Multi-Parameter Optical Fiber Sensor for Simultaneous Corrosion and Humidity Monitoring

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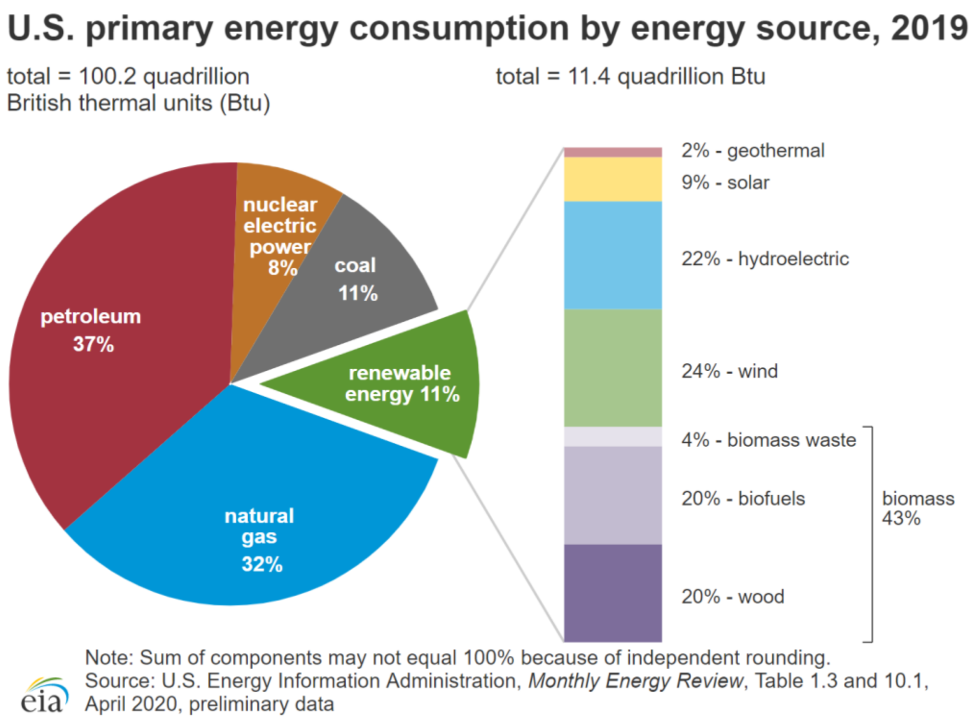
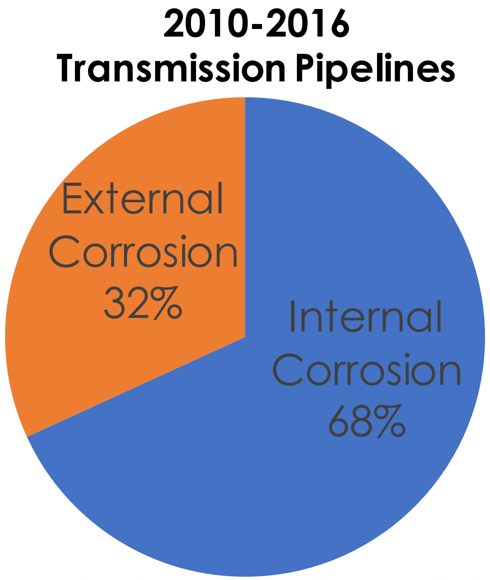
Outline

- Research background
- Experimental setup
- Results and discussion
- Conclusions
- Disclaimer

Corrosion in Oil and Gas Infrastructure





Corroded production casing pipe sample from downhole

(University of North Dakota Energy & Environmental Research Center)

- $1.4 billion annually: direct corrosion costs in domestic oil and gas exploration and production in the U.S.
- $589 million: surface piping and facility costs
- $463 million: downhole tubing expenses
- $320 million: capital expenditures related to corrosion.
- **25-30% can be saved** with optimal corrosion management.

Koch, G. H., Brongers, Michiel, P. H., Thompson, N. G., Virmani, Y. P. and Payer, J. H., "Corrosion costs and preventive strategies in the United States" (2002).

Corrosion is an Electrochemical Process Causing Mass Loss and Structural Deterioration

