# Fe-Coated Optical Fiber for Distributed Corrosion Monitoring in Soil and Aqueous Environments

NATIONAL ENERGY TECHNOLOGY LABORATORY

***Badri Mainali***

*Research Scientist/NETL Support Contractor*

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# Authors and Contact Information

*Badri Mainali[1,2]; Alexander Shumski[1,2]; Nathan Diemler[1,2]; Ruishu Wright[1]*

*[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA*

*[2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA*

# Outline

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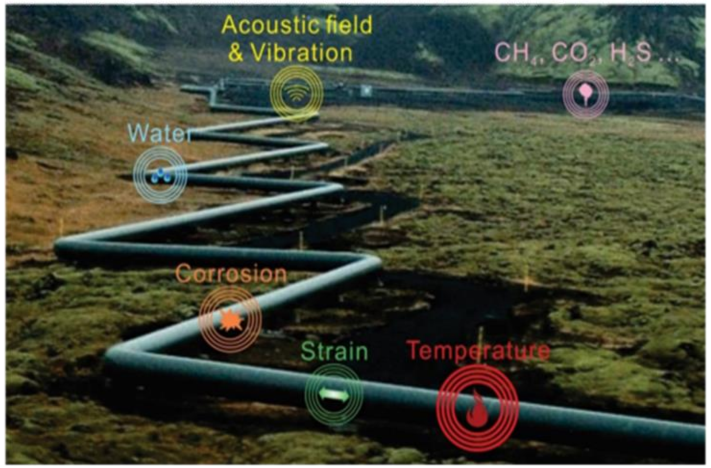
  - Background
  - Essence of optical fiber sensing
- **Key Objectives and Experimental**
- **Results and Discussion**
  - Monitoring factors causing corrosion (humidity and gases)
  - Intensity-based corrosion monitoring in aqueous environment
  - Transmission-based corrosion monitoring in aqueous environment
  - Corrosion monitoring in soil
- **Conclusions**
- **Acknowledgements**

# Background




- Annual loss of ~$14.0 billion occurs due to corrosion across oil and gas pipelines and exploration
- Monitoring of corrosion requires identification and quantification of $H_2O$, $CO_2$, and $H_2S$
- Conventional monitoring techniques have limited capability to identify corrosion failures before they occur
- Therefore, real-time monitoring is needed to detect and mitigate pipeline risks

Sensors **2019**, 19, 3964.

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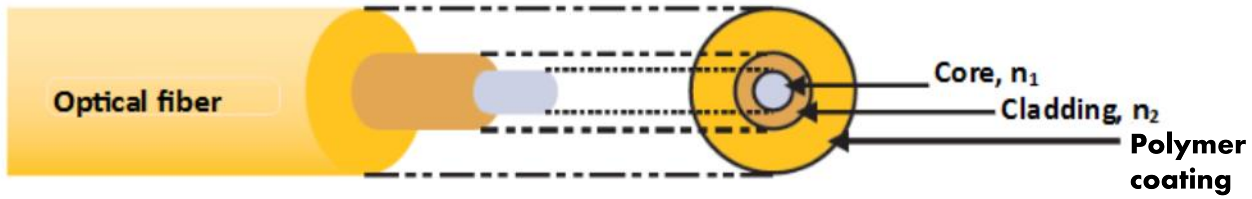
# Optical Fiber Sensing





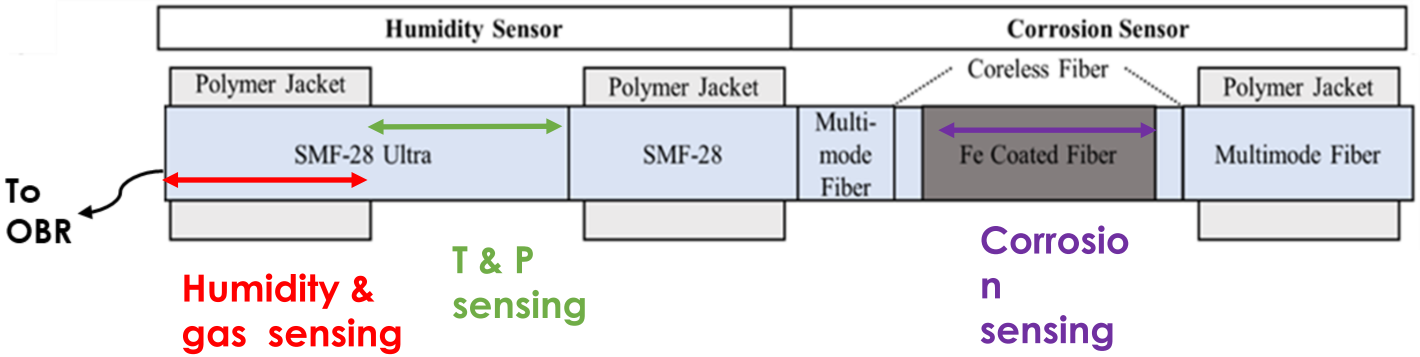
## Advantages of optical fiber sensors (OFS):

