Advanced Sensors for Real-Time Monitoring of Natural Gas Pipelines

FWP-1022424, Project No.1611133

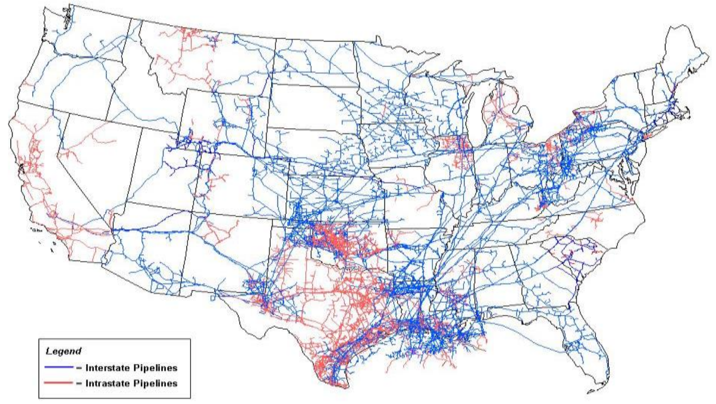
Presenter: Dr. Ruishu Wright, NETL

Dr. Michael Buric, Dr. Ping Lu, Dr. Jagannath Devkota,
Dr. Margaret Ziomek-Moroz, Dr. Jeffrey Culp, NETL

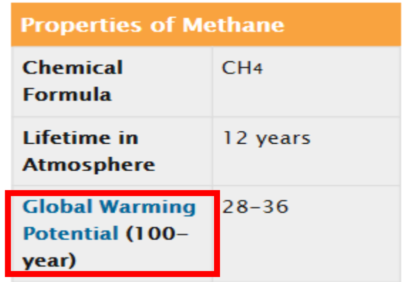
Prof. Kevin Chen, University of Pittsburgh

U.S. Department of Energy
National Energy Technology Laboratory
2021 Carbon Management and Oil and Gas Research Project Review Meeting
August 2021

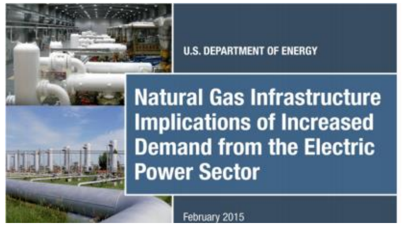
Reliability & Resiliency of Natural Gas Infrastructure



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

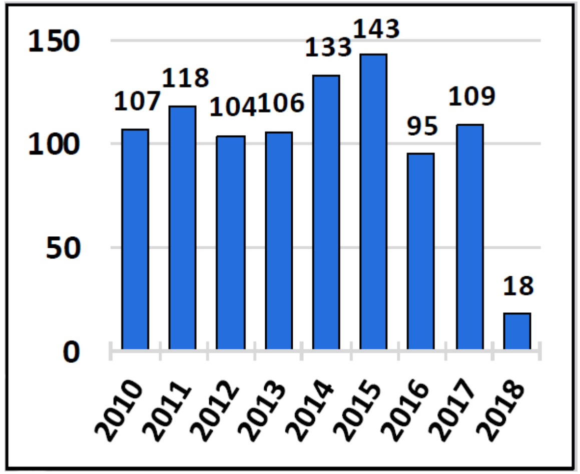


Properties of Methane	
Chemical Formula	CH_4
Lifetime in Atmosphere	12 years
Global Warming Potential (100–year)	28–36

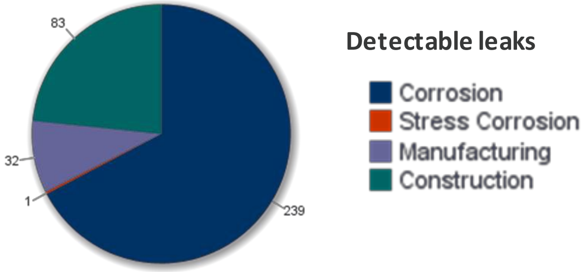


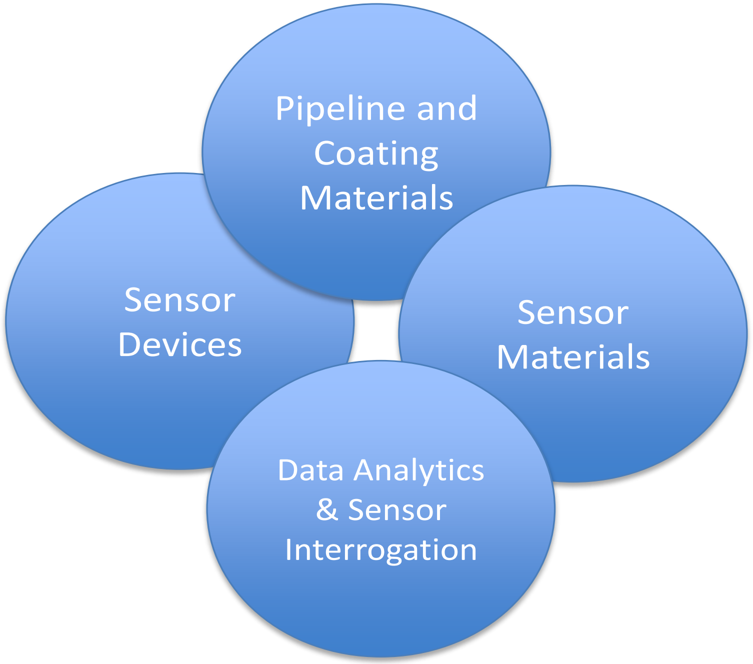
http://energy.gov/sites/prod/files/2015/02/f19/DOE%20Report%20Natural%20Gas%20Infrastructure%20V_02-02.pdf