Dissolution of CO_2: $CO_2(g) \leftrightarrow CO_2(aq)$

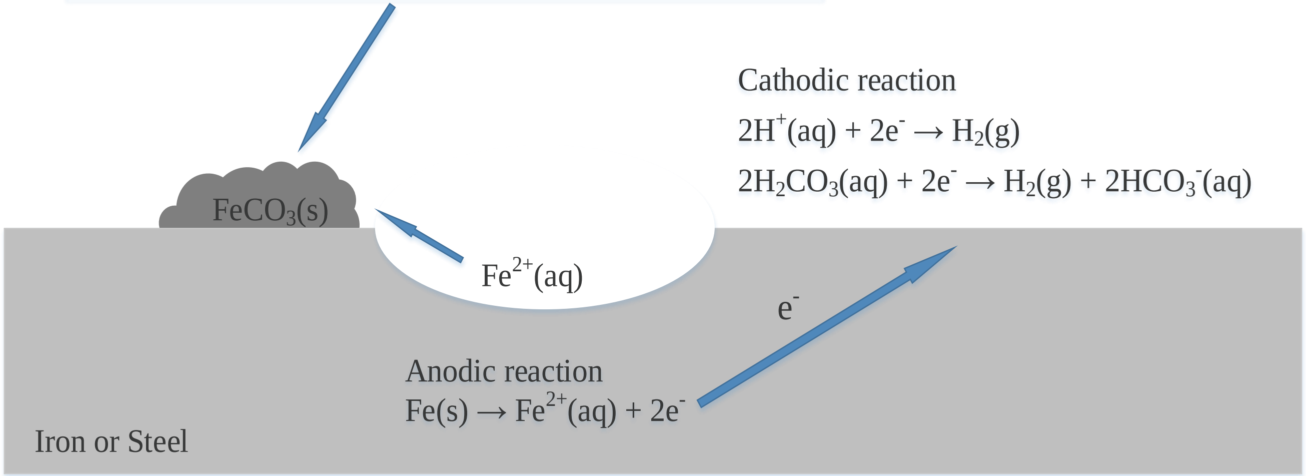
Hydration of CO_2: $CO_2(aq) + H_2O(l) \leftrightarrow H_2CO_3(aq)$

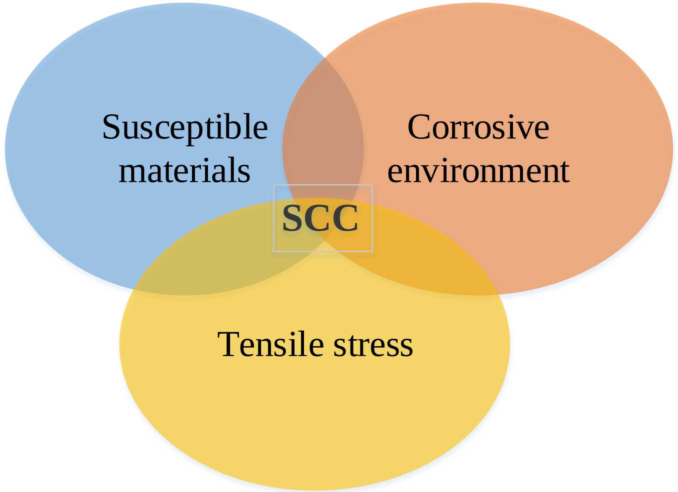
~ 0.2% of $CO_2(aq)$ and quite slow

Dissociation of $H_2CO_3(aq)$:

