Corrosion Rate Measurements of SC-CO2: impurity effects

NIST, MML, Applied Chemicals and Materials Division, Fatigue and Fracture Group
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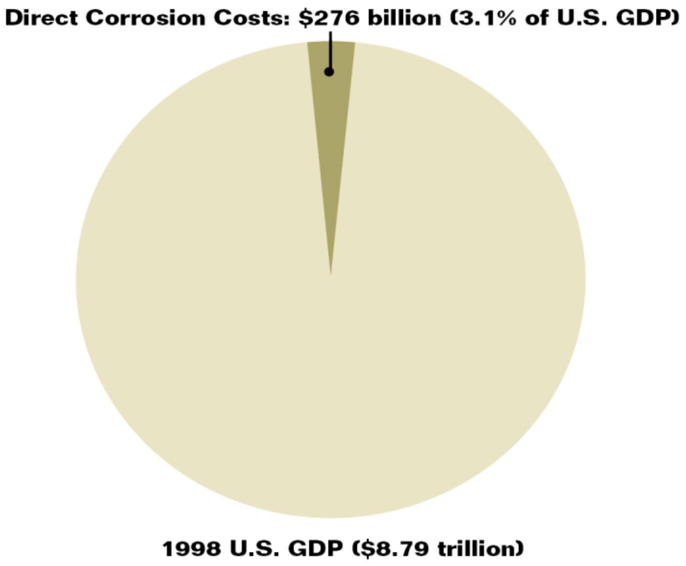
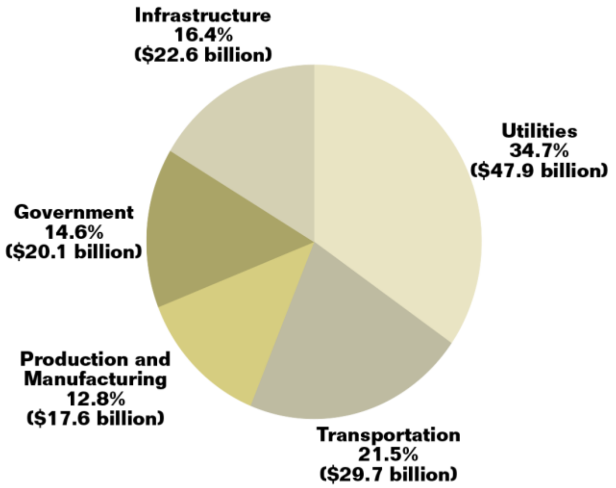
General Corrosion Costs

- In 1998, NACE found direct costs of corrosion in the US was $276 billion
  - Estimated 25-30% saving if proper mitigation procedures used
- In 2013, costs had grown to $450 billion in US; $2.5 trillion world-wide
  - Again 15-35% saving with proper mitigation procedures
- Corrosion will continue or increase
  - Sour conditions are increasingly the norm
  - Hydrogen blending into natural gas
  - Hydrogen fuel cells



COST OF CORROSION IN INDUSTRY CATEGORIES ($137.9 BILLION)



NACE Report on Corrosion Costs and Preventive Strategies in the US (2002)

Pipeline Failures May Cause Public Safety Hazards

According to the World Research Institute's 2008 report on CCS:

- "The main cause for CO_2 pipeline incidents appears to be material failure (i.e., relief valve failure, valve/gasket/weld or packing failure), followed by corrosion and outside force (Gale and Davidson 2007; Kadnar 2007)."
- "While CO_2 is more benign than many other fluids transported through pipelines, it is important to note that the CO_2 pipeline incident statistics are also probably related to the fact that there are many fewer miles of CO_2 pipelines than pipelines transporting other fluids, and they tend to be located in less populated areas."

- **Current $SCCO_2$ pipelines have well regulated quality.**
- **A large array of point sources will produce various levels of $SCCO_2$ quality, which pipelines must accommodate.**

What are acceptable levels of contaminants in $SCCO_2$ to maintain pipeline integrity?

