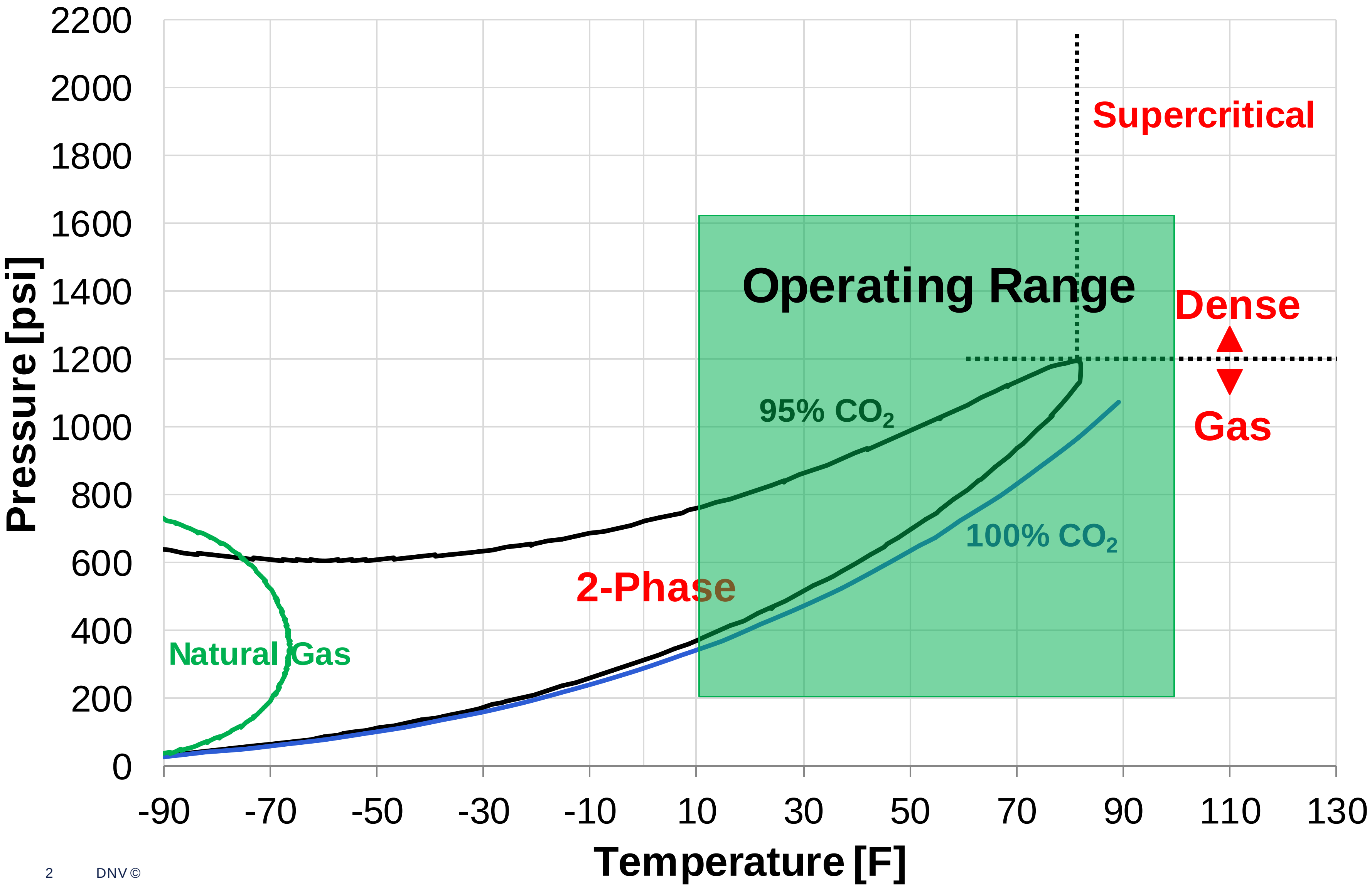
WHEN TRUST MATTERS

Low Temperature Brittleness and Ductile Propagation Testing in CO_2 Depressurizing Scenarios