$H_2CO_3(aq) \leftrightarrow H^+(aq) + HCO_3^-(aq)$, $pK_1=6.35$ at 25 °C

$HCO_3^-(aq) \leftrightarrow H^+(aq) + CO_3^{2-}(aq)$, $pK_2=10.33$ at 25 °C

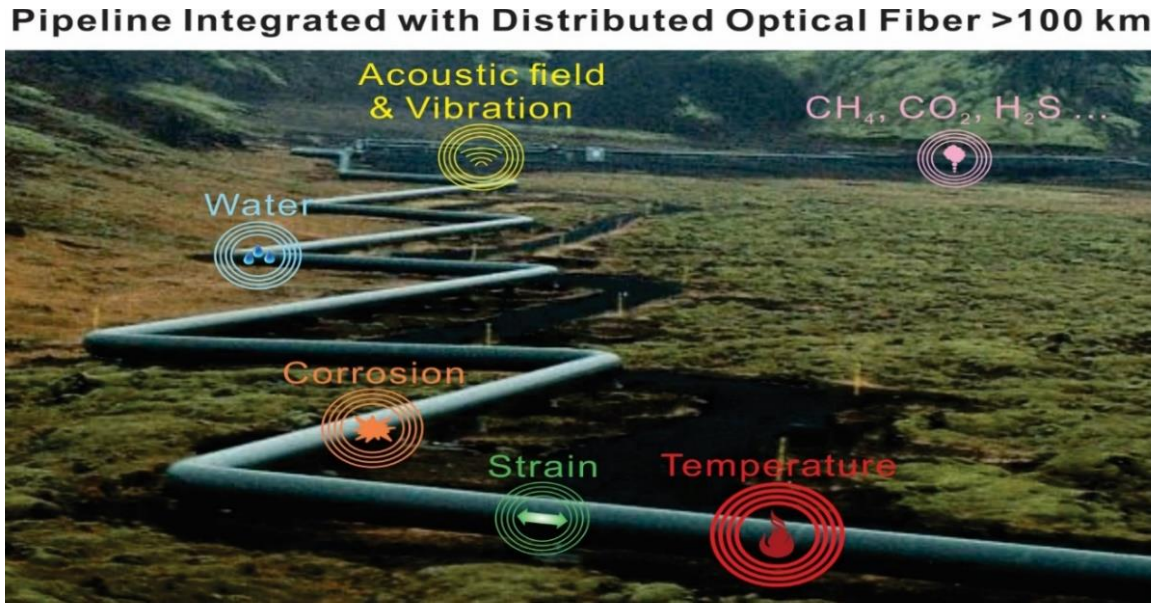




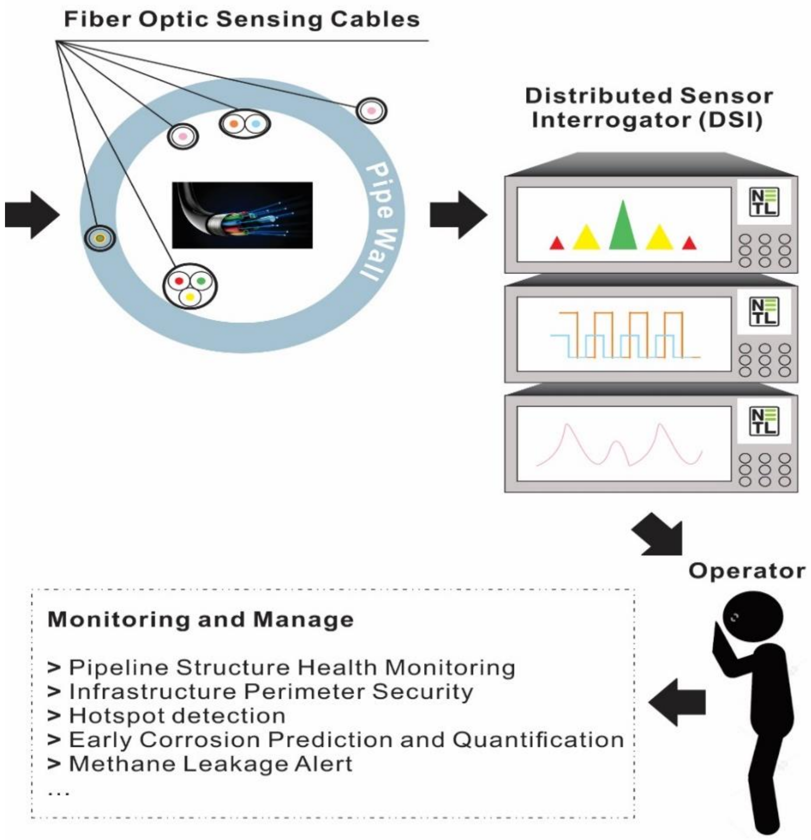
https://corrosion.ksc.nasa.gov/stresscor.htm

Jones, D. A., Principles and Prevention of Corrosion, P 237.
Han, J., Nesic, S., Yang, Y., Brown, B., Electrochimica Acta, 2011, 5396-5404.

Optical Fiber Sensor Platform for Natural Gas Pipelines



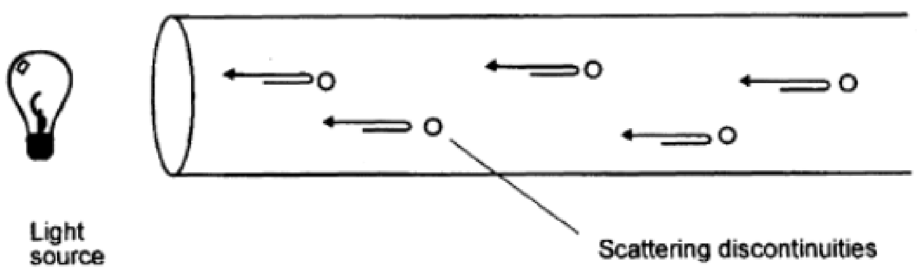
- Early Corrosion Onset Detection
- Methane Leak Detection



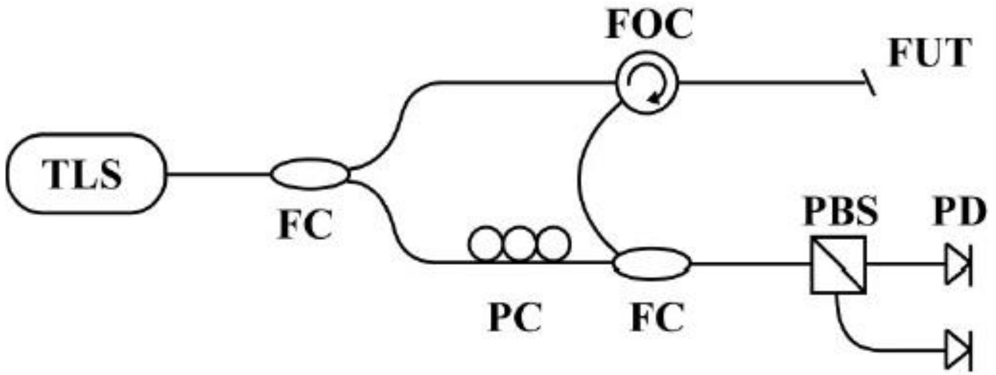
A Multi-Parameter, Distributed Optical Fiber Sensor Platform Enabling Reliability & Flexibility

Target Metrics = >100km Interrogation, <1m Spatial Resolution

Optical Backscatter Reflectometer (OBR)



- This instrument measures the Rayleigh backscattering from the fiber-under-test (FUT).
- Provides spatially distributed measurements along the fiber with location and sensing information.