$SCCO_2$: 5300 miles

To meet CCTS demands, may grow to the size of natural gas network

Natural Gas: >1,200,000 miles

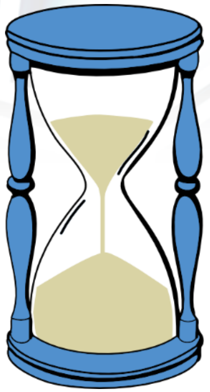
Nordhaus and Pitlick 2009

Pipeline Steel Degradation in SC-CO2

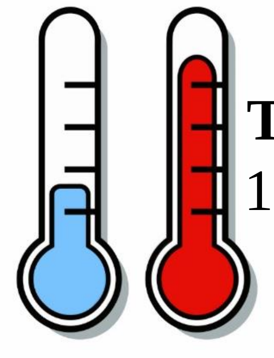
Constituents	Typical U.S. Industry Standard	DYNAMIS EU Standard	"Dried" Anthropogenic CO_2
H_2O	< 600 ppm	500 ppm	>2000 ppm?
H_2S	200 ppm	200 ppm	6,000 ppm
CO	2,000 ppm	2,000 ppm	4,000 ppm
O_2	< 1,000 ppm	< 4 vol. %	6,000 ppm
CH_4	< 5 vol. %	< 4 vol. %	-
$N_2/Ar/H_2$	< 4 vol. %	< 4 vol. %	41,000 ppm
SO_X	100 ppm	100 ppm	5,000 ppm
NO_X	100 ppm	100 ppm	100 ppm
CO_2	> 99.5 vol. %	> 99.5 vol.%	-

Presence of water is a prerequisite for pipeline corrosion: keep water content low

Range of Conditions in the Literature



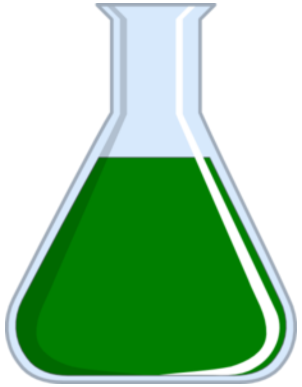
Duration
hours – >1 year



Temperature
12°C – 265°C

Pressure
80 – 240 bar

Flow Rate
many static, a few with flow

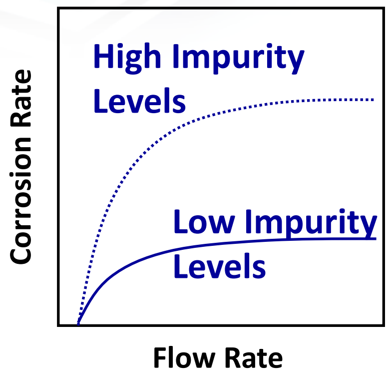


Contaminants
H_2O, H_2S, O_2, NO_2, SO_2
(often in combination)

Result: reported corrosion rates **vary** over **four orders of magnitude** (0.01 – 100 mm/year)

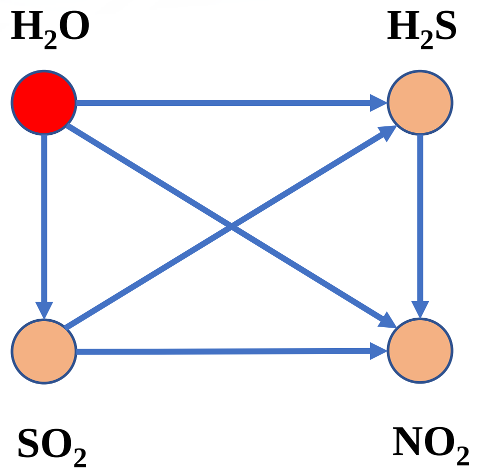
Material Measurement Needs

Effect of Fluid Flow

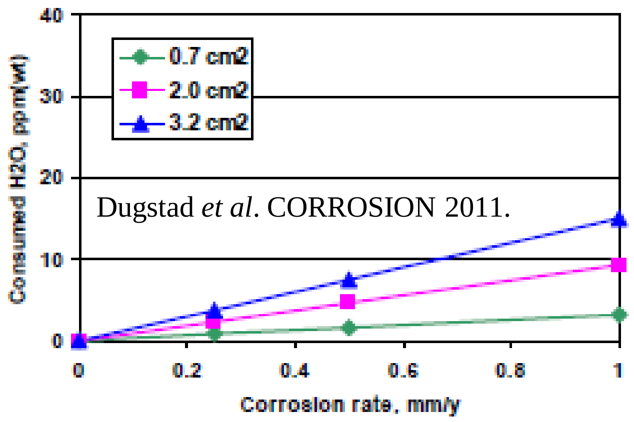


Higher impurity levels are expected to produce thicker corrosion products which could lead to spallation and erosion-corrosion