Roadmap for CO_2 Transport Fundamental Research Workshop

Dr. Ben Hanna

CO_2 Phase Diagrams



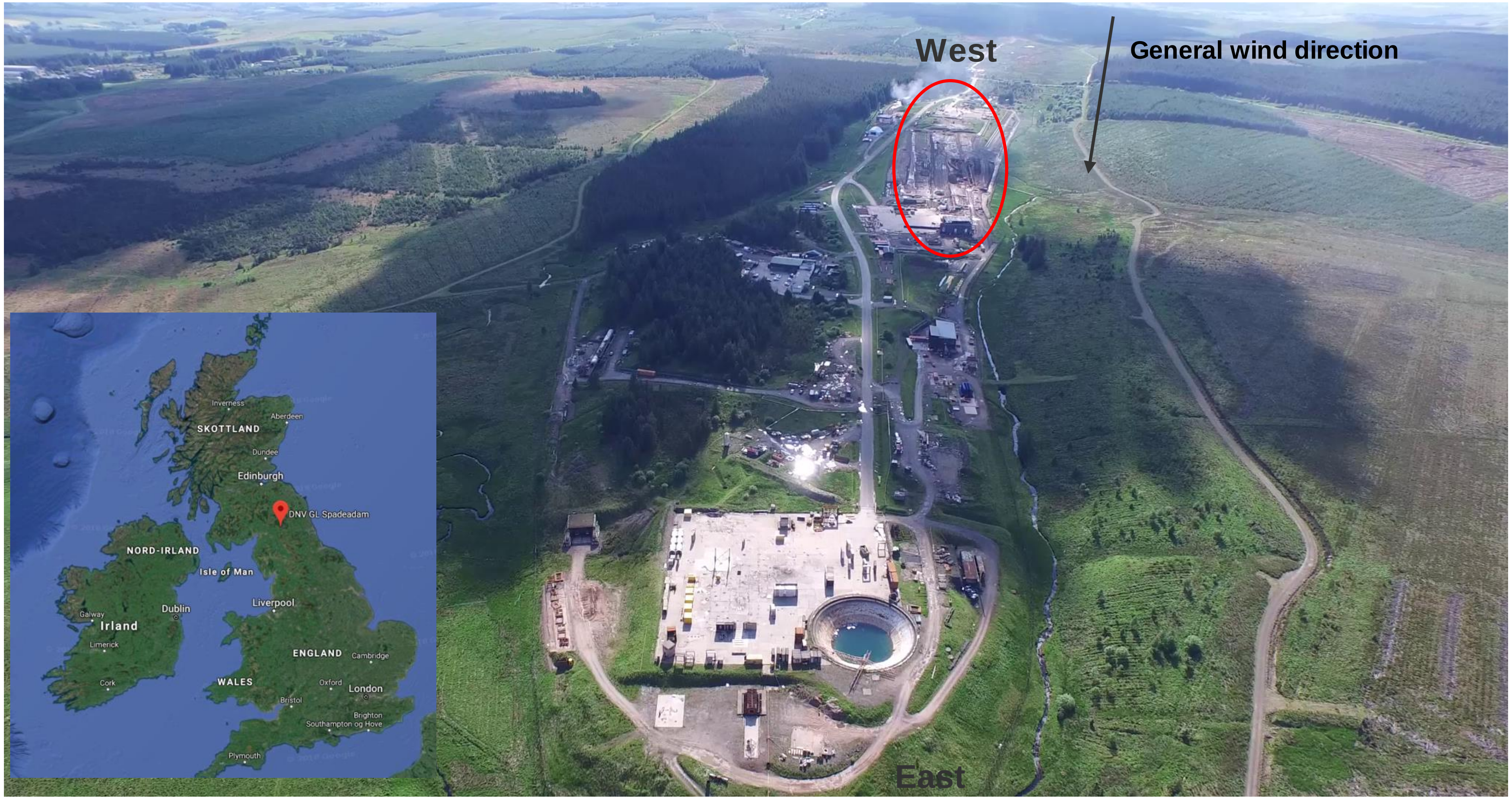
Typical operating range for pipelines spans multiple CO_2 phases.

Two options:

- Low pressure gas phase
- High pressure dense phase

As dense phase CO_2 decompresses to atmospheric pressure, the pipe gets very cold.

