
# Multi-parameter Optical Fiber Sensor for Simultaneous Monitoring of Humidity, Pressure, $CO_2$, and Corrosion

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## Background

- Estimated $13.4 billion is lost annually, primarily from corrosion in natural gas transmission pipeline infrastructure.
- Internal corrosion in the natural gas transmission pipelines occurs through condensation of water droplets onto the pipe interior.
- Dissolved contaminants such as $CO_2$, $H_2S$, and salts elevate the corrosion rate.
- Strategies to better identify and quantify the causative factors behind corrosion and its real-time monitoring are necessary to minimize the corrosion caused loss and risks of possible catastrophic events.

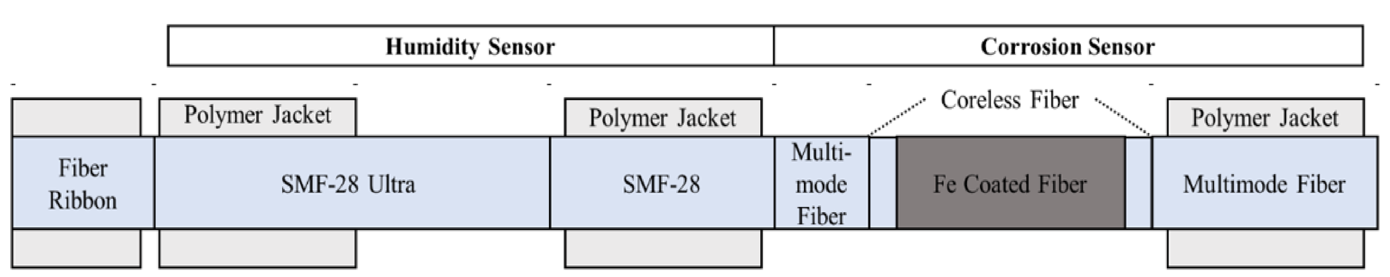

### Advantages of Optical Fiber Sensors:

- Optical fiber-based sensing has lately been explored due to its advantages of small size, light weight, flexibility, improved safety in presence of flammable gases, inherent immunity to electromagnetic interference, and long-range and distributed sensing capabilities.

## Proposed Optical Fiber Sensing for Pipelines

- The polymer jacket of commercially available single-mode fiber (SMF) undergoes strain changes due to absorption of water, $CO_2$, and $CH_4$ which can serve as a sensing layer.
- The unjacketed SMF section serves as a pressure sensor due to change in strain upon exposure to varying pressures, without contribution from the jacket.

**Design of a single optical fiber with multiple functions**

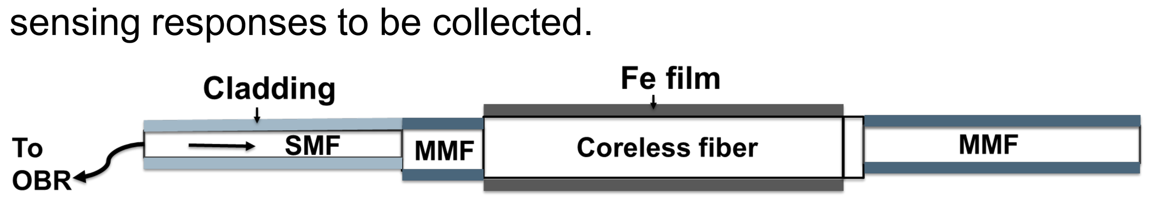



- Metallic iron (Fe) coated onto the coreless fiber section spliced together with multi-mode fiber (MMF) serves as a corrosion proxy to the pipeline wall.
- Upon exposure to corrosive environment such as H+, Fe undergoes oxidative dissolution (corrosion) which is accompanied by hydrogen evolution reaction.

$$Fe_{(s)} \longrightarrow Fe^{2+}_{(aq)} + 2e^- \qquad H^+_{(aq)} + 2e^- \longrightarrow H_{2\,(g)}$$