Impurity Interactions

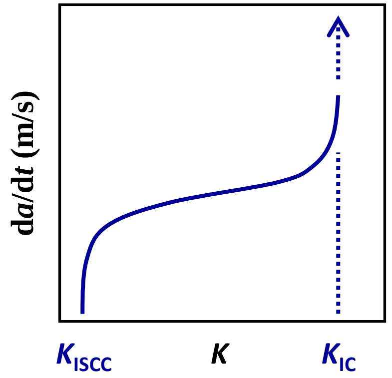


Contaminant Consumption



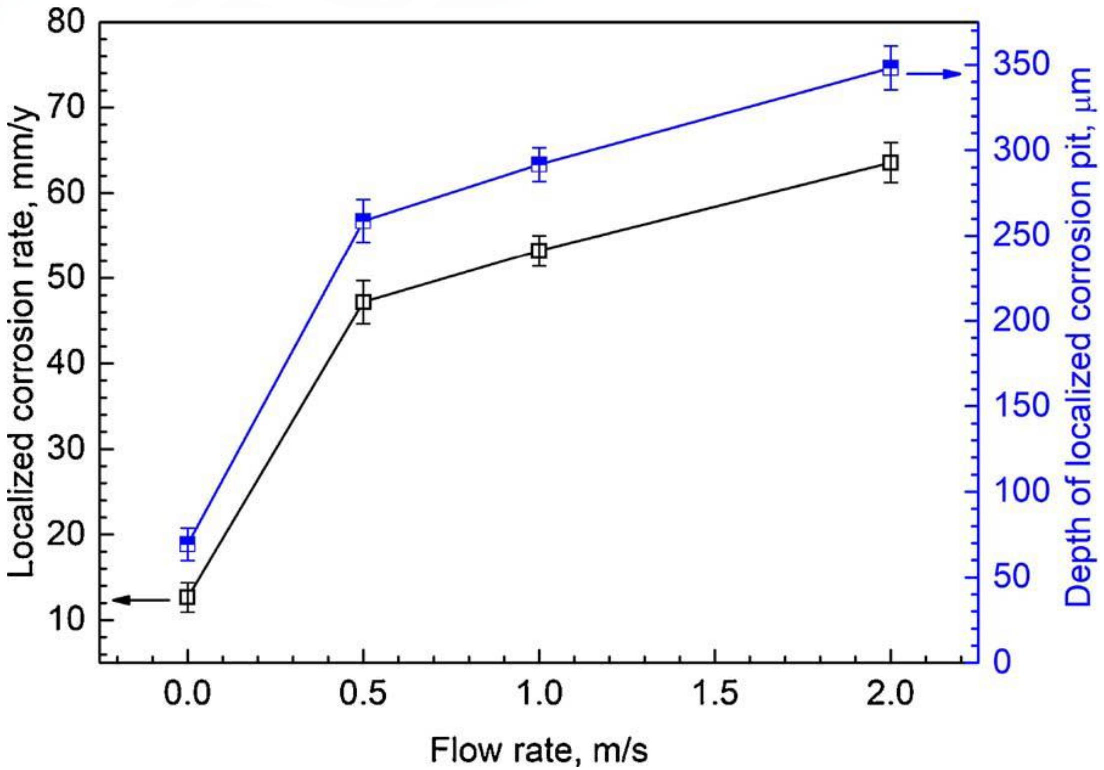
Fracture and Fatigue?