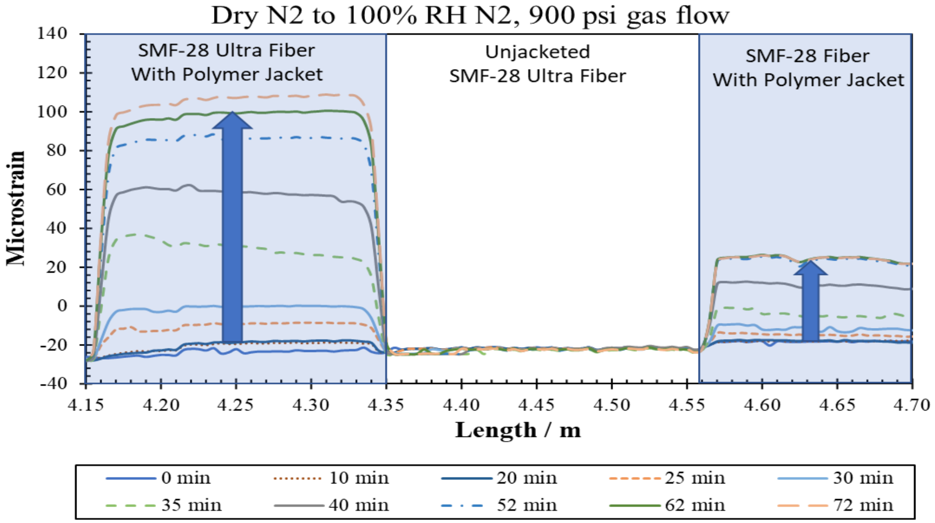
- Capable of nondestructive and in-situ distributed measurement
- Small size, lightweight, and flexible
- High sensitivity and accuracy
- Improved safety in the presence of inflammable gases
- Inherent immunity to electromagnetic interference
- Compatible with optical fiber data communication systems

Sensors **2019**, 19, 3964.
Optical Fiber Communications, Gerd Keiser, 2002.

# Multi-Parameter OFS for Monitoring Humidity and Corrosion

## Design of OFS for humidity and corrosion sensing

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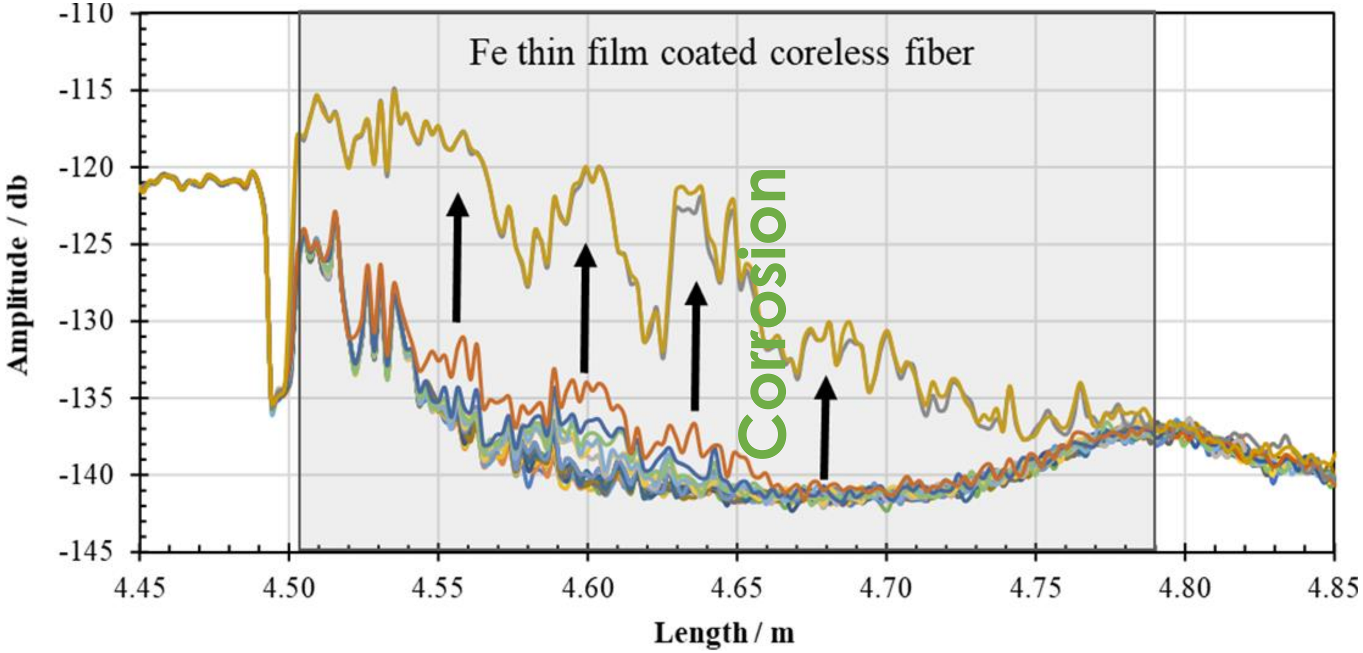
- Jacketed single mode fiber (SMF)-28 ultra undergoes swelling upon absorption of $H_2O$/gases resulting in strain development
- Humidity is monitored based on the strain developed along the jacketed SMF
- Unjacketed SMF is insensitive to humidity/gas sensing but sensitive to temp (T) and pressure (P)
- Fe-coated coreless fiber section acts as a corrosion sensor

# Corrosion Sensing

100% RH $CO_2$




Backscattered light intensity amplitude along the Fe thin film-coated coreless fiber section in wet $CO_2$.