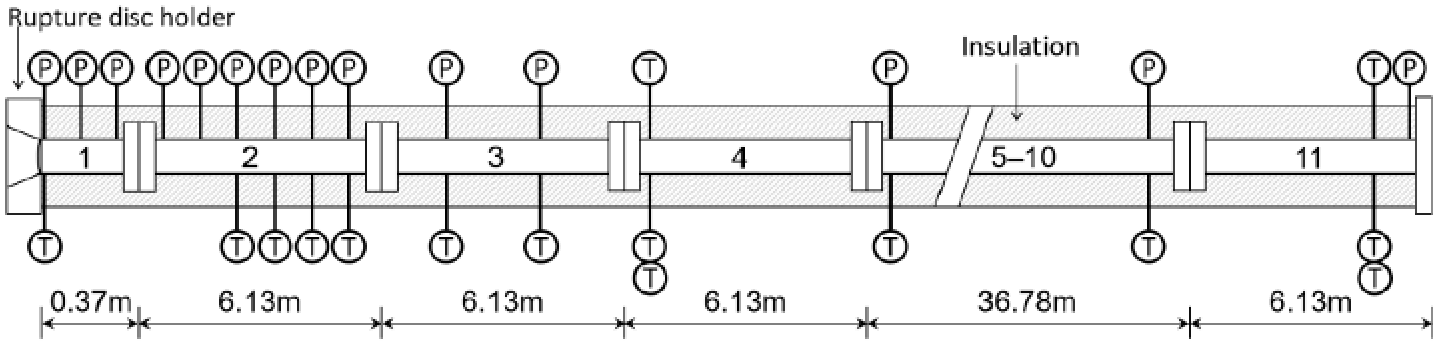
DNV Spadeadam Test Site

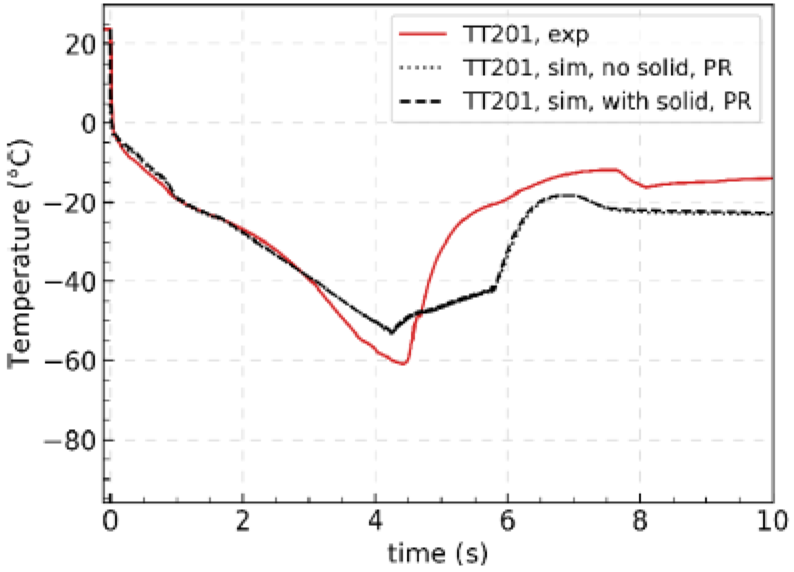


Flange Releases – Low Temperature Leaks

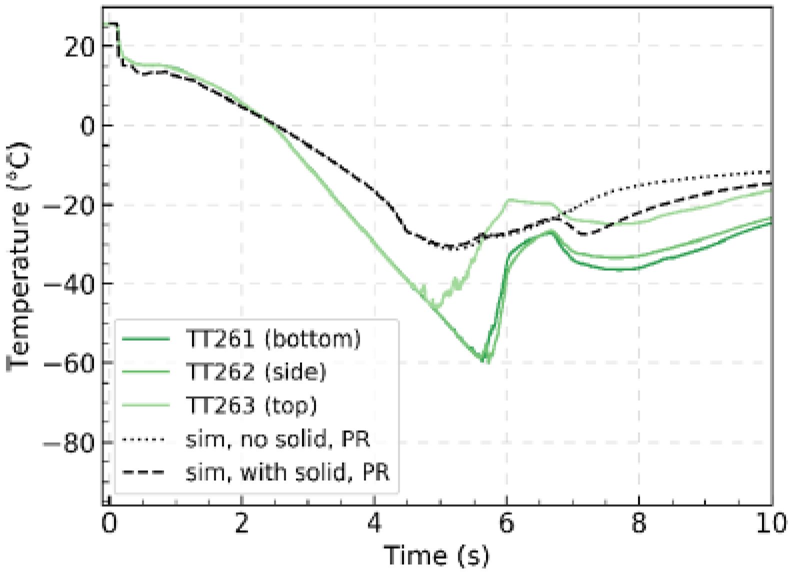
- Spadeadam research on releases from flanges on dense phase CO_2 pipe
- Potential low temperatures on flange and bolts
- Mitigation by insulation

Depressurization Experiments





(a) Temperature at $x = 0.080$ m.



(c) Temperature at $x = 46.085$ m.

SS316, 2” OD, 0.335” WT

Release of dense phase 98.2%CO_2-1.8%N_2 mixture from rupture disc

Rapid temperature drop within 30 ms, down to -60ºC (-76ºF) after 4.5 s

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

Munkejord, S.T. et al., International Journal of Greenhouse Gas Control 109 (2021)