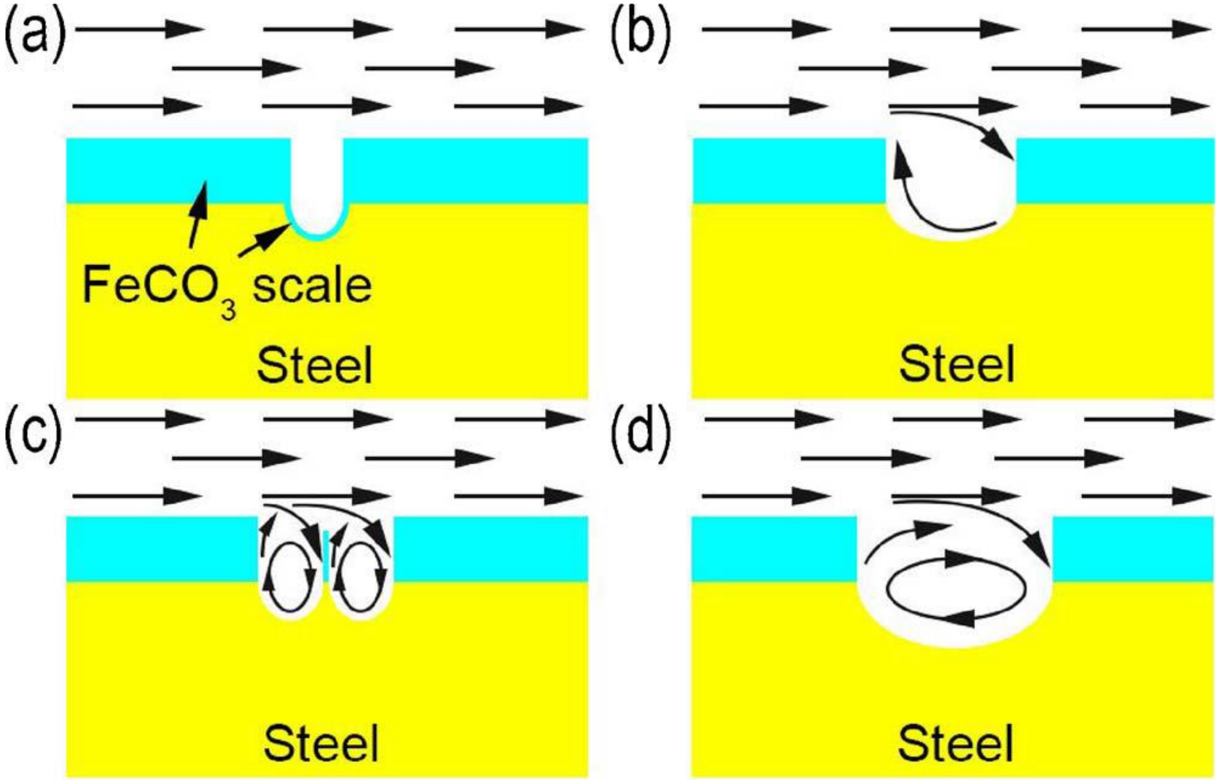
In SC-CO2 with and without impurities



No published research has shown the influence of $SCCO_2$ environments on environmentally assisted cracking

Flow rate is a key parameter





L. Wei, X. Panga, K. Gaoa, Effect of flow rate on localized corrosion of X70 steel in supercritical CO2 environments, Corr. Sci. ***136*** *(2018)*

Flow rate is a key parameter

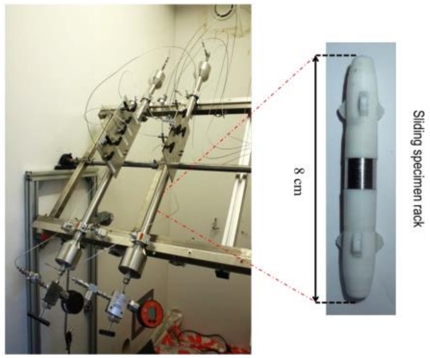
Rotating Cage

What is the impact of flow rate?
How is flow rate simulated in the lab?

ASTM G184-06
Standard Practice for Evaluating and Qualifying Oil Field and Refinery Corrosion Inhibitors Using Rotating Cage