- Fe undergoes corrosion when exposed to corrosive environment (e.g., aqueous $CO_2$)

Hydration-dissociation:

$$2CO_{2(aq)} + 2H_2O_{(l)} \rightarrow 2H^+_{(aq)} + 2HCO_3^-{}_{(aq)}$$

Anode:

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$$

Cathode:

$$2H^+_{(aq)} + 2e^- \rightarrow H_{2\,(g)}$$

- Corrosion is monitored based on the change in backscattered light intensity amplitude before and after corrosion of Fe

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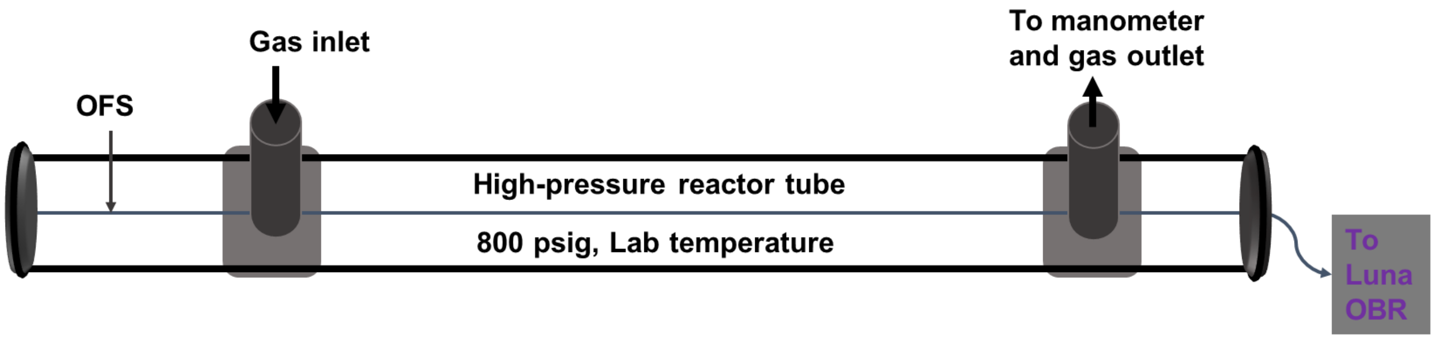
# Key Objective and Experimental Setup-I

**Objective A:** Extending the capability of the OFS for calibrating strain response of SMF under controlled humidity and gas composition conditions

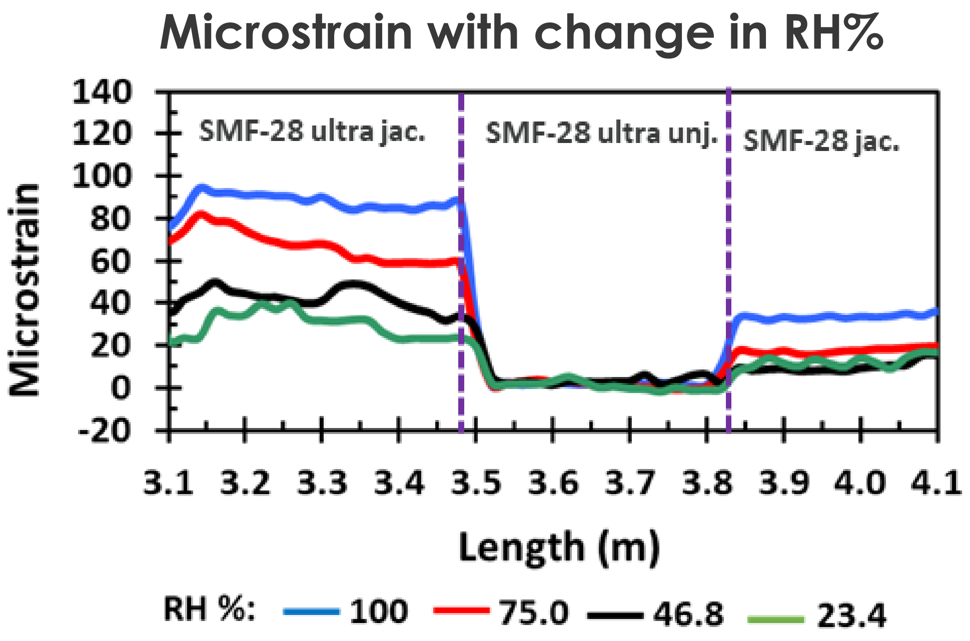



- Humidity was maintained by controlled dilution of 100% humid gas ($N_2$, $CH_4$, or $CO_2$) with respective dry gas (verified by humidity sensor)

    RH% studied: 100, 75.0, 46.8, and 23.4%

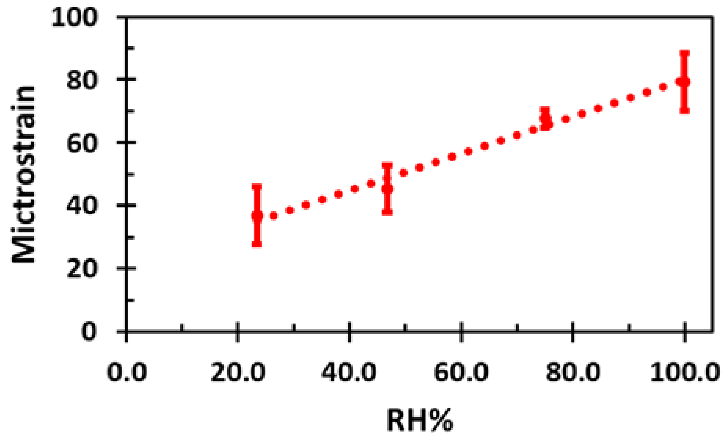
- Gas composition was maintained by proportional mixing of the respective gases based on their partial pressures

# Microstrain Measurement for Monitoring Humidity/Gases




Reference trace: 800 psig dry $N_2$.