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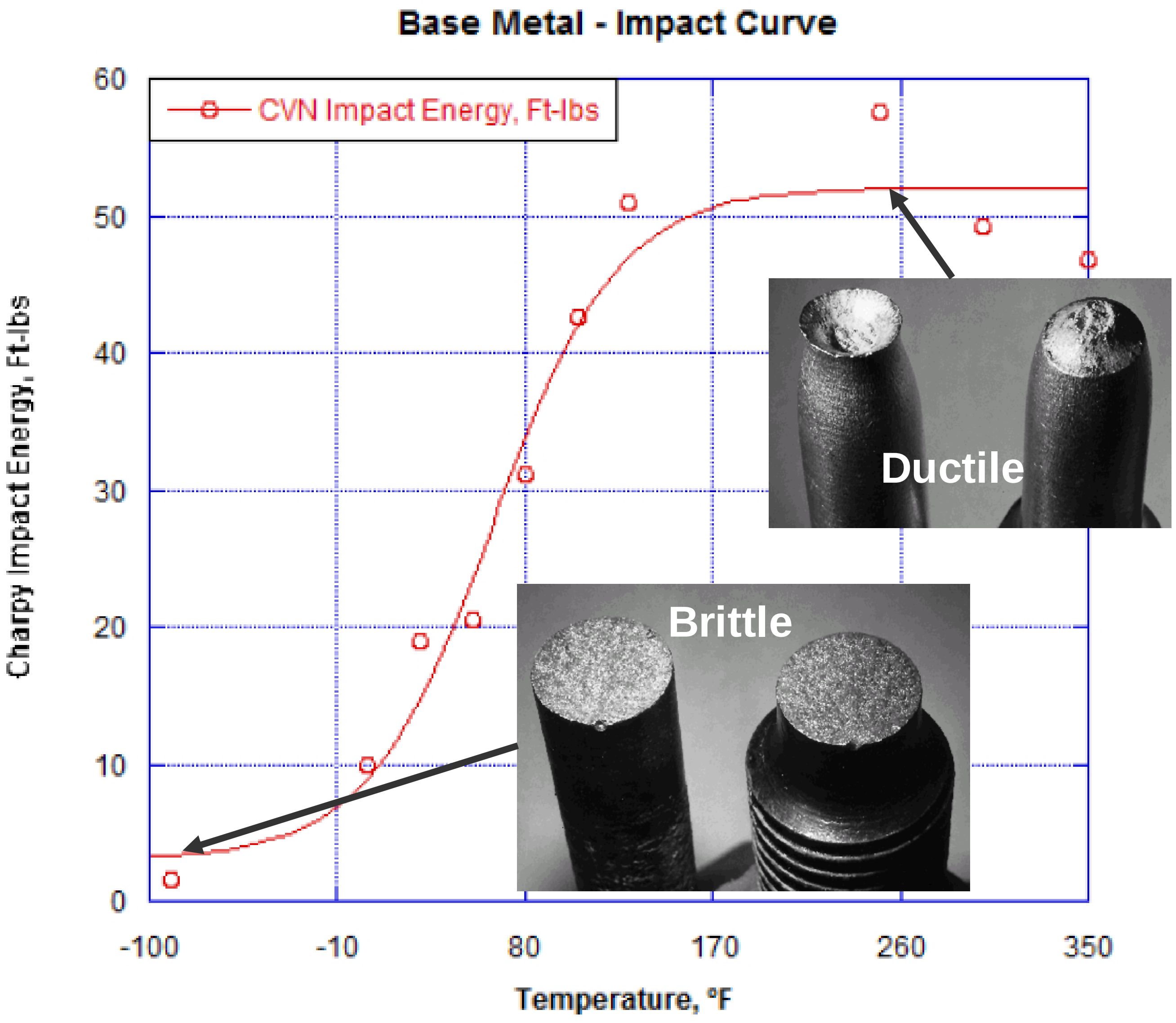
Charpy Impact Energy Transition Curve

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.