Flow Loop

Rocking autoclave



Dugstad et al. 2014

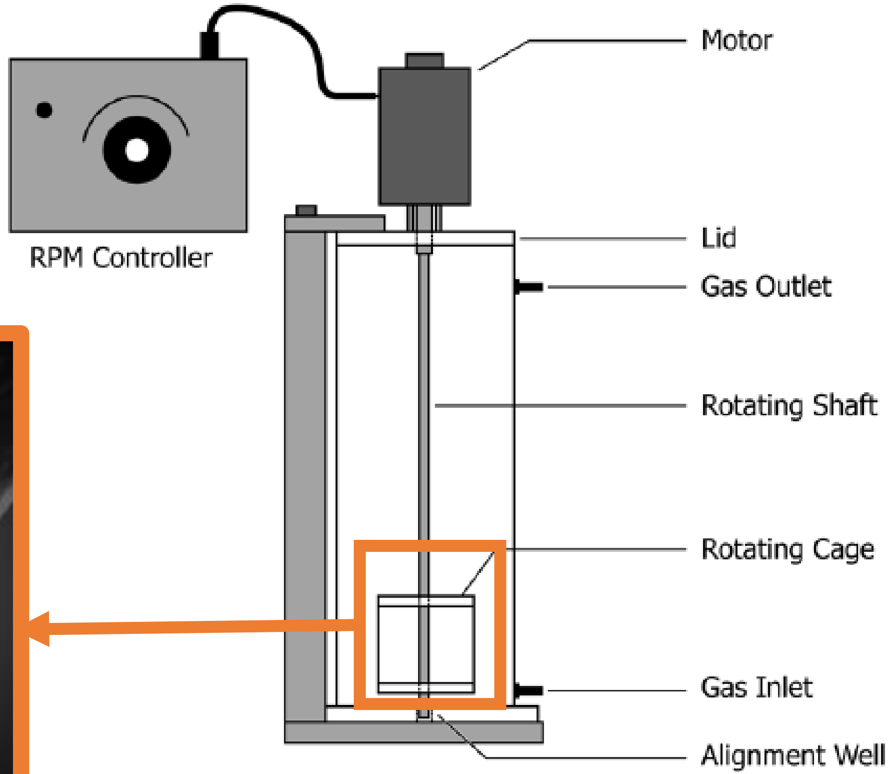


FIG. 1 Schematic Diagram of Rotating Cage

ASTM G184-06

NIST Supercritical Corrosion Facility

- State-of-the-art test facility for $SCCO_2$ environmental testing
- Static and dynamic test applications to evaluate flow-induced damage on multiple alloys simultaneously
- 77 bar, 54 °C and 84 bar, 40 °C tests
- IGS Analyzer (FTIR) for contaminant monitoring
- Precision imaging facility for characterization of microscopic structures and corrosion processes on steel alloys.

NIST Supercritical Corrosion Facility

- Inside a walk-in fume hood for compatibility with H_2S testing
- Remote monitoring and continuous data-logging capabilities