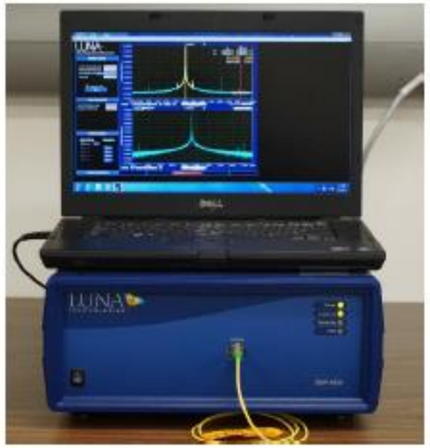
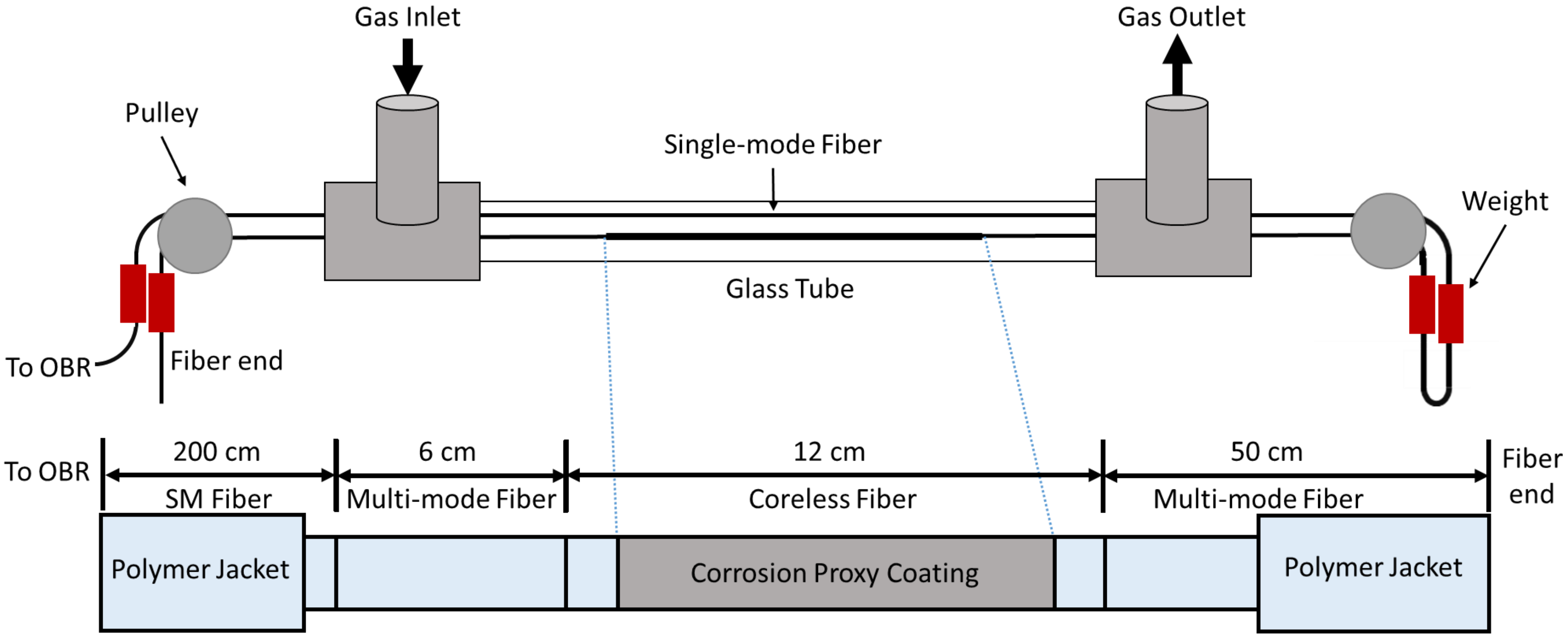