- Microstrain was measured under equilibrium (1 hr)
- Microstrain increases with increasing RH%

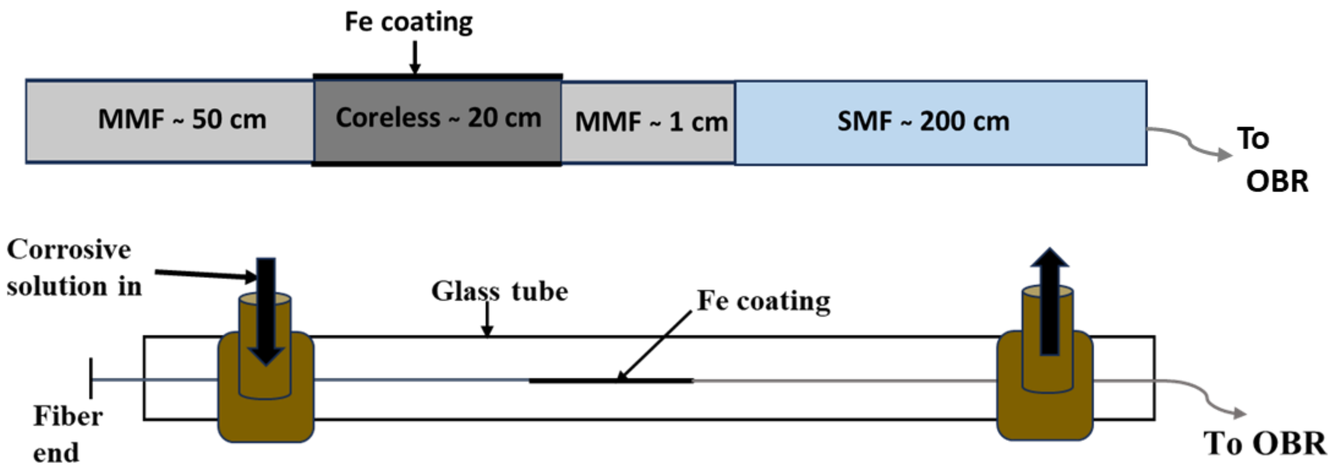



- Calibration curve shows good linear response of microstrain with RH% change ($R^2 = 0.998$)

$CO_2$ and $CH_4$ under different RH% and gas composition conditions were monitored similarly.

# Key Objective and Experimental Setup-II

**Objective B:** Extending the capability of the Fe-coated OFS for monitoring accelerated corrosion rates in aqueous environment




- Electroless coating of a thin Fe film onto the coreless fiber section with controlled film thickness (~25-225 nm)

- Corrosion was studied in $CO_2$ saturated 3.5% aq. NaCl + HCl, pH = 3.2

- Corrosion rate of Fe = $\dfrac{\text{Fe film thickness (nm)}}{\text{Time for attaining steady state backscattered intensity amplitude of the light upon complete corrosion of Fe (min)}}$

# Monitoring Corrosion

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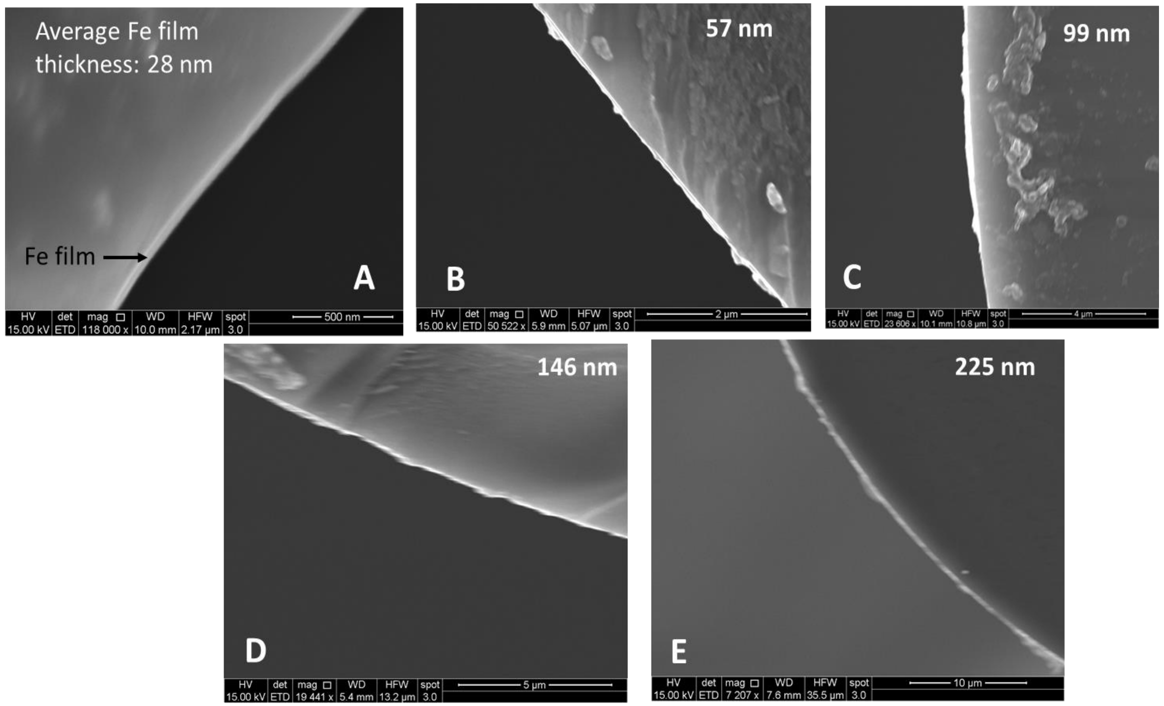
## Coating of Fe film on the OFS surface