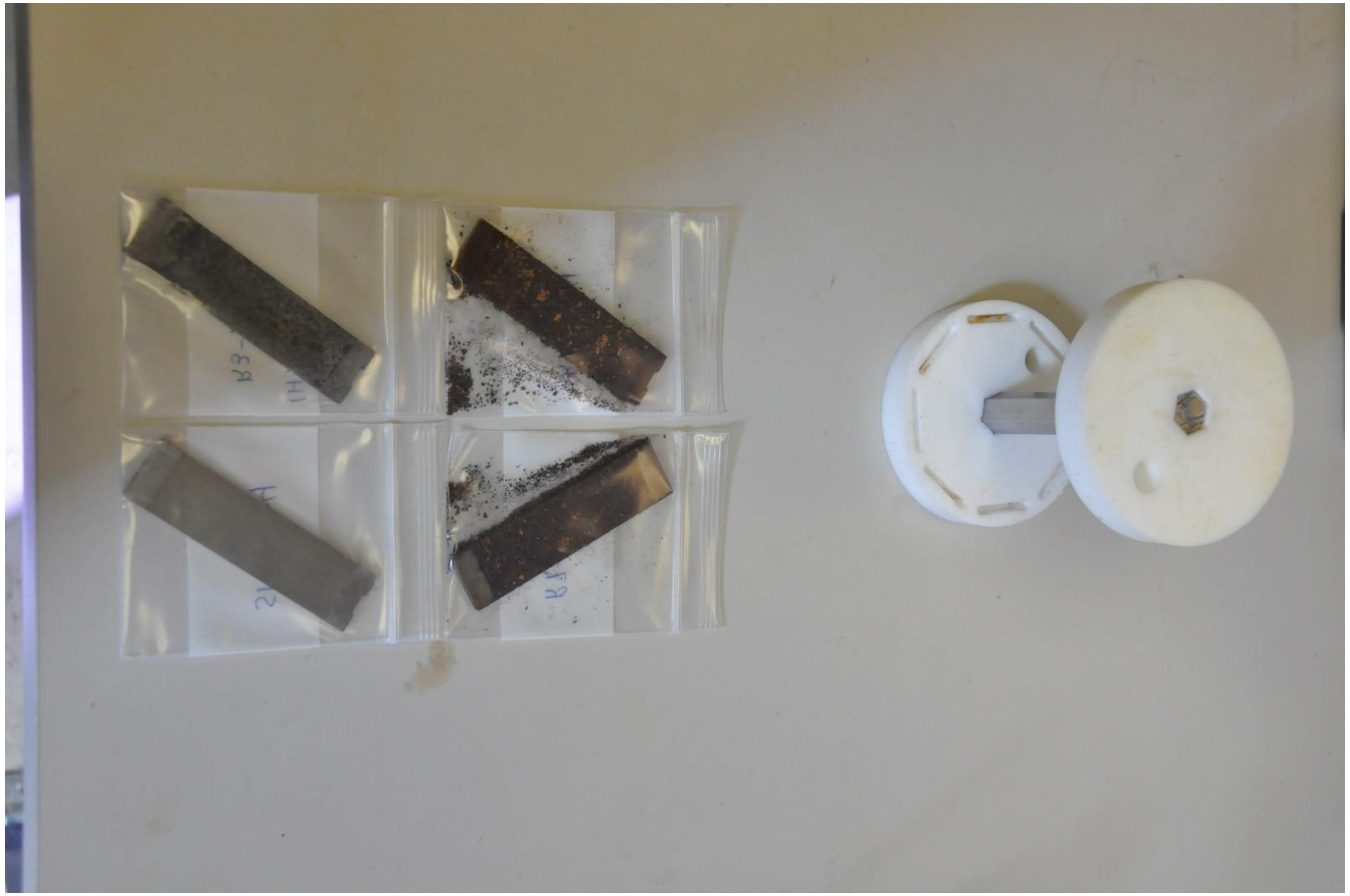
NIST Supercritical Corrosion Facility

Specification	Large Pressure Vessel	Small Pressure Vessel
Number Available	1	2
Internal Volume	7.7 L	4.0 L
Construction Material	316 SS	316 SS
Max Allowable Working Temperature	250 °C	500 °C
Max Allowable Working Pressure	206 bar (3000 psi)	103 bar (1500 psi)
Stirring Capabilities?	YES	NO

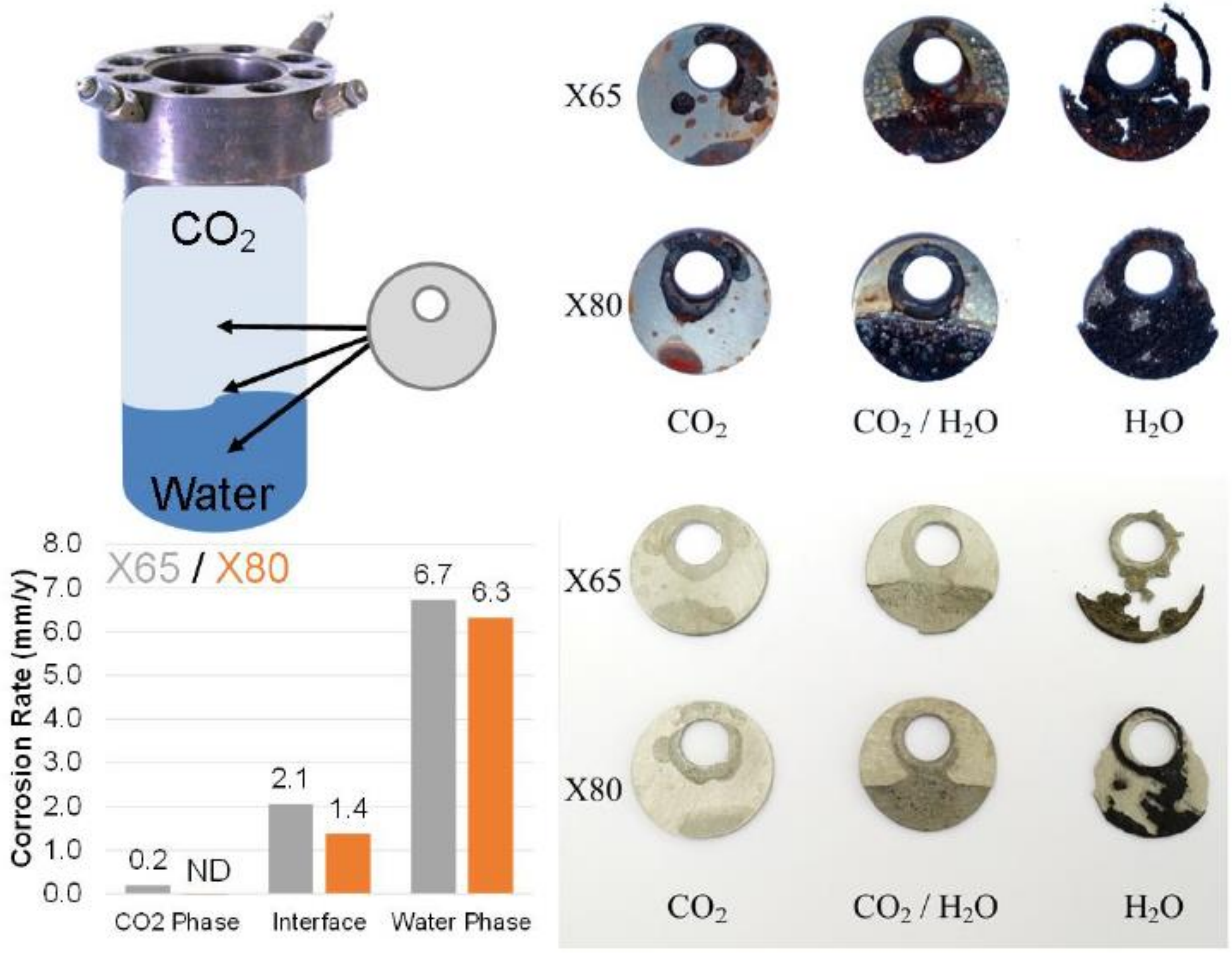
3 high-temperature, high-pressure test chambers. Rated for 300 bar at 500 °C. One stirred chamber (can vary flowrate)