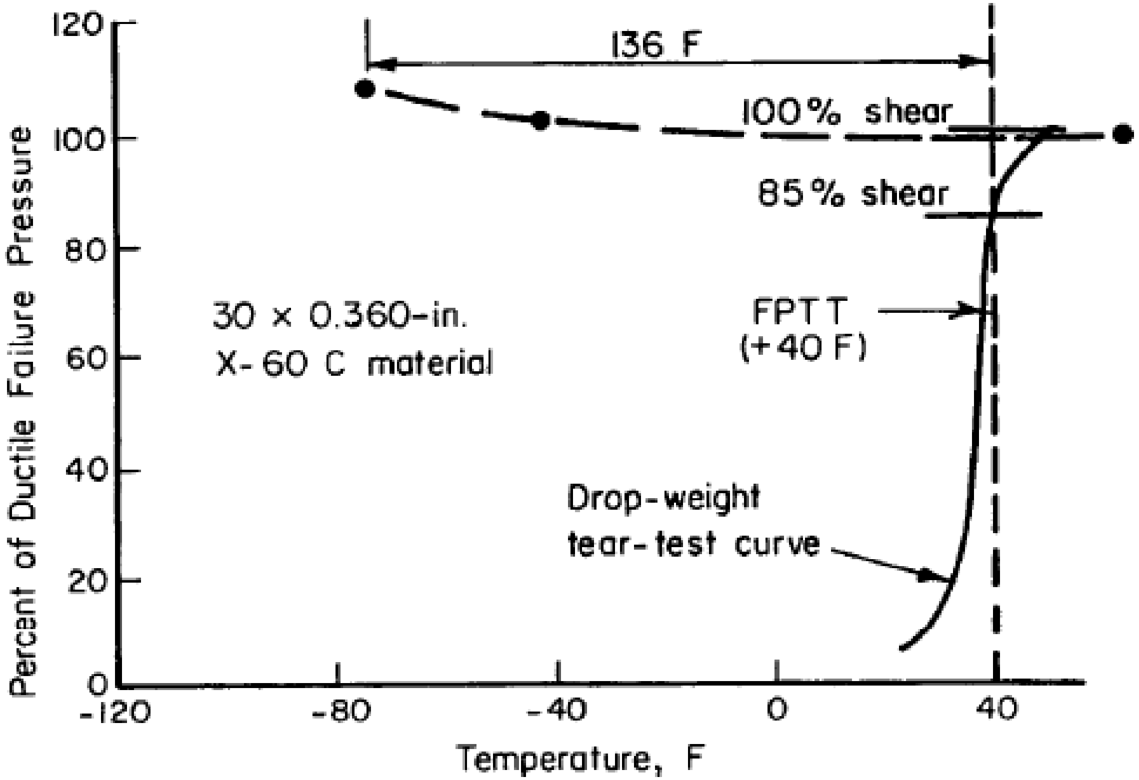
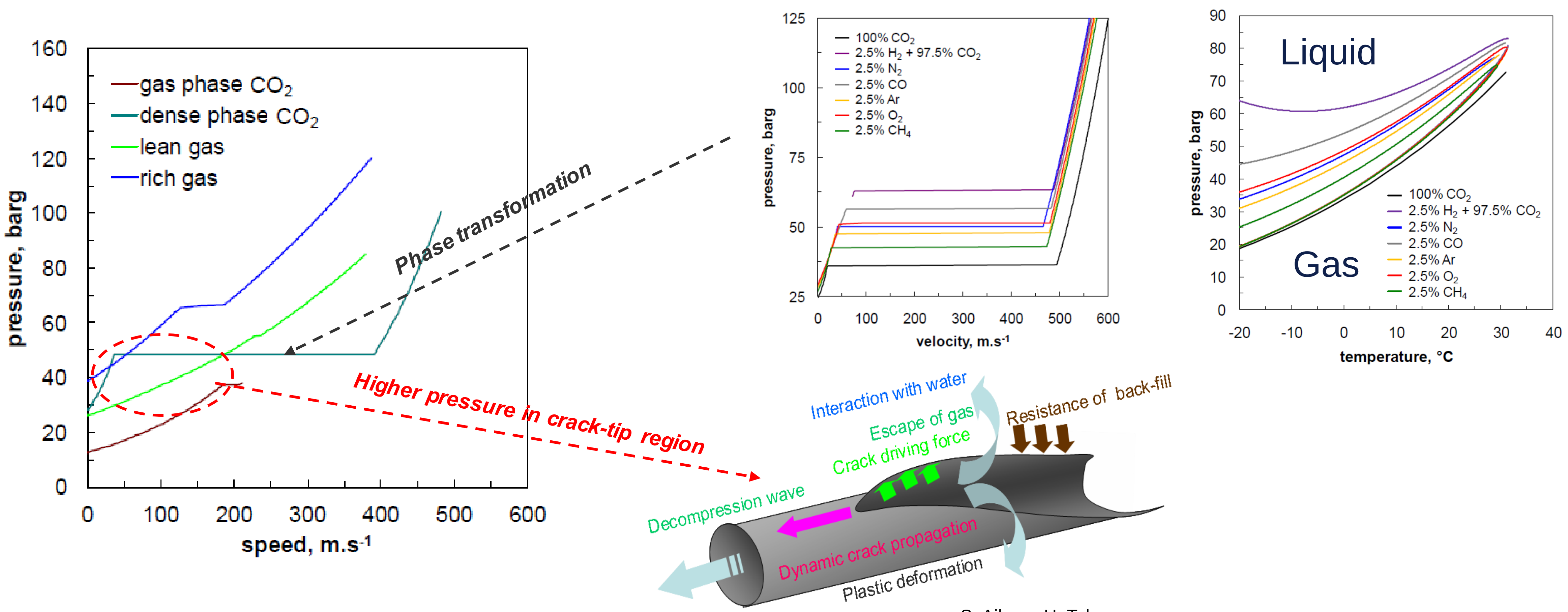


Figure 8. Illustrating the fracture-initiation transition temperature for part-through-wall defects

PRCI Report No. PR-003-00108, 2001

Running Ductile Fracture in CO_2 Pipelines



S. Aihara, U. Tokyo

Fracture control for dense phase CO_2 pipelines based off of saturation pressure.

CO2SafeArrest – Test Layout

Test 2
14.x mm

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

	4W	4W	3W	3W	2W	2W	1W	1W
Product ID	146798		146810		146713		146782	
Pipe ID	4005		4008		4002		4011	
	N	S	S	N	N	S	N	S
All Avg. (x1.7) [Pa]	***8.31***	***7.83***	8.23	8.23	7.89	7.41	6.19	5.88
Broken Avg. (x1.7) [Pa]	NA	NA	***8.12***	***7.36***	***7.25***	***7.05***	***6.19***	***5.88***
$Rp_{0.2}$ [MPa]	502	465	508	507	492	463	458	445
DWTT Propagation [J]	6307	7529	5289	5236	4090	5277	3350	3333
Broken Charpy Energy [J]	NA	NA	301	177	190	191	116	121

	1E	1E	2E	2E	3E	3E	4E	4E
Product ID	146776		146729		146760		146801	
Pipe ID	4009		4001		4004		4010	
	S	N	S	N	N	S	N	S
All Avg. (x1.7) [Pa]	6.08	6.37	7.35	7.96	7.88	8.08	***8.01***	***8.33***
Broken Avg. (x1.7) [Pa]	***6.08***	***6.37***	***7.35***	***7.48***	***7.85***	***8.02***	NA	NA
$Rp_{0.2}$ [MPa]	457	450	463	494	492	501	478	502
DWTT Propagation [J]	3235	3364	4738	4548	5178	5204	7317	5599
Broken Charpy Energy [J]	110	134	253	220	316	343	NA	NA