Number of natural gas transmission pipeline incidents (2010-2018)



Gas Transmission Leak Sources



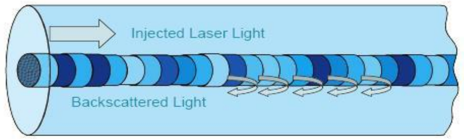


Real-time Monitoring and Leak Detection/Mitigation for the Natural Gas Infrastructure is Increasingly Important. New Sensing Technologies are Being Developed to Address these Needs.

Approach: Advanced Sensor Technologies

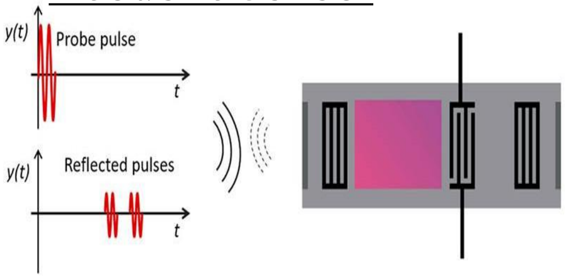
Distributed Optical Fiber Sensor

Imperfections in fiber lead to Rayleigh backscatter.

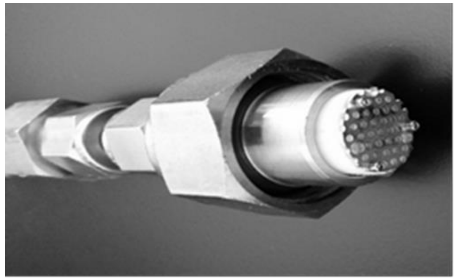


Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

Passive Wireless Surface Acoustic Sensor



Advanced Electrochemical Sensor

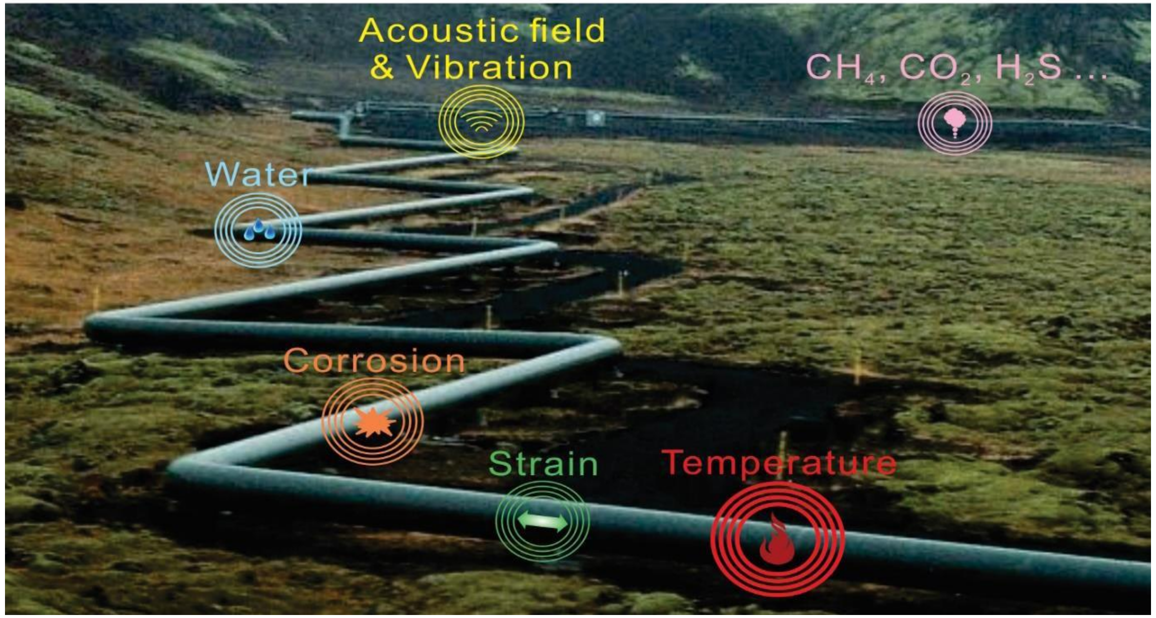


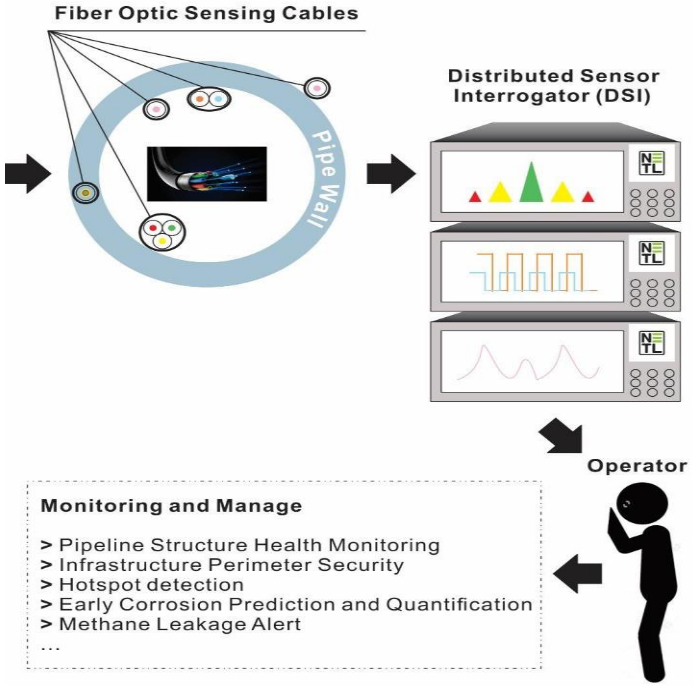
	Geospatial Attributes	Cost	Targeted Function
Distributed Optical Fiber Sensors	Linear Sensor Adjustable Distance and Resolution	Cost Per Sensor "Node" Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, H_2, etc.) Early Corrosion/pH Detection
Passive Wireless SAW Sensors	Point Sensor	Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, H_2, etc.) Early Corrosion/pH Detection
Advanced Electrochemical Sensor	Point Sensor	Moderate	Water Content, Corrosion Rate, T, Pitting Corrosion