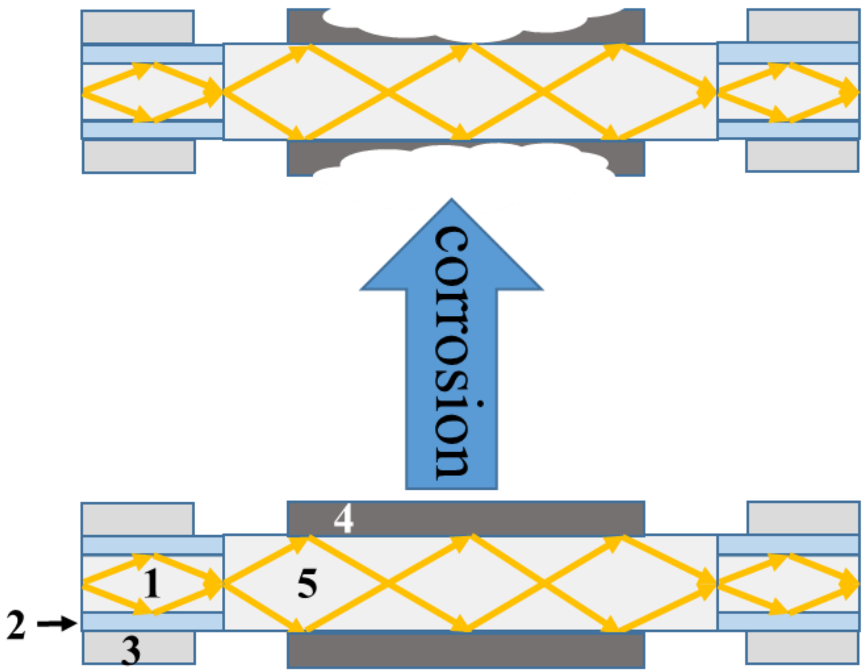
Figure 1 – LUNA OBR 4600 distributed interrogator LEFT: internal components (TLS: tunable laser source, FC: fiber coupler, FOC: fiber optic circulator, PC: polarization controller, PBS: polarizing beamsplitter, PD: photodiode); RIGHT: photo of instrument.

Experimental Setup



Schematic diagram of the spliced optical fiber sensor configuration and the experimental setup for distributed measurements in a glass tube.

Corrosion Sensing Principle



1—multi-mode fiber core; 2—cladding; 3—polymer jacket; 4—coated metallic film; 5—coreless optical fiber.

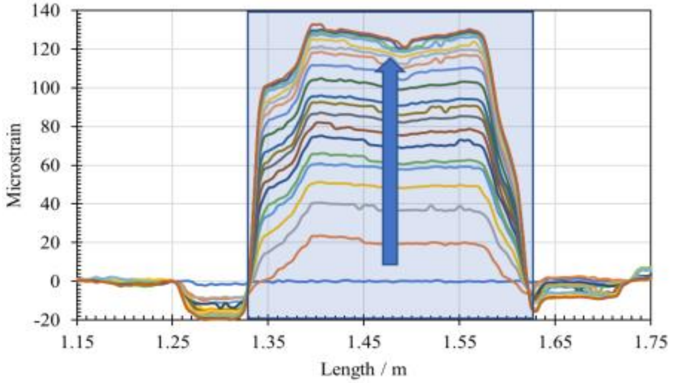
- The metallic thin film leads to broadband light absorption in the evanescent field, which occurs at the interface between the optical fiber and the thin film along the fiber.
- As the metallic film gets thinner, the light absorption of the film decreases; therefore, the light transmission increases through the optical fiber.

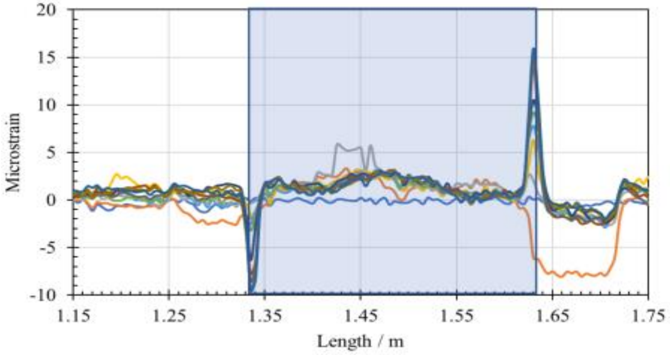
Simultaneous Monitoring of Water and Aqueous Corrosion

From 0%RH to 100%RH N_2

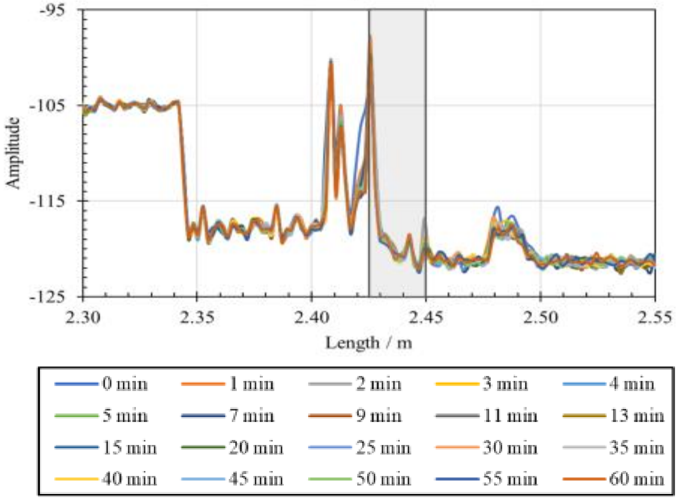
From 100%RH CO_2 to HCl solution (pH 3)