Exposed half | Buried half

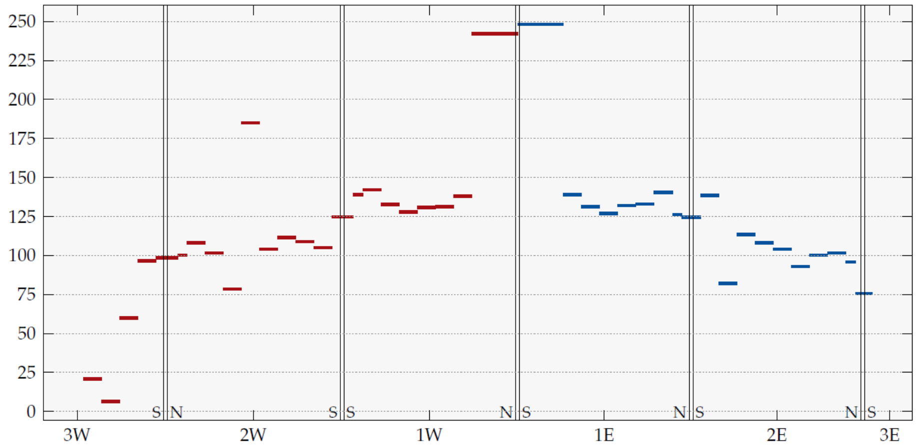
CO2SafeArrest

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 CO_2 pipeline projects.