Three Synergistic Sensor Platforms with Complementary Cost, Performance, and Geospatial Characteristics are Being Developed with an Emphasis on Corrosion & Gas Composition.

Real-time Smart Sensor Network for Pipelines

Pipeline Integrated with Distributed Optical Fiber >100 km





Emphasis Within NETL Research & Innovation Center:

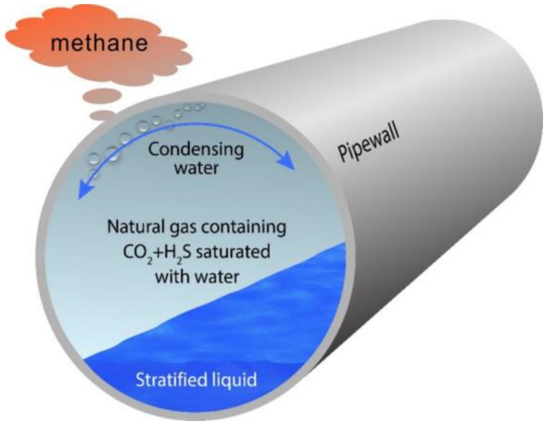
- ➢ Optimize Interrogation System (Range, Resolution, Cost)
- ➢ Early Corrosion On-Set Detection
- ➢ Methane Leak Detection & In-Pipe Gas Composition Monitoring

→ Predictive Signatures
→ Direct Signatures

Multi-Parameter, Distributed Optical Fiber Sensor Platform to Enable Reliable and Resilient Pipelines.

<u>Target Metrics</u>: >100 km Interrogation, <1 m Spatial Resolution

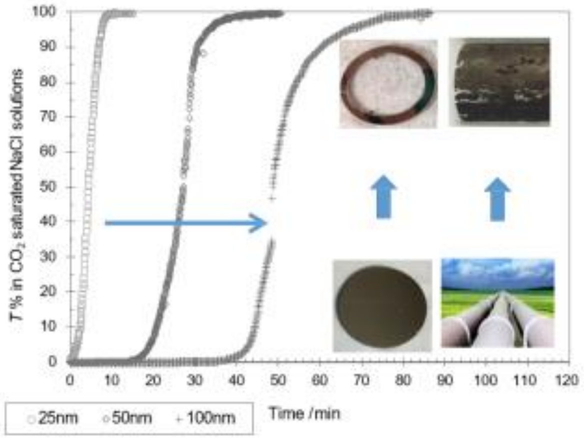
Methane Leak Monitoring and Corrosion Detection



Methane Leak Monitoring and In-pipe Gas Sensing

- ✓ Engineered Metal-organic Framework (MOFs) Layers
- ✓ Engineered Polymer Coating Layers
- ✓ Nanoparticle and Nanocomposites Based Upon Polymers / MOFs

Target metrics: <1% CH_4 in air (external), multicomponent H_2O, CO_2, CH_4, H_2, H_2S (internal)



Early Corrosion Onset Detection and Localization

- ✓ Corrosion Proxy Sensing Materials (e.g. Fe-Based Metallic Films)
- ✓ Detection and Chemical Characterization of Condensed Water Phases (e.g. pH, dissolved CO_2, etc.)