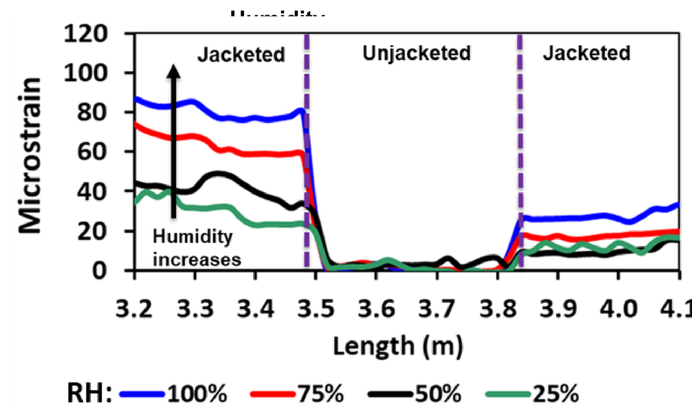
### Distributed Corrosion Sensing by Optical Backscattered Reflectometer (OBR):

- Corrosion of Fe coated onto the coreless fiber section is detected based on the increase in amplitude of backscattered light intensity as Fe undergoes corrosion.
- Backscattered light can be measured in the time and frequency domains, allowing for distributed sensing responses to be collected.

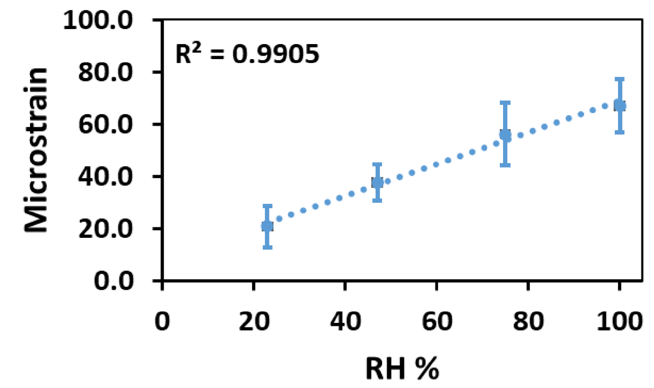





## Humidity Sensing

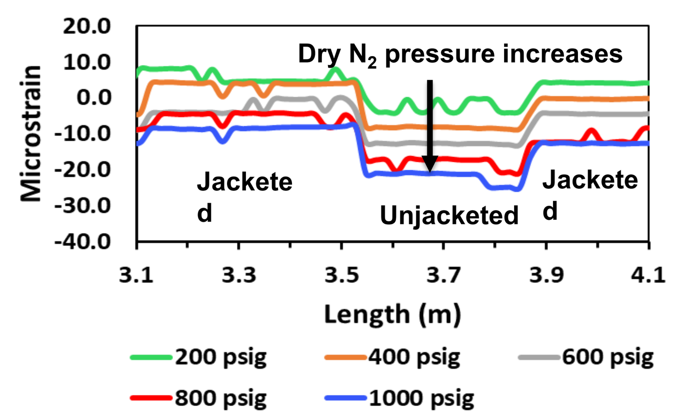



Reference trace: 800 psig dry $N_2$

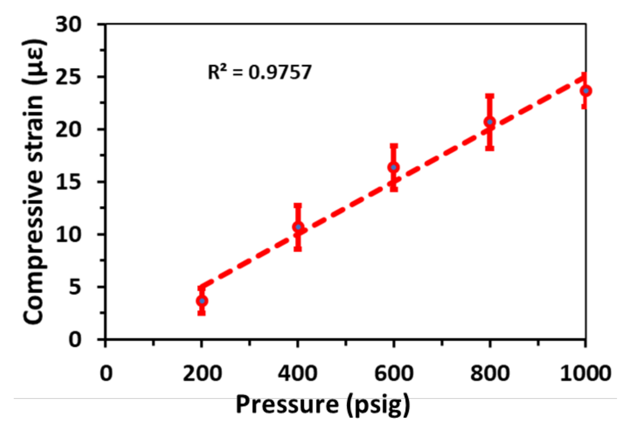



- Microstrain along the jacketed SMF (SMF-28-ultra) increases with increasing relative humidity (RH).
- A good linearity between microstrain change and RH % is observed.
- Strain along the unjacketed fiber section remains unaffected by a change in RH.