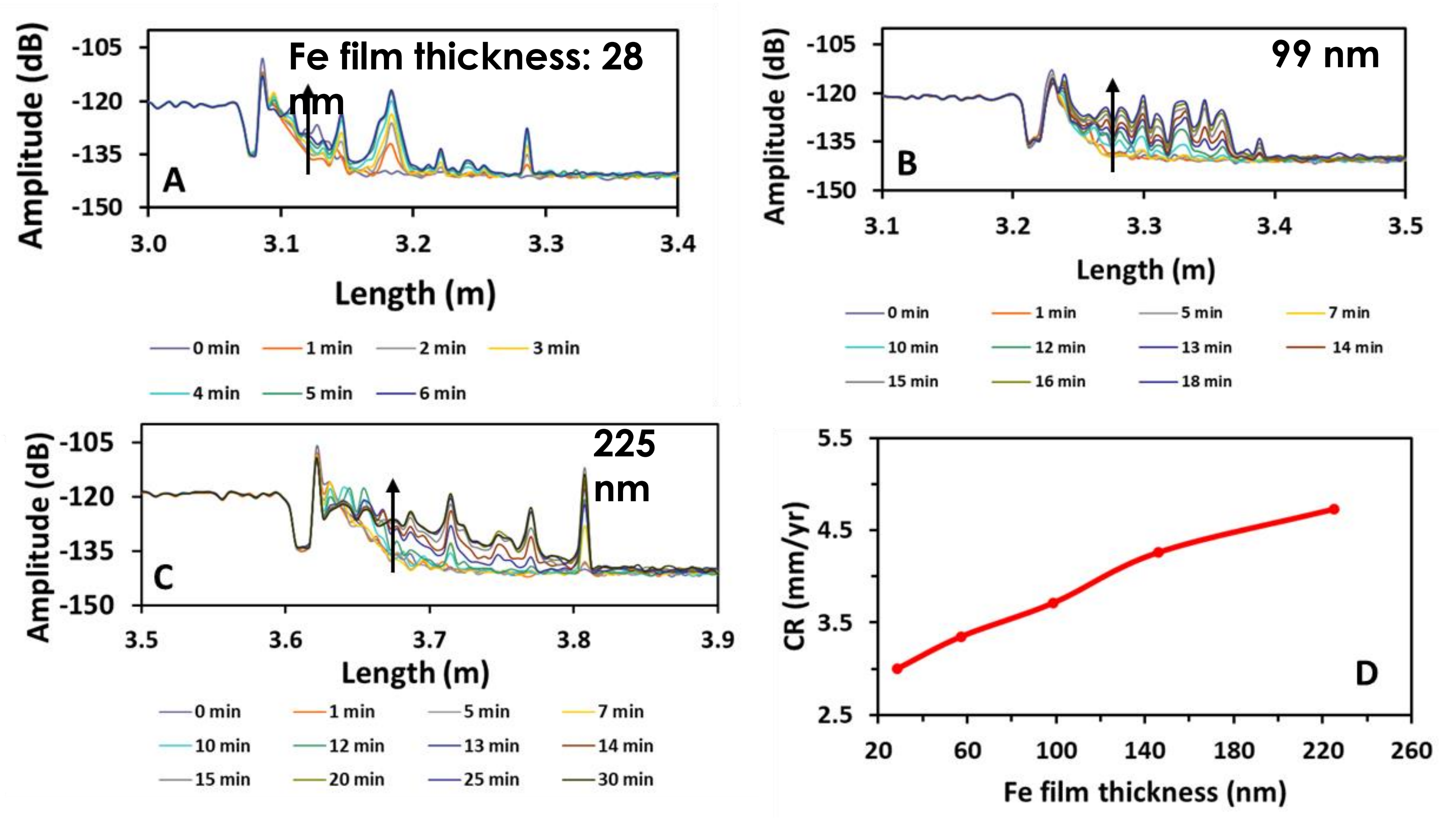



SEM images of the cross-section of the Fe-coated OFS prepared by the electroless coating.

- Performed electroless coating of Fe on to the OFS surface with variable coating thickness by immersing the fiber into the coating bath for different times:
  1 min: 28 nm
  2 min: 57 nm
  3 min: 99 nm
  4 min: 146 nm
  5 min: 225 nm

# Corrosion Sensing: Monitoring Corrosion Rate

## Changes in backscattered intensity amplitude of light along Fe-coated OFS section

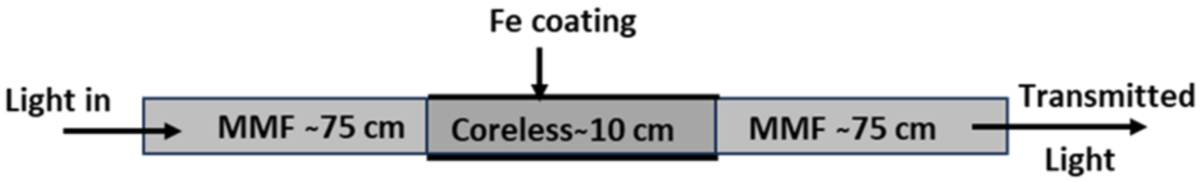



- Rate of change of Fe film thickness over time provides corrosion rate (CR)
- CR increases with increasing Fe film thickness, possibly due to rougher film surface at higher thickness