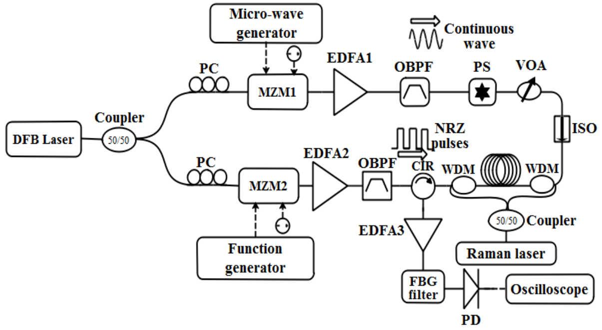
Target Metrics: Early Corrosion Onset Detection,

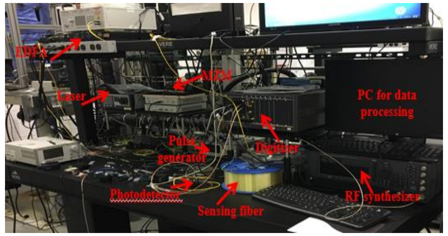
< 0.1 mm Thickness Reduction

Distributed Optical Fiber Interrogation

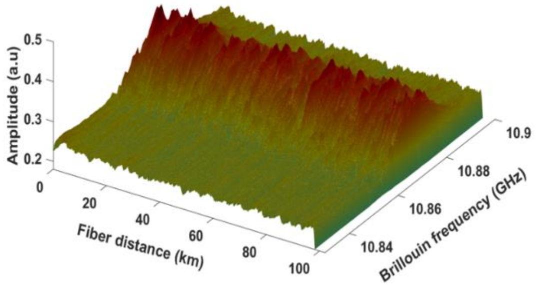
NATIONAL ENERGY TECHNOLOGY LABORATORY

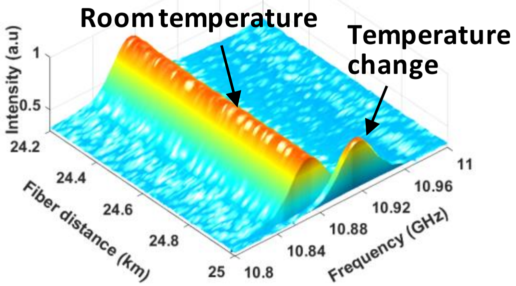
(1) Super-long-distance temperature and strain measurement





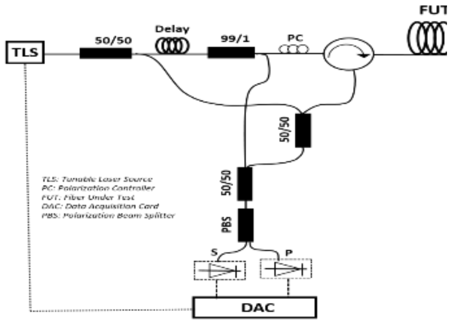
Brillouin Optical Time-domain Analysis (BOTDA)

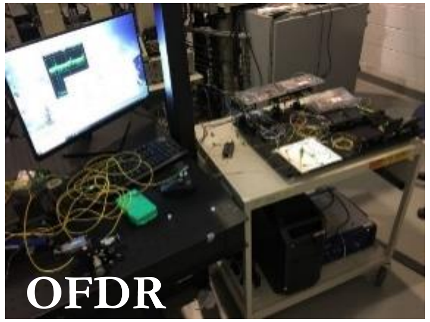




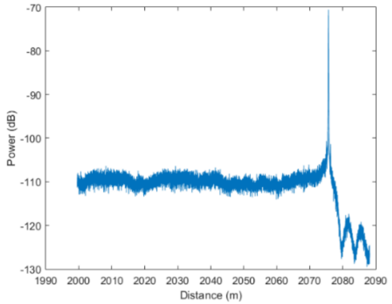
Measurement distance: >150 km
Spatial resolution: 1 m
Sensing range: 1 °C / 100 µε

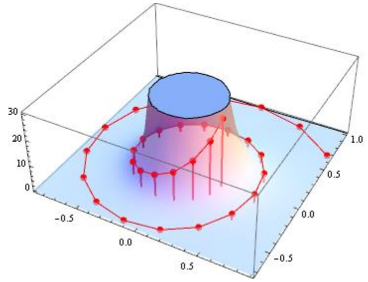
(2) Super-high-resolution temperature / strain / vibration measurement





Optical Frequency Domain Reflectometry (OFDR)





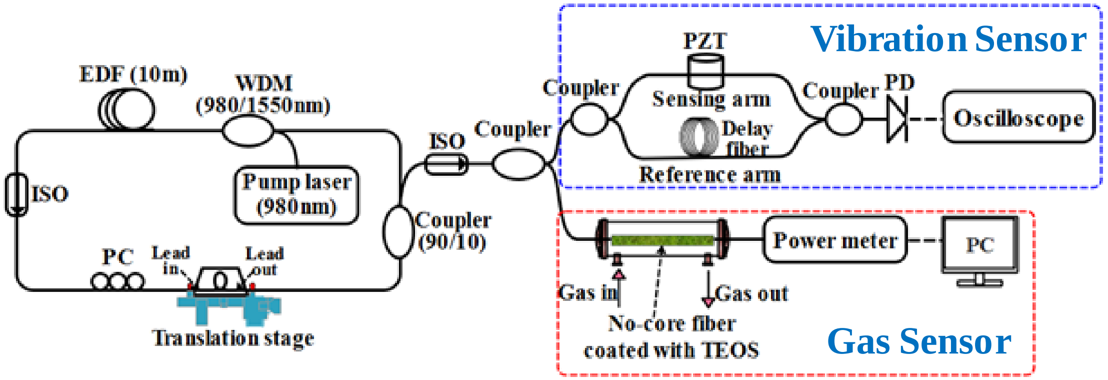
Measurement distance: ~2 km
Spatial resolution: 0.3 mm
Sensing range: 0.1 °C / 10 µε