## Pressure Sensing




Reference trace: 0 psig dry $N_2$

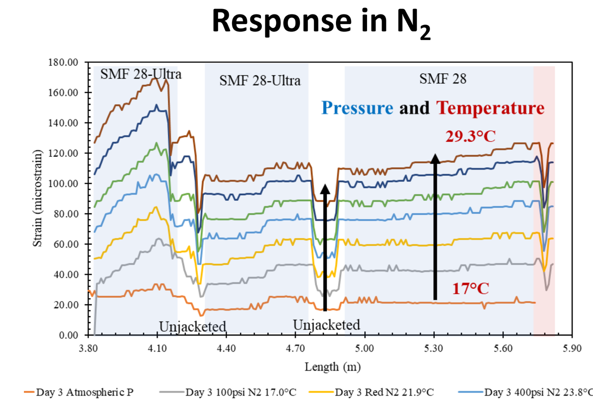



- A compressive microstrain is observed along the unjacketed SMF section with increasing dry $N_2$ pressure.
- A linear response between microstrain change with pressure is observed.

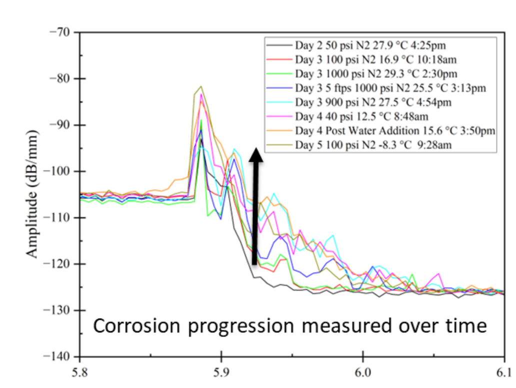
## NETL Sensor Capabilities

**Southwest Research Institute (SwRI) Field Test**

**Pressure and Temperature Strain Response in $N_2$**



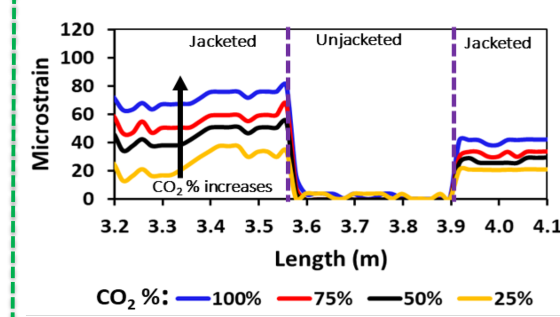

**Corrosion Sensing**



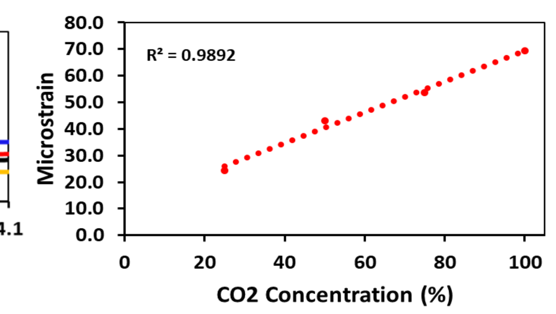

## Conclusions

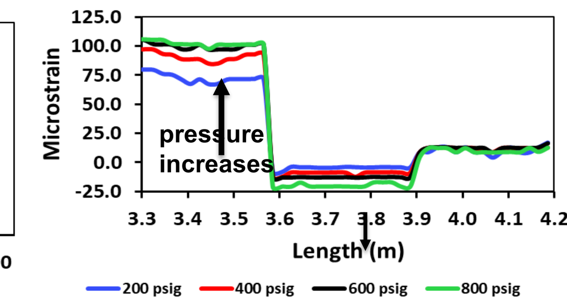
- Successfully demonstrated use of optical fiber sensors for monitoring humidity, pressure, $CO_2$, and corrosion in natural gas pipeline relevant conditions.
- Demonstrated SMF for monitoring humidity and $CO_2$ along the jacketed portion of the fiber based on the strain changes, while unjacketed fiber section is used for monitoring pressure.
- The Fe-coated coreless fiber section acts as a corrosion sensor where the corrosion rate for different Fe film thickness was successfully measured based on the change in amplitude of backscattered light intensity.
- The corrosion rate of Fe increased with increasing film thickness (28-225 nm range) possibly due to increase of roughness at higher thickness.