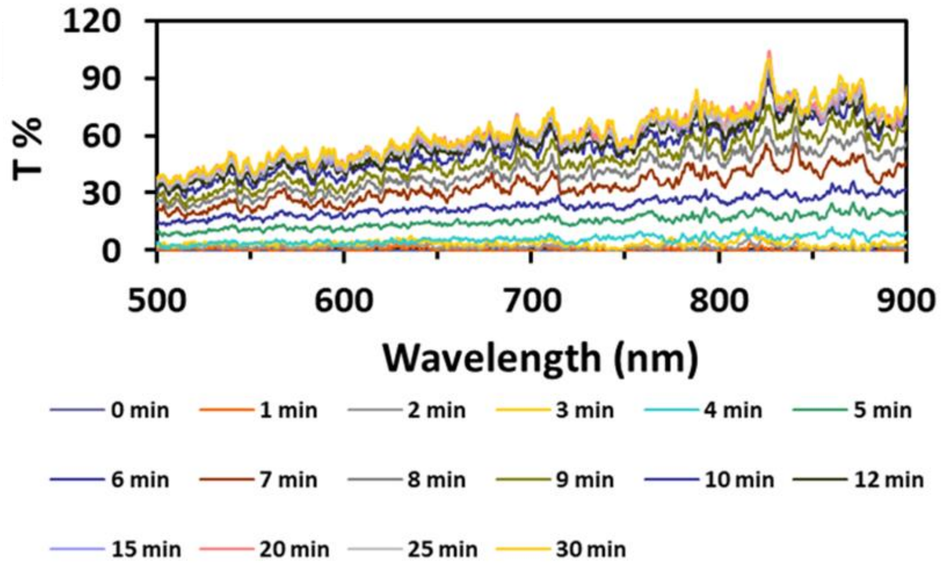
Corrosion was studied in $CO_2$ saturated aqueous 3.5% NaCl + HCl, pH 3.2.

# Corrosion Monitoring via Transmission Measurement





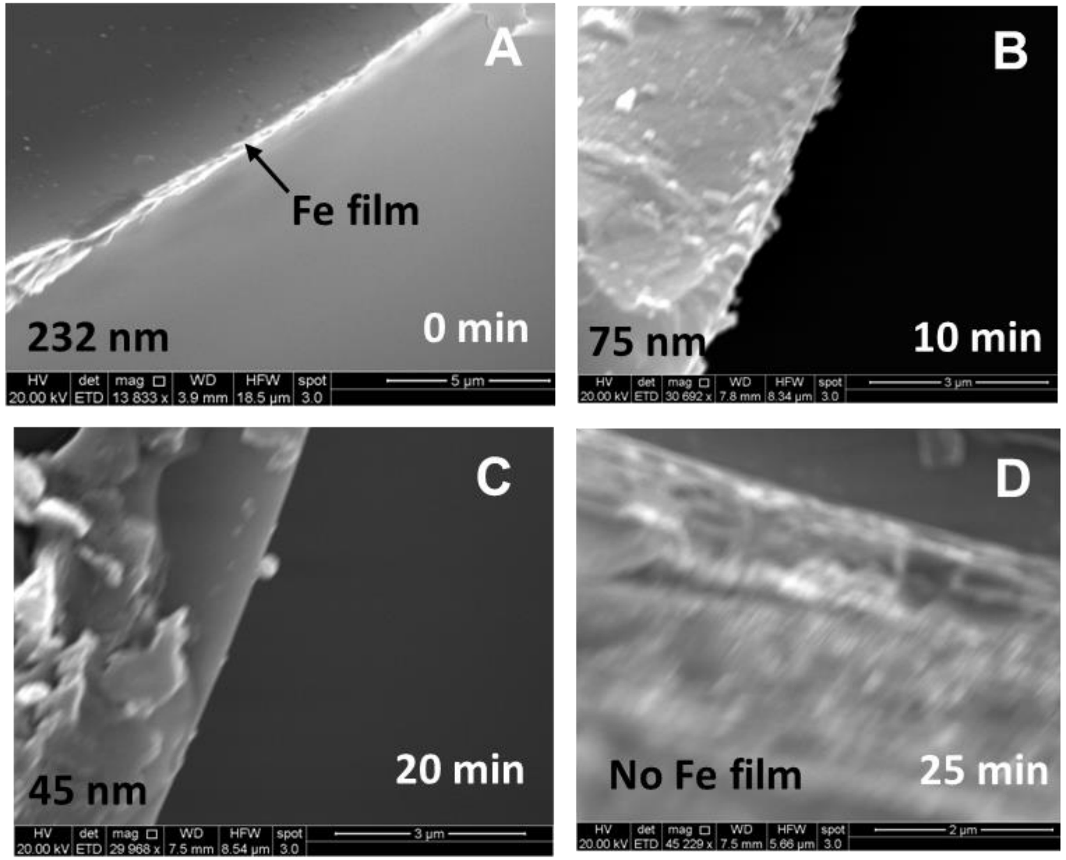

Design of experiment for monitoring corrosion of Fe in transmission mode.