NIST Supercritical Corrosion Facility

- Specimens tested in stirred chamber
- Test coupons are 75 mm x 19 mm x 3 mm thick



Test Results



Thermodynamics Issues

- **RefProp software**
- Chris Muzny, Mark McLinden
- Thermophysical properties of CO_2 plus impurities
- Can be used for pipeline blowdown calculations, for instance

Key Takeaways and Next Steps

- NIST has SC-CO2 testing facility – capabilities for multiple impurities, flow effects, and mechanical load
  - Facility not currently active – needs 2 months to bring back up
    - Resource needed – 1 student/technician to help bring up and to run tests
- SC-CO2 corrosion rates due to impurity interactions need to be measured – as function of temperature/pressure/flow rate/…
  - Start with "dry anthropogenic CO2" condition then reduce to individual effects?
- Round-robin testing should be a goal when multiple corrosion laboratories are up and running
- Goal: Help determine conditions for NACE or equivalent standards
- Reach goal: Determine mechanism of corrosion to see whether mitigating technologies can be developed

Thank You!

Questions?

NIST Supercritical Corrosion Facility

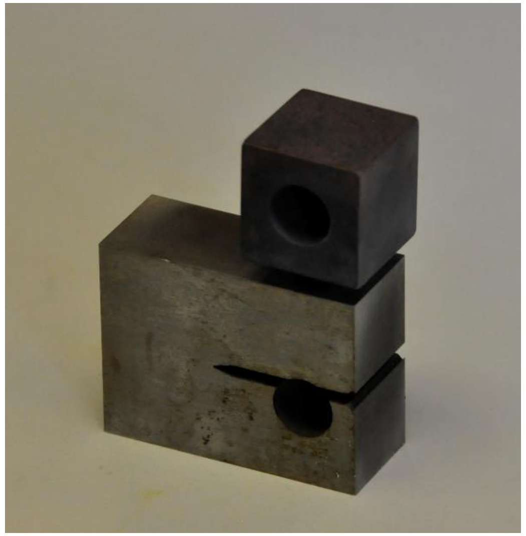
- 3 high-temperature, high-pressure test chambers. Rated for 300 bar at 500 °C.
- One stirred chamber (can vary flowrate)