FFT-segmented chirp-Z transform

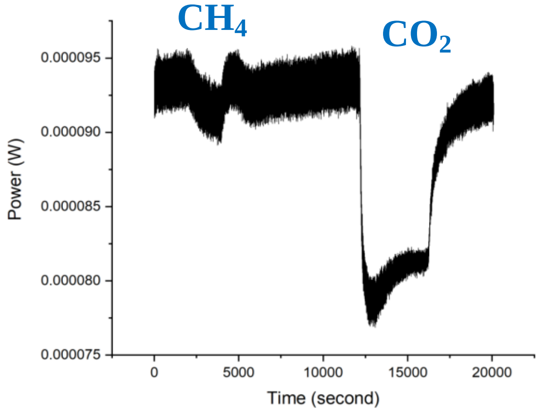
A Number of Different Optical Backscattering Methods were Employed to Enable Distributed Measurements of Temperature, Strain, and Vibration.

Distributed Optical Fiber Interrogation

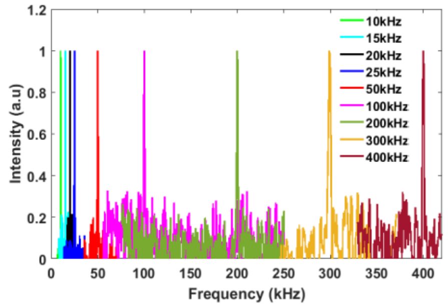
(3) Simultaneous gas detection and vibration monitoring based on a tunable fiber ring laser



Gas Sensing

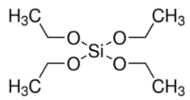


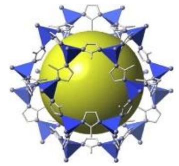
Vibration Sensing



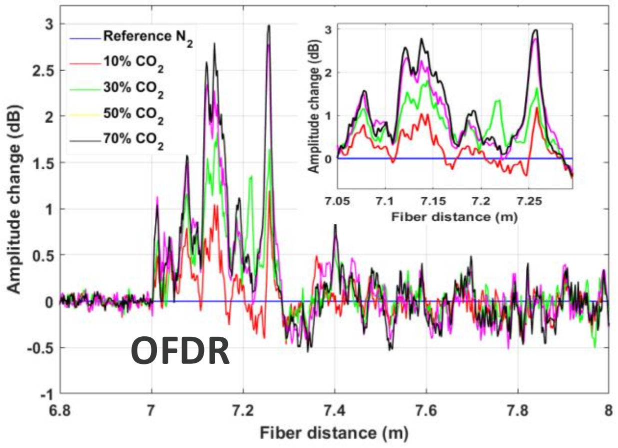
10 Hz to 400 kHz

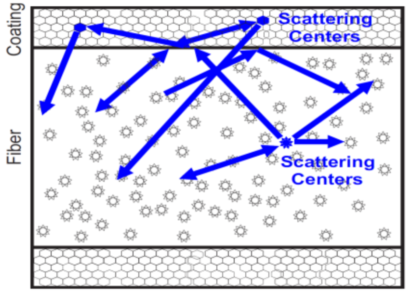
(4) Distributed gas sensing using OFDR





Functional Material (e.g. TEOS, MOF, polymer) Coated Fiber





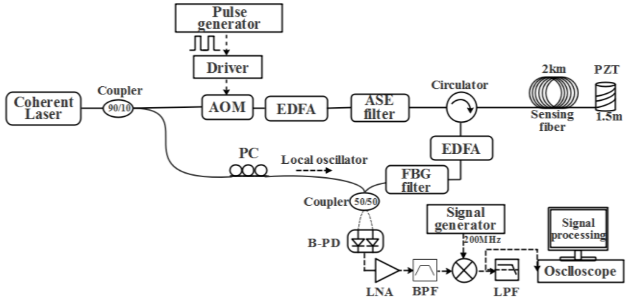
Rayleigh Scattering due to inhomogeneities in both fiber and its coating layer.

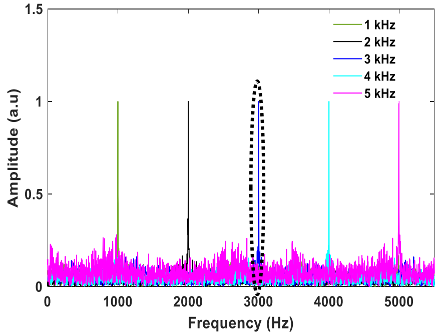
Measurement distance: 2 km
Spatial resolution: 1 cm
Sensing resolution: 10% CO_2/N_2

Different Optical Backscattering Methods were Employed to Enable Distributed Measurements of Gas Composition and Vibration.

