.
DNV Spadeadam Test Site

General wind direction

West

East
Flange Releases – Low Temperature Leaks

- Spadeadam research on releases from flanges on dense phase CO₂ pipe
- Potential low temperatures on flange and bolts
- Mitigation by insulation
Depressurization Experiments

SS316, 2” OD, 0.335” WT

Release of dense phase 98.2%CO₂-1.8%N₂ mixture from rupture disc

Rapid temperature drop within 30 ms, down to -60°C (-76°F) after 4.5 s

Rise in temperature due to dry-out (no liquid left)

(a) Temperature at x = 0.080 m.

(c) Temperature at x = 46.085 m.

Charpy Impact Energy Transition Curve

At very low temperatures, pipe more likely to be brittle.

- Low toughness
- Catastrophic fracture
Does Brittle Pipe Mean Brittle Failure?

30” OD by 0.360” WT X60 pipe – 50%WT flaw

• Burst tests at decreasing temperatures.
  • Burst pressure did not decrease as the pipe moved from ductile to brittle area of toughness curve.
  • Ductile initiation is typically assumed up to 136°F below what is considered fully ductile.

• New PRCI project (IM-1-08) to validate this temperature shift for other pipe types.

Figure 8. Illustrating the fracture-initiation transition temperature for part-through-wall defects

PRCI Report No. PR-003-00108, 2001
Running Ductile Fracture in CO$_2$ Pipelines

Fracture control for dense phase CO$_2$ pipelines based off of saturation pressure.
**CO2SafeArrest – Test Layout**

Test 2 14.0 mm

Telescopic layout based on increasing required arrest pressure determined by broken Charpy specimens

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- **Exposed half**
- **Buried half**
Validation of fracture arrest models and design requirements will:

- Eliminate project specific full scale fracture arrest tests.
- Remove excessive conservatism (sufficient wall thickness and material properties identified).
- Reduce costs for new CO₂ pipeline projects.
Results Generated from the Tests

**Crack velocities**

**CO₂ concentration vs. time**

**Theoretical vs. actual crack tip pressure**

- **Wave Velocity [m.s⁻¹]**
  - 0 to 500

- **Pressure [barg]**
  - 25 to 150
General Observations from Large-Scale Tests

- CO₂ pipettrans
  - 2*16"

- Cooltrans
  - 2*36, 1*24"

- Sarco2B
  - 2*24"

- CO₂ Safe Arrest
  - 2*24"

- In total 9 tests

![Graph](image-url)

**Cut-off based on observations**

- Prop Cool
- Prop Sarco
- Prop Safe
- Arrest Cool
- Arrest Sarco
- Arrest Safe

**Demarcation line arrest/propagation**

**No experimental arrest observations**
Evaluation based on special assessments

Evaluation based on small-scale testing

Propagation expected

Certain range of validity
Safety Factors for Battelle Two-Curve Method (BTCM)

- Two full-size tests as part of COOLTRANS program – 36" OD, 1" WT, X65.
- Needs correction factor of 1.5 on BTCM to correctly predict all failures of Test 1, and correction factor of 2.4 for Test 2.
- A crack will propagate if any part of a crack velocity curve is below the fluid decompression curve.
- Validated for natural gas.
Key Takeaways and Next Steps

• A rapid phase change of CO$_2$ from liquid to gas can cause auto-refrigeration.
  • The pipeline components can become brittle, which will have deleterious consequences on integrity.
  • There’s limited empirical research of this phenomenon on full-sized pipelines.
  • New PRCI project to quantify the likelihood that fracture initiates in a brittle manner.

• Fracture propagation is a point of emphasis for dense phase CO$_2$ pipelines.
  • High saturation pressures require material properties that vintage pipelines likely do not possess.
    • Add crack arrestors
  • There’s limited empirical research to validate BTCM or extend the method in RP-F104 to cover most scenarios.