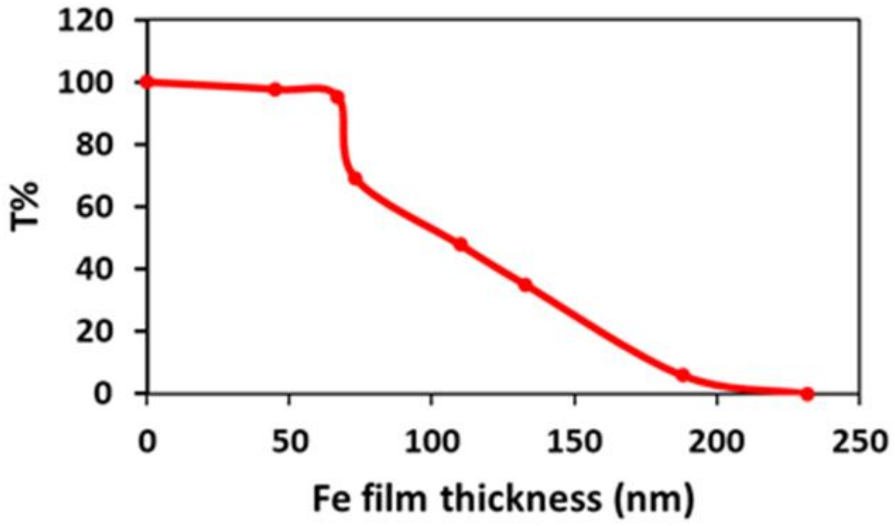

Normalized transmission (T%) of light in the visible range (500–900 nm) with time during corrosion of Fe.

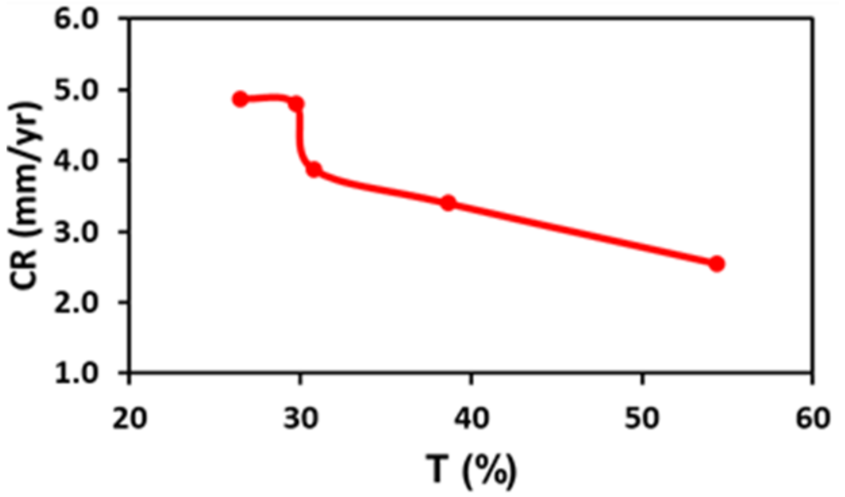
- Fe absorbs visible light
- Transmission of light increases with decrease in Fe film thickness due to corrosion
- Change in light transmission rate measures CR

# Correlating Corrosion Rate with Transmission



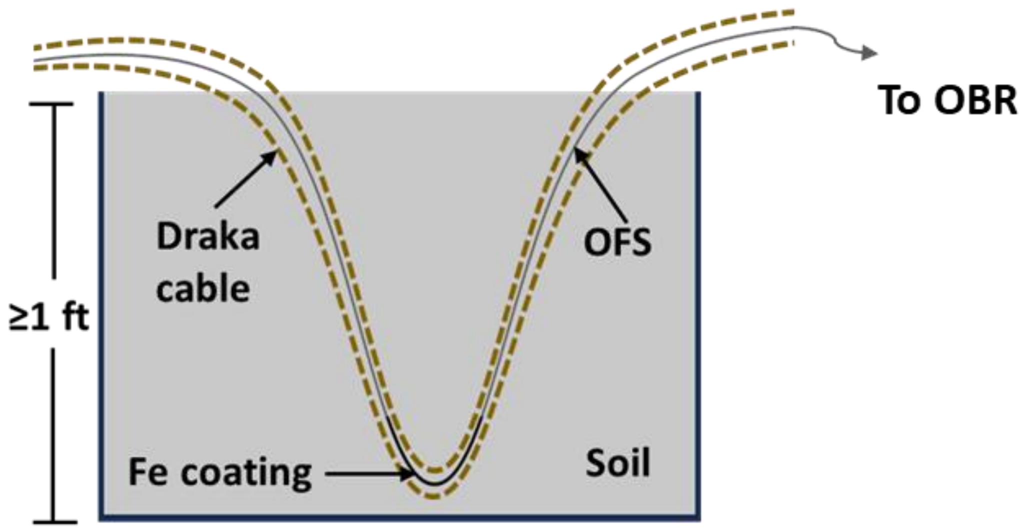

Decrease of film thickness of Fe coated onto the OFS with time immersed in corrosive solution.