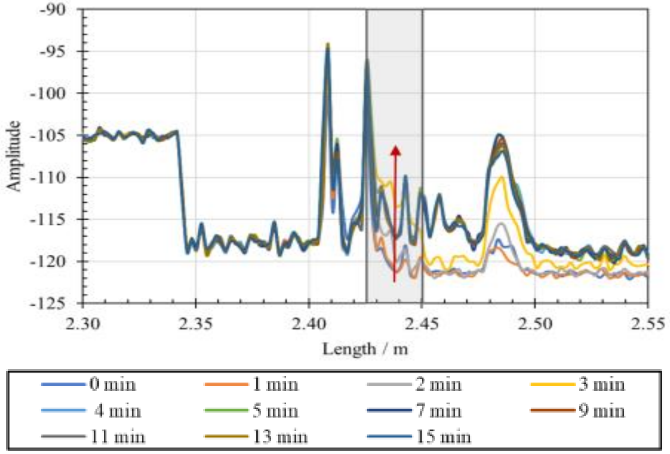
Humidity Sensor





Corrosion Sensor





- Humidity increased strain by ~125 με due to water-induced swelling of optical fiber polymer jacket.
- Corrosion increased the backscattered light intensity in the X65 thin film coated location.

Simultaneous Monitoring of Water and Corrosion in Wet CO_2

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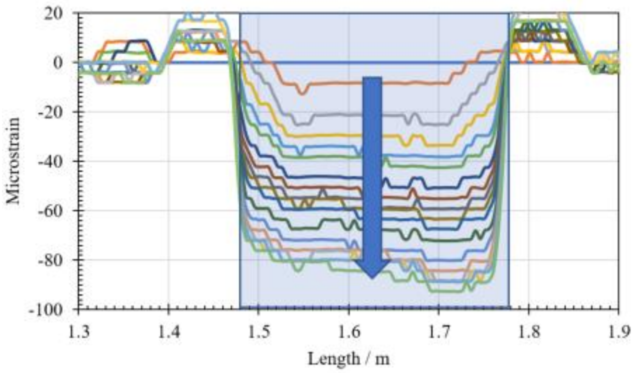
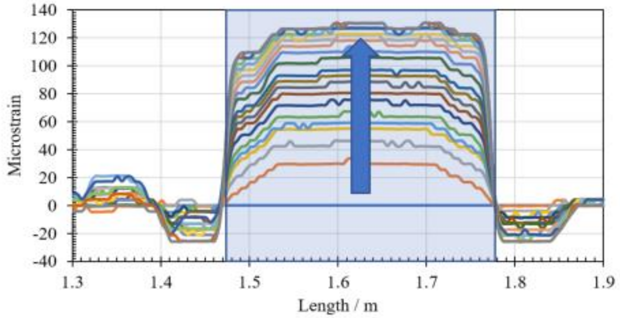
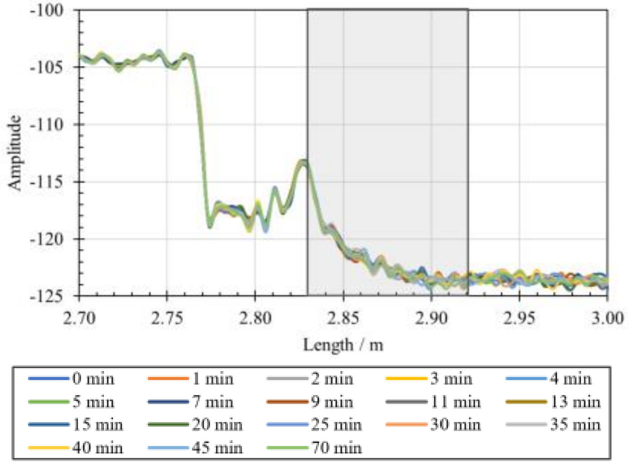
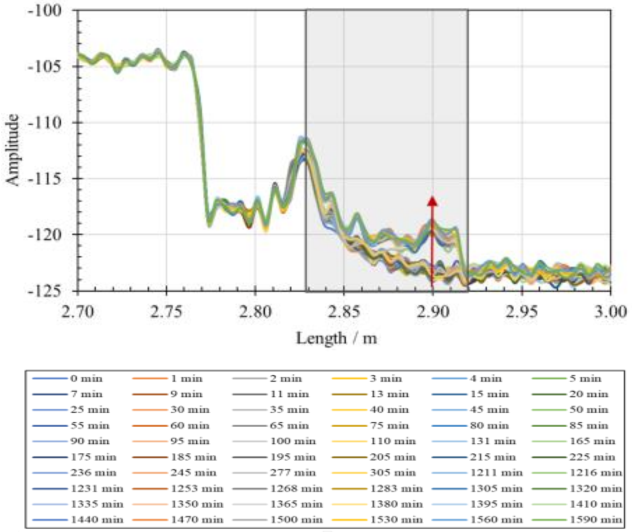
	From Atmospheric RH to 0%RH N_2	Dry 0%RH N_2 to Wet 100%RH CO_2
Humidity Sensor		
Corrosion Sensor		