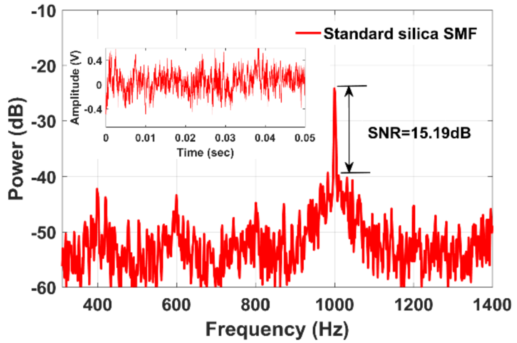
Distributed Optical Fiber Interrogation

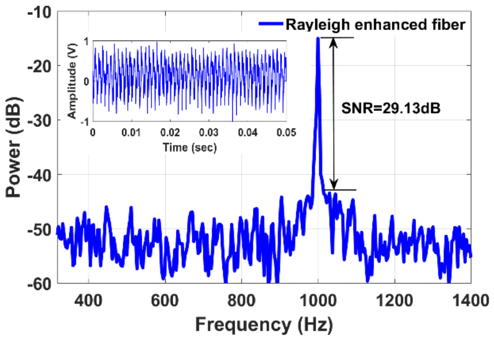
(5) Ultrasonic acoustic / vibration monitoring





Phase-sensitive optical time domain reflectometry (Φ-OTDR)

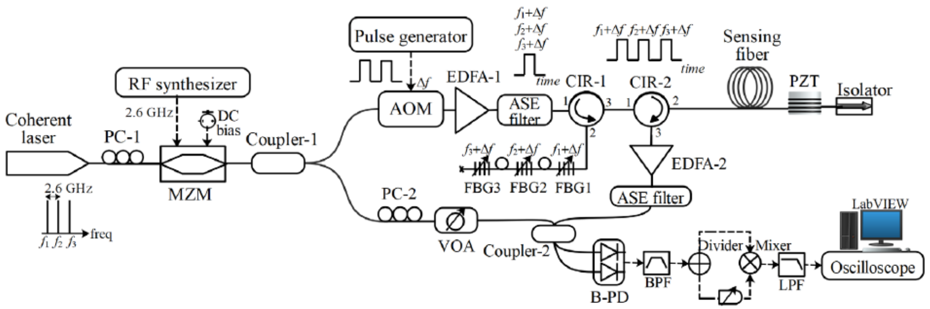


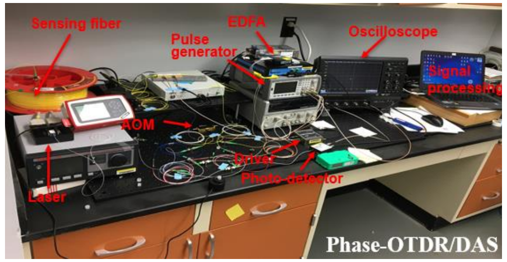


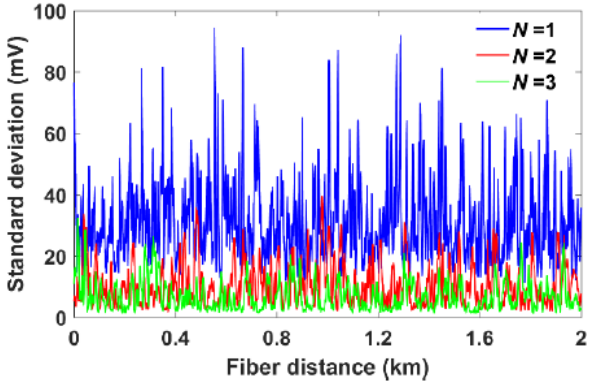
Measurement distance: 2 km
Spatial resolution: 1 m
Frequency range: 100 Hz – 25 kHz

Noise reduced by half using Rayleigh enhanced fibers.

(6) Φ-OTDR with wavelength diversity technique for enhanced Signal-to-noise ratio (SNR)





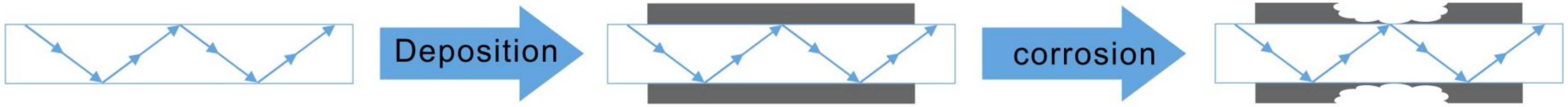


Fading noise was significantly minimized.