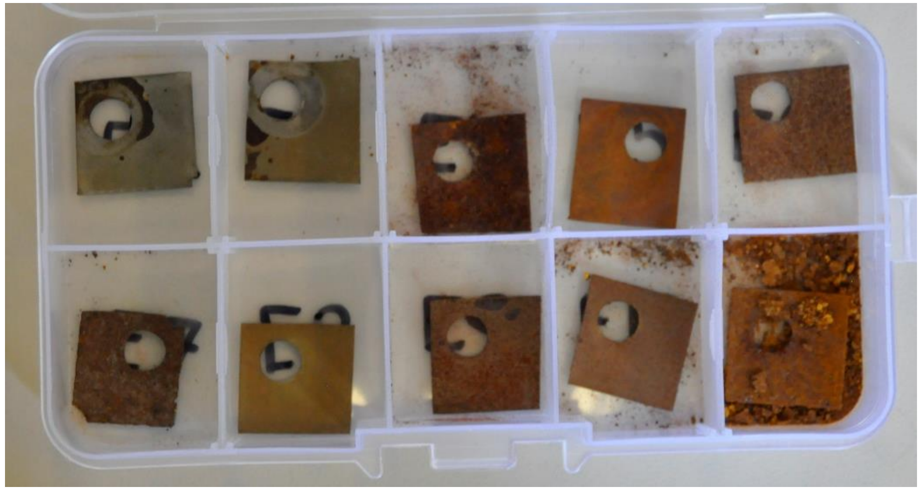
NIST Supercritical Corrosion Facility

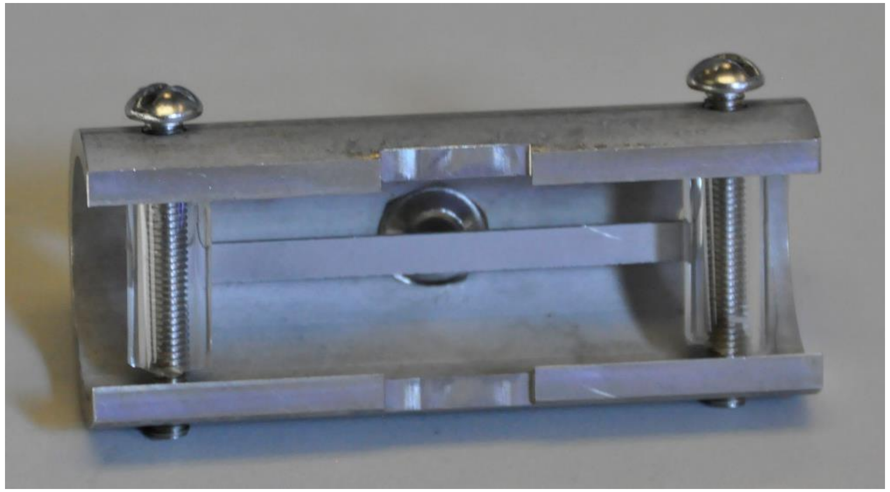
- 3 high temperature, high-pressure test chambers. Rated for 300 bar at 500 °C.
- One stirred chamber (can vary flowrate)

NIST Supercritical Corrosion Facility

- Specimens tested in static chambers







Test Results - FTIR

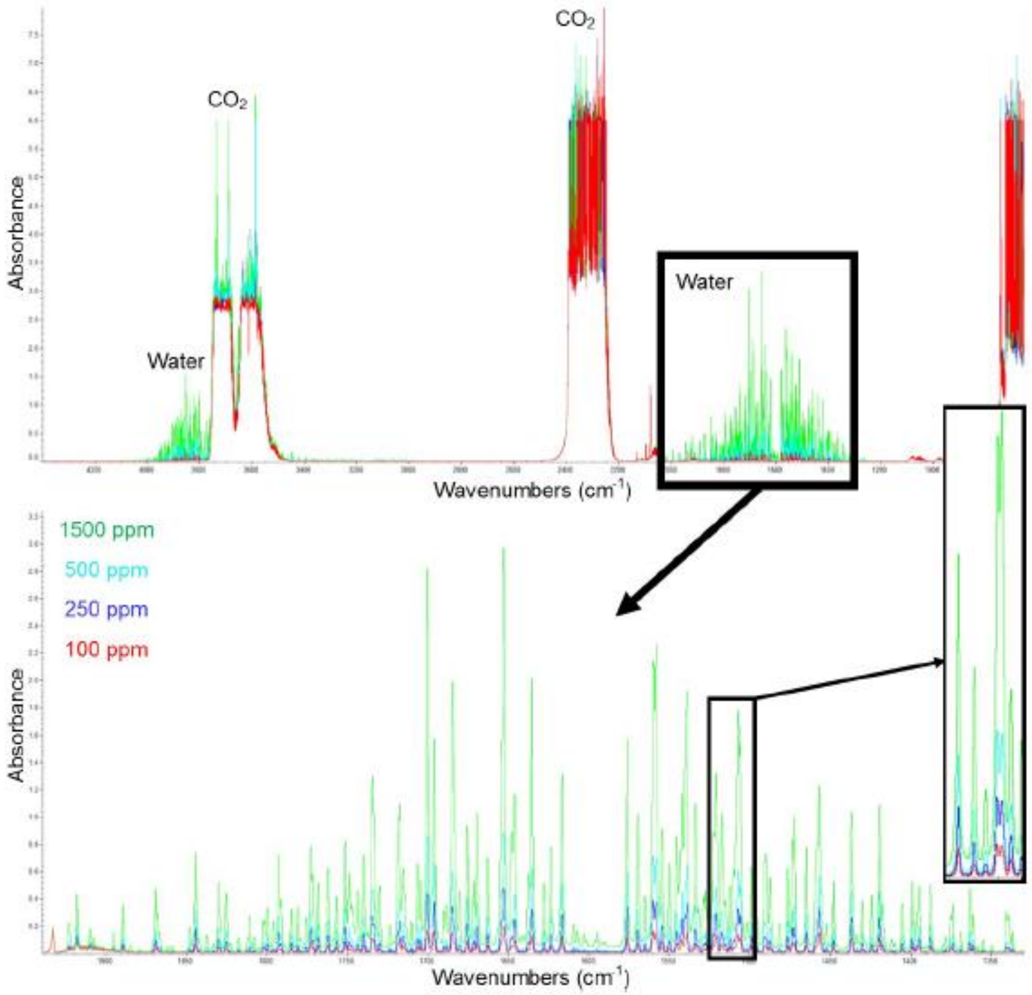


Figure 4: FTIR Spectra taken in a CO_2 matrix with varying water concentrations. Both the full spectrum (top) and an enlarged region containing several bands for water (bottom) are shown for water contents varying from 100 – 1500 ppm.