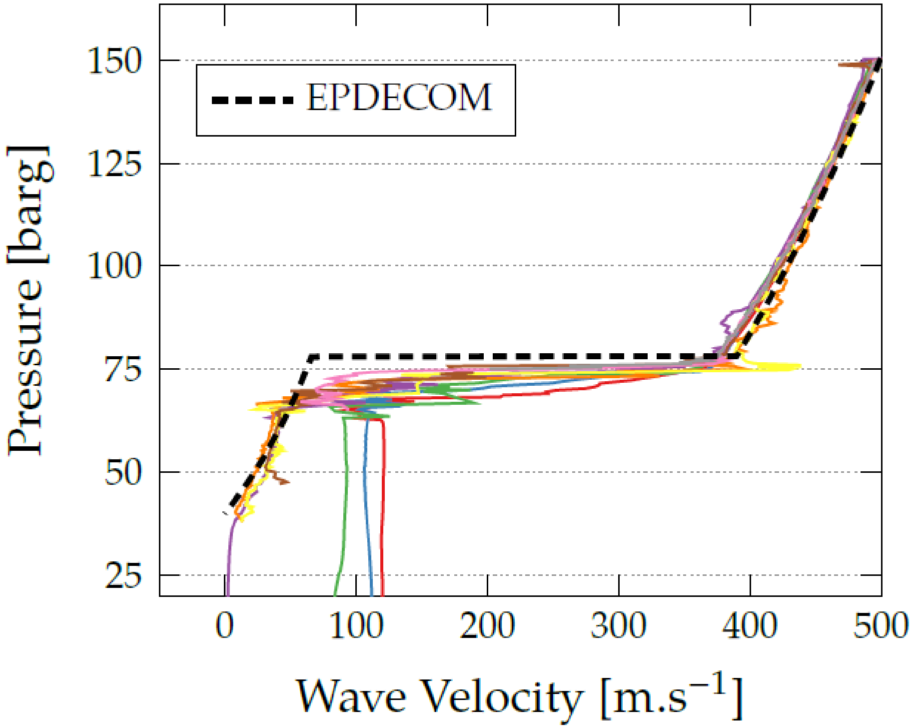
Results Generated from the Tests

Crack velocities



CO_2 concentration vs. time

Theoretical vs. actual crack tip pressure



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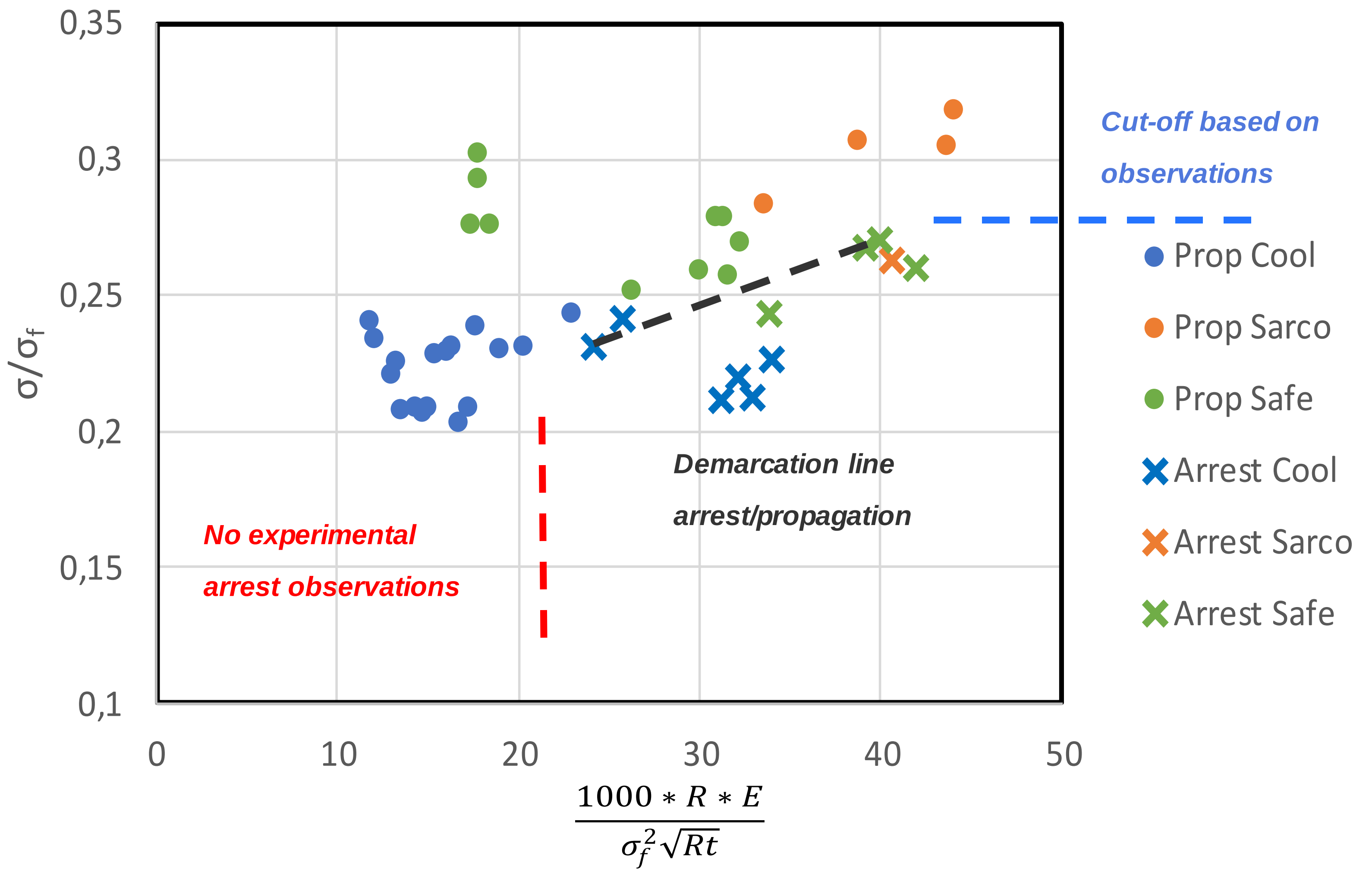
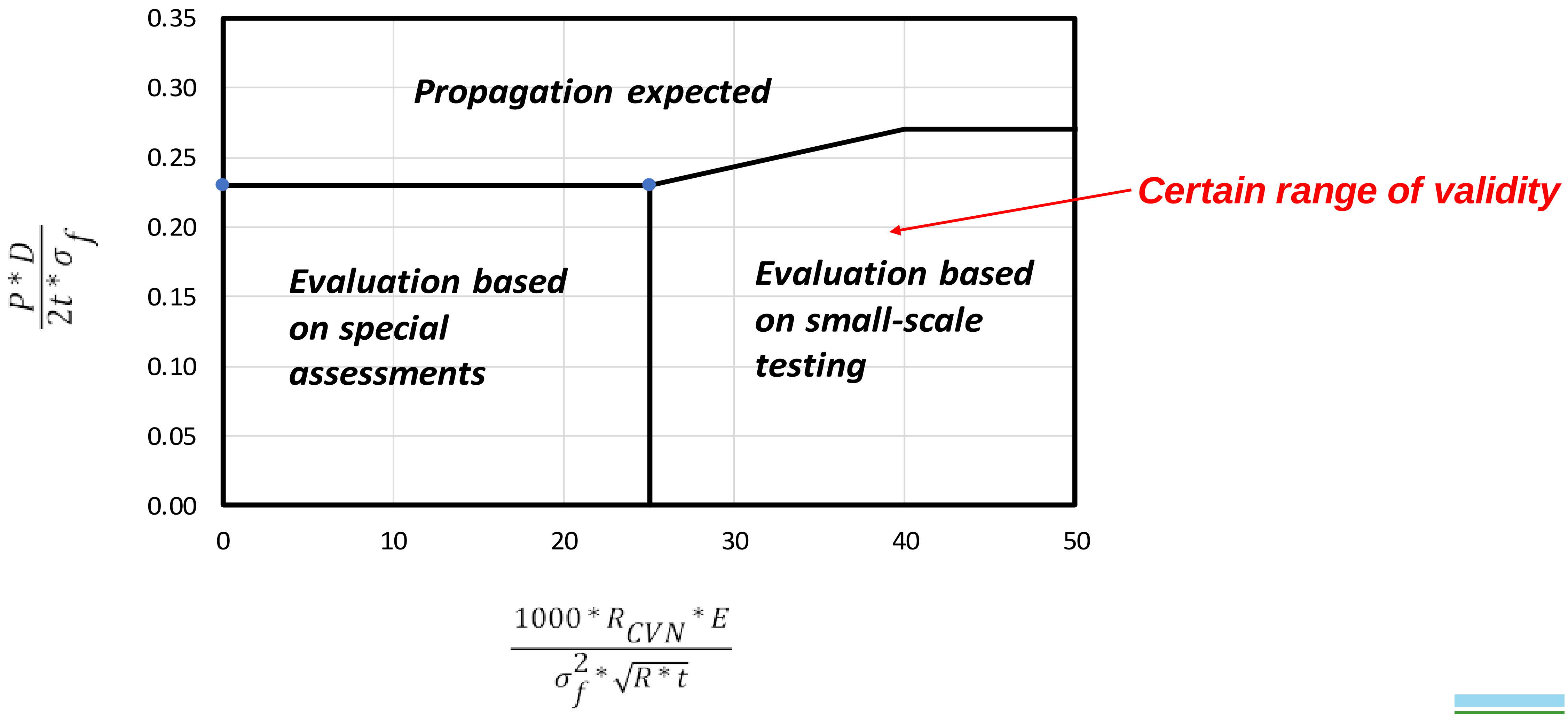
General Observations from Large-Scale Tests