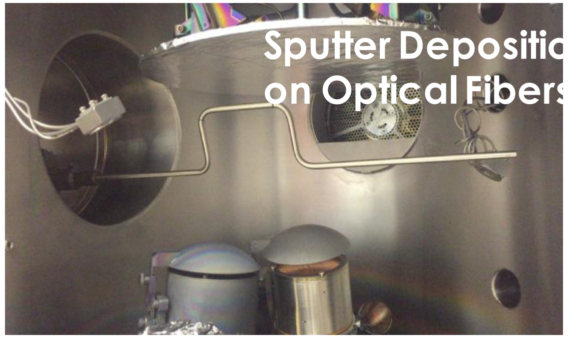
Novel Approaches to Improve SNR in Different Optical Backscattering Methods for Distributed Measurements of Acoustic Waves and Vibration.

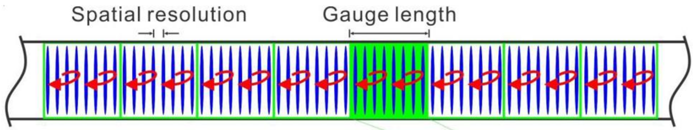
Corrosion Sensing and Early Onset Detection

Power variation: Thin Film Corrosion Proxy-Coated Optical Fiber

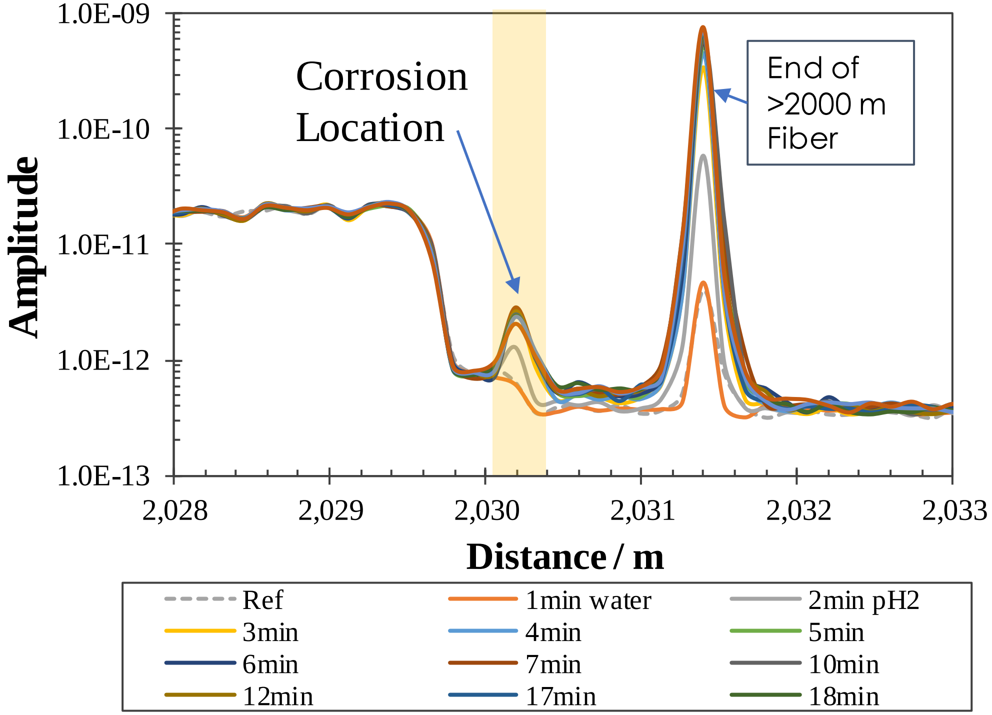


Iron or carbon steel thin film





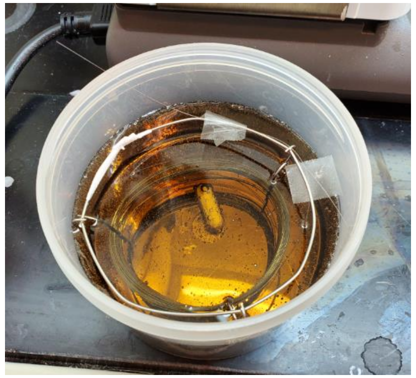
Optical Fiber Interrogator

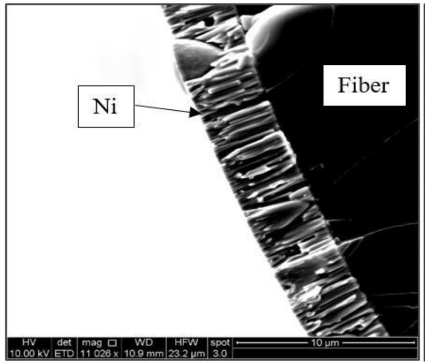


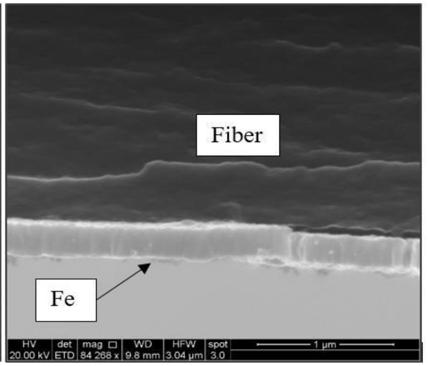
Successful Demonstration of Corrosion Monitoring of Metallic Thin Film as a Function of Time and Location for 2 km with 10 cm spatial resolution.