- Corrosion proxy sensor doesn't have cross-sensitivity to humidity.
- Wet CO_2-caused localized corrosion was monitored as only a few locations of the Fe coating showed an increase in the backscattered light intensity.

SEM Characterization of Metallic Thin Films on Optical Fibers Before and After Corrosion

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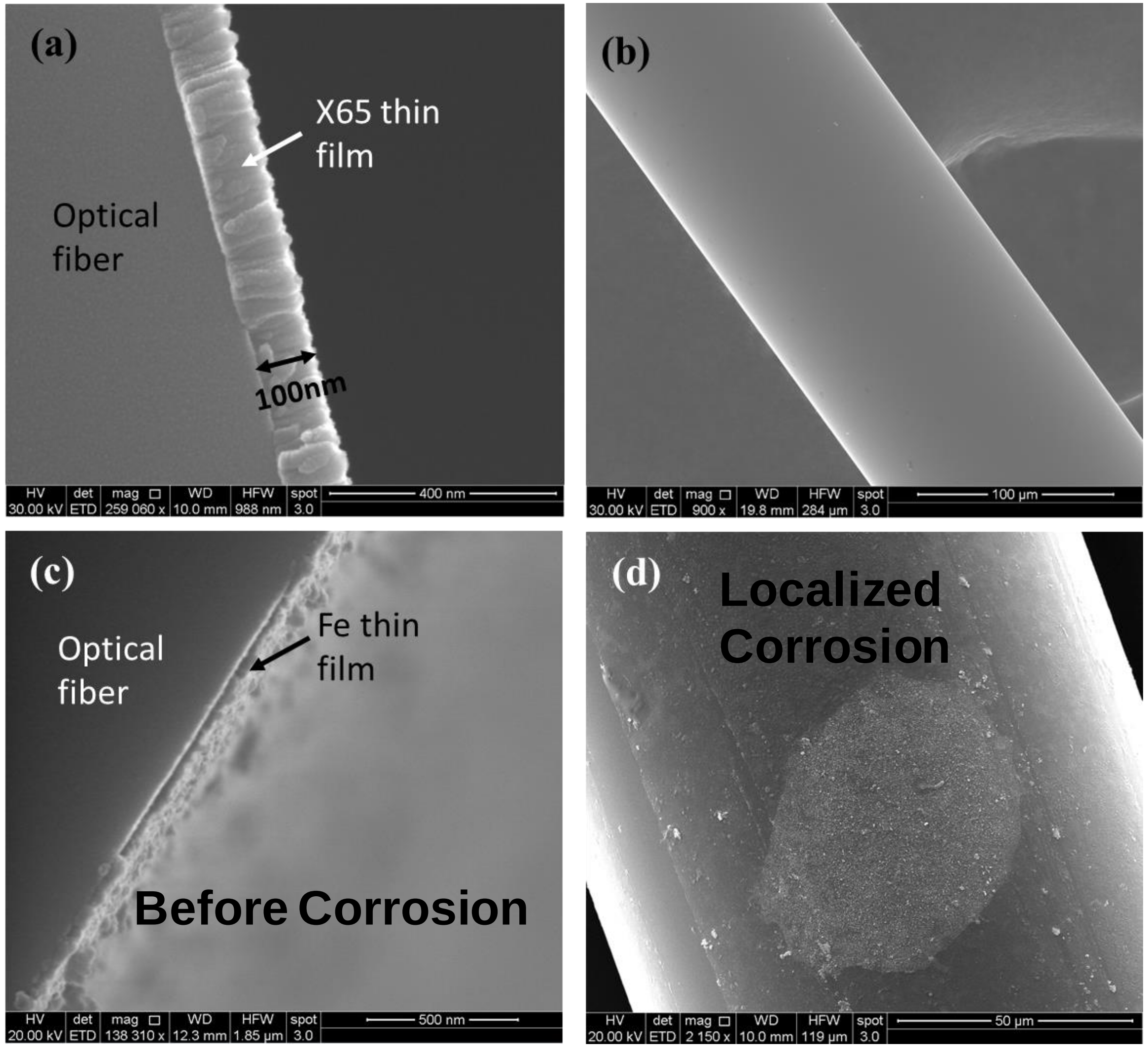
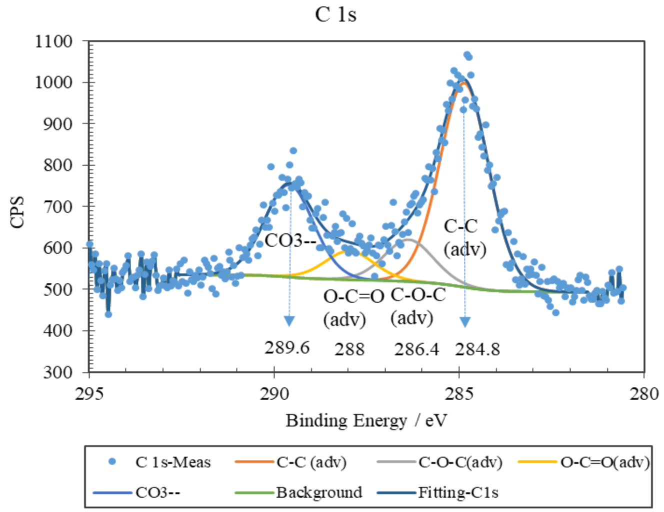
Cross-section | **Surface**