- CO_2pipetrans
  - 2*16”
- Cooltrans
  - 2*36, 1*24”
- Sarco2B
  - 2*24”
- CO_2SafeArrest
  - 2*24”

- *In total 9 tests*

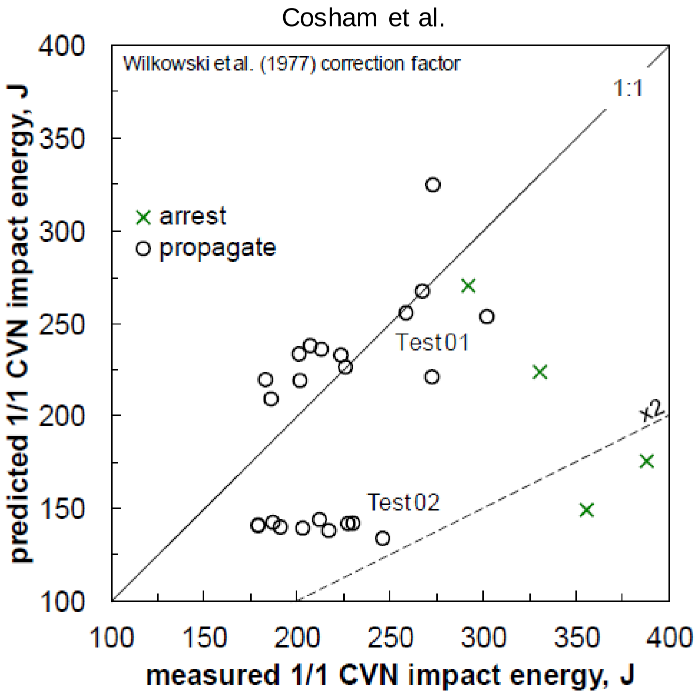


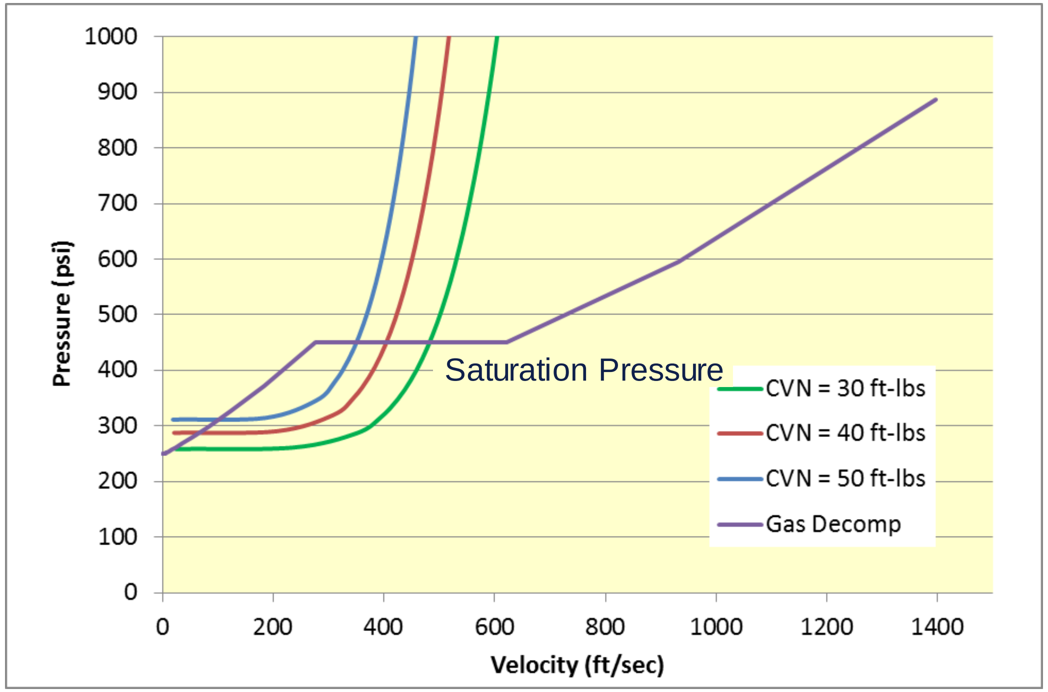
DNV-RP-F104



0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
Propagation expected
Evaluation based on special assessments
Evaluation based on small-scale testing
Certain range of validity
$\frac{P * D}{2t * \sigma_f}$
$\frac{1000 * R_{CVN} * E}{\sigma_f^2 * \sqrt{R * t}}$

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.

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