## $CO_2$ Sensing




Reference trace: 800 psig dry $N_2$

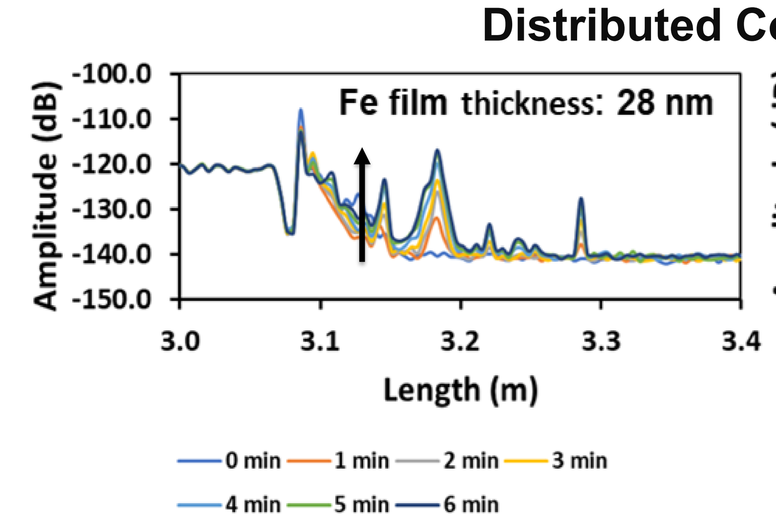


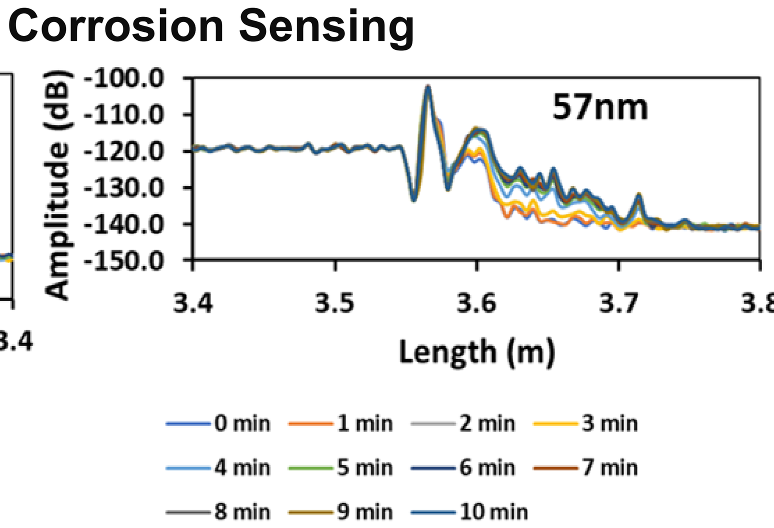



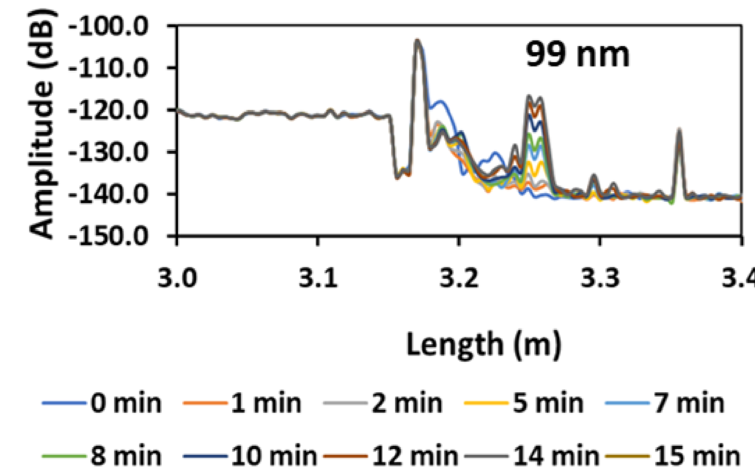

Reference trace: 0 psig dry $N_2$

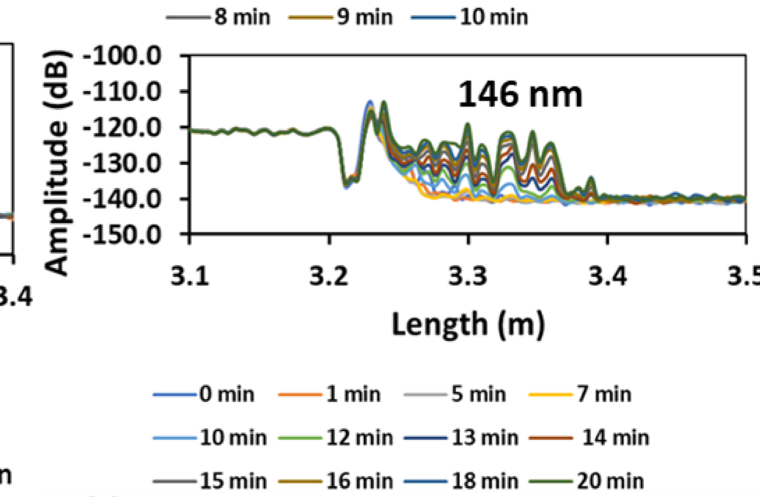
- Microstrain along the jacketed SMF (SMF-28-ultra) increases with increasing dry $CO_2$ concentration mixed with dry $N_2$ at a total pressure of 800 psig.
- Strain along the unjacketed fiber section remains unaffected by a change in $CO_2$ composition.