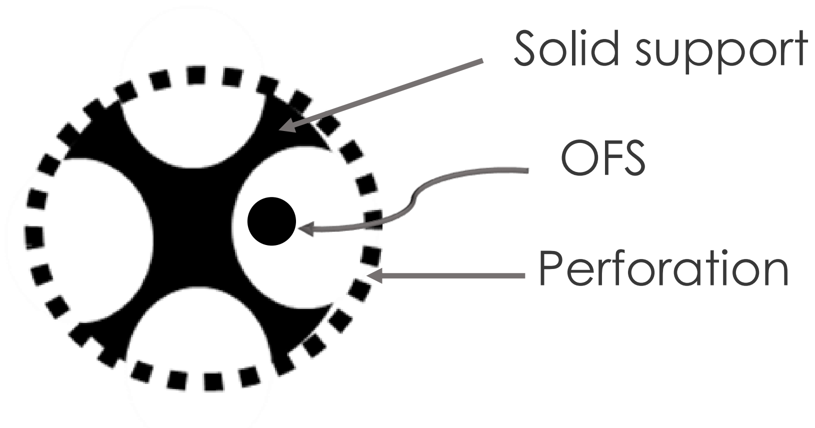


# Key Objective and Experimental Setup-III

**Objective C:** Extending the capability of the Fe-coated OFS for monitoring corrosion in soil

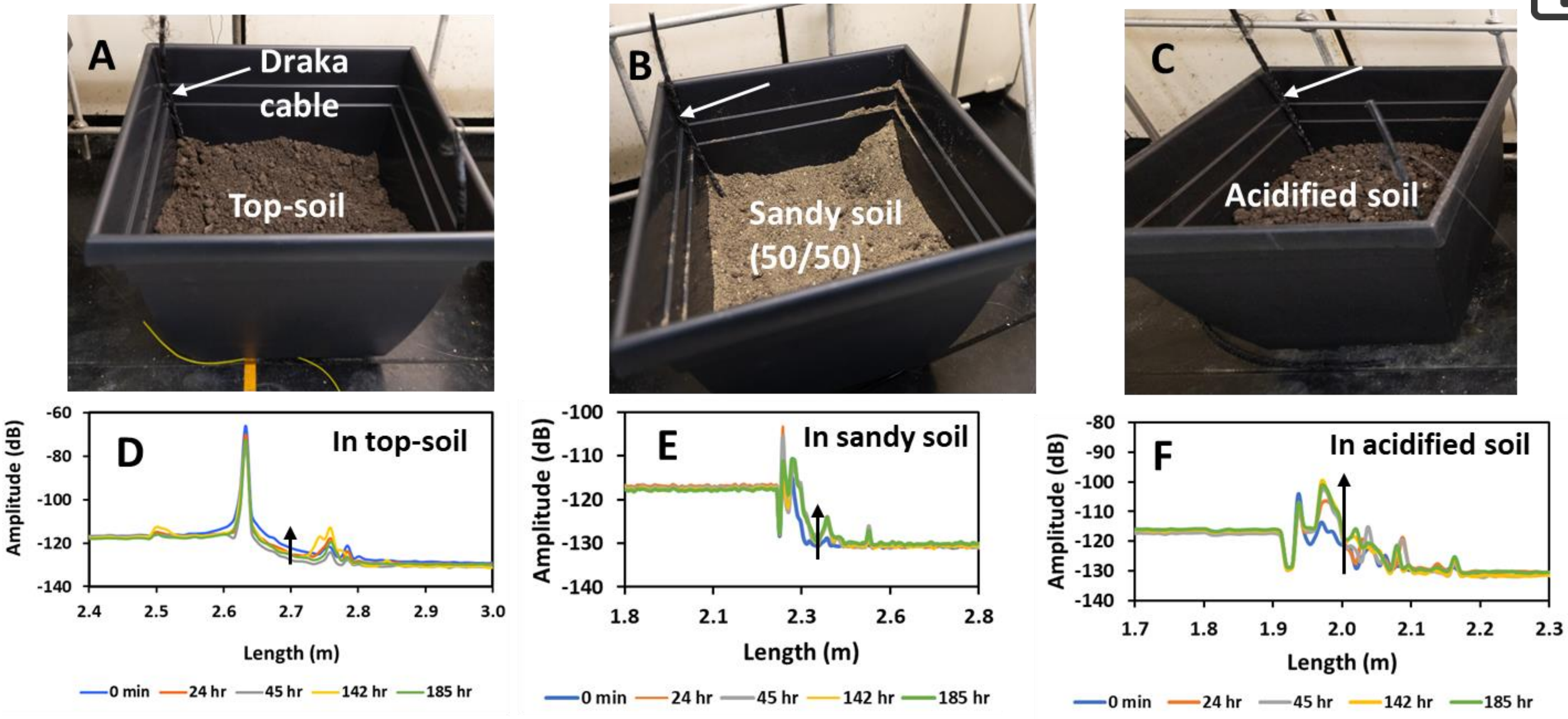



Cross-section view of Draka cable with OFS.

- Soil provides stress to the OFS rendering it susceptible to mechanical disturbance or breakage
- Draka cable provides physical support to the relatively fragile OFS and also allows exposure of the sensor to the outside environment

# Corrosion Monitoring in Soil




- Types of soil used for the corrosion experiment: (A) top-soil, (B) sandy soil, and (C) acidified soil
- Draka cable provides physical support for burying the fiber sensor in soil
- CR: highest in acidified soil, moderate in sandy soil, and least in topsoil

# Conclusions

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- Optical fiber sensors provide long distance distributed sensing of humidity, $CH_4$, and $CO_2$ in natural gas pipeline relevant conditions.
- Corrosion was successfully monitored by using Fe-coated OFS, where Fe acts as a corrosion proxy.
- Accelerated corrosion rate was monitored by measuring the rate of change of backscattered light intensity amplitude during corrosion of Fe exposed to the corrosive aqueous environment.
- Physical protection of the OFS by a solid support such as a Draka cable enabled corrosion monitoring in soil.


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# Acknowledgments

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CONTACT:
Badri Mainali
Badri.Mainali@netl.doe.gov