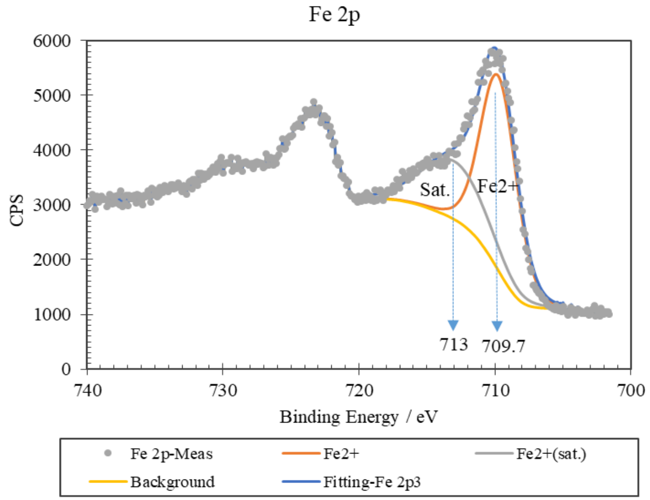
X65 Carbon Steel Thin Film

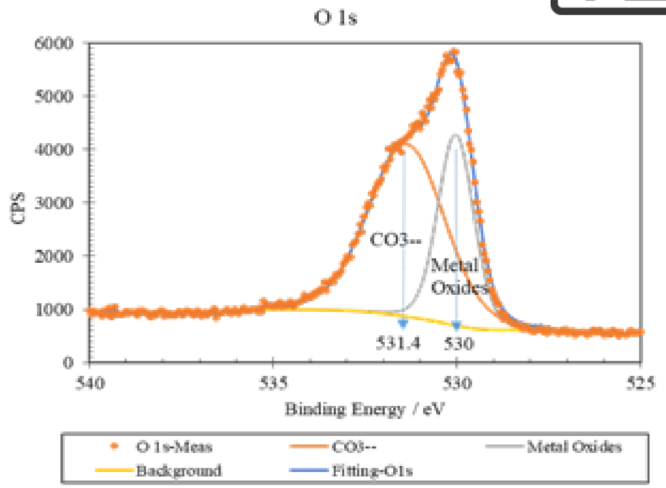
Fe Thin Film



XPS Characterization of Fe Thin Film on Optical Fiber after Wet CO_2 Corrosion







XPS-determined chemical composition of Fe thin film after exposure in wet CO_2 gas after 1 min ion sputtering (2 KeV).

Element	Carbon	Oxygen	Iron
atm%	15.8	58.84	25.35

- A carbonate (CO_3^{2-}) peak was found in the C 1s and O 1s XPS spectra, indicating the formation of iron carbonate ($FeCO_3$) as a corrosion product.
- The Fe 2p3/2 spectrum contains an Fe(II) satellite, consistent with the oxidation of Fe to $FeCO_3$.

Conclusions

- A multi-parameter optical fiber sensor was developed and demonstrated for simultaneous monitoring of corrosion and water/humidity with location information along the optical fiber.
- The multi-parameter sensor was prepared by combining a corrosion sensor and a water sensor, which were then connected to and interrogated by an OBR. Corrosion was detected from light intensity changes associated with the corrosion proxy metallic coatings, and changes in water/humidity were monitored based on the water-induced strain changes along the optical fiber.
- The corrosion proxy sensor didn't show cross-sensitivity to humidity variation.
- After the wet CO_2 corrosion, localized corrosion was monitored through the non-uniform increase in the backscattered light intensity at a few locations along the optical fiber. This is representative of localized corrosion in natural gas pipelines.
- SEM results confirm localized corrosion of the Fe thin film after corrosion in wet CO_2 gas. The XPS results indicate the formation of iron carbonate on the surface of the Fe thin film after wet CO_2 corrosion.

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