- Strain changes along the jacketed SMF increase with pressure.
- A compressive microstrain is observed along the unjacketed fiber section.

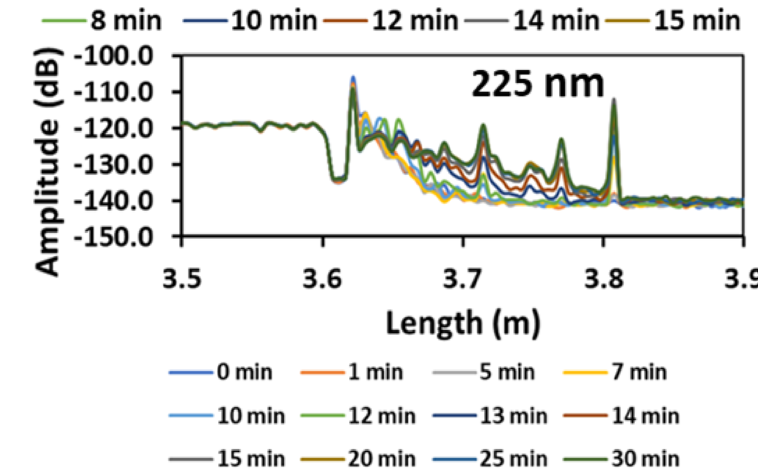
## Distributed Corrosion Sensing

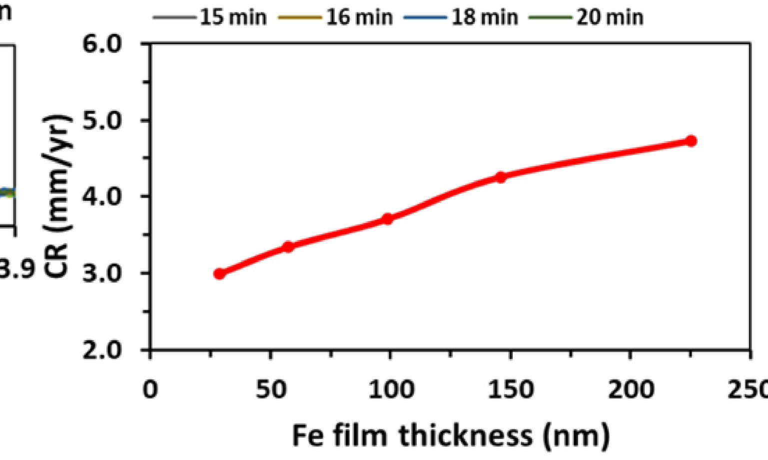



- Corrosion is studied in $CO_2$ saturated 3.5% NaCl solution, acidified with HCl (pH 3.2).
- Corrosion causes changes (increase) in backscattered light intensity amplitude as measured by OBR.
- Corrosion rate (Fe film thickness/time for complete corrosion) increases with the Fe film thickness.