Distributed Corrosion Monitoring

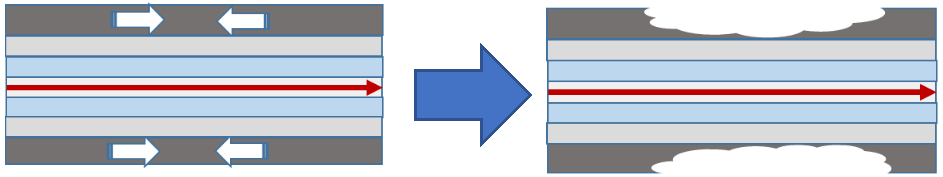
Electroless Plating

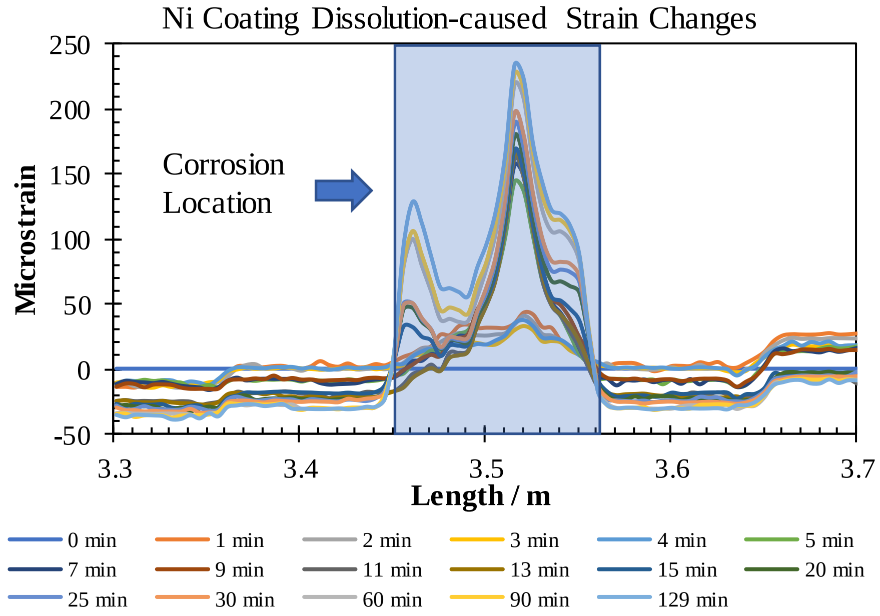






Strain Based, Fully distributed Optical fiber Corrosion Sensor



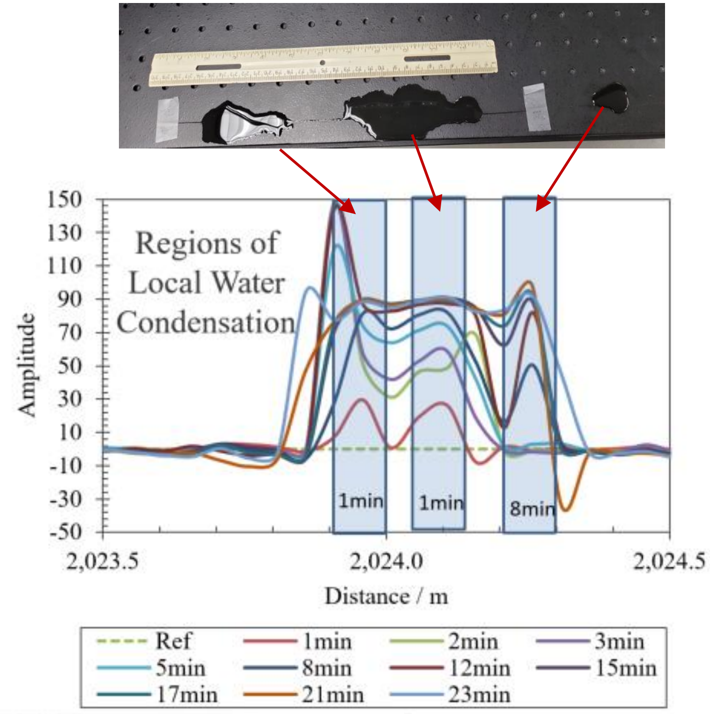


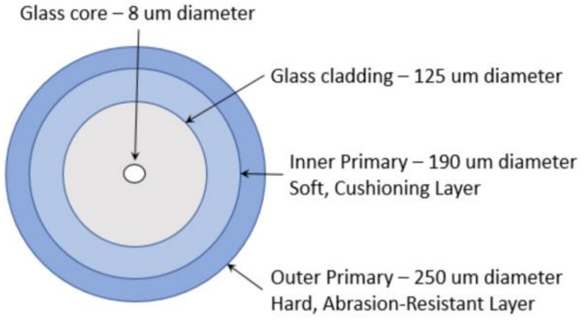
- Electroless plating successfully coated the optical fibers with metallic film (Ni, Fe) for a long length.
- Corrosion of metallic film released the internal stress of deposition and caused the strain changes on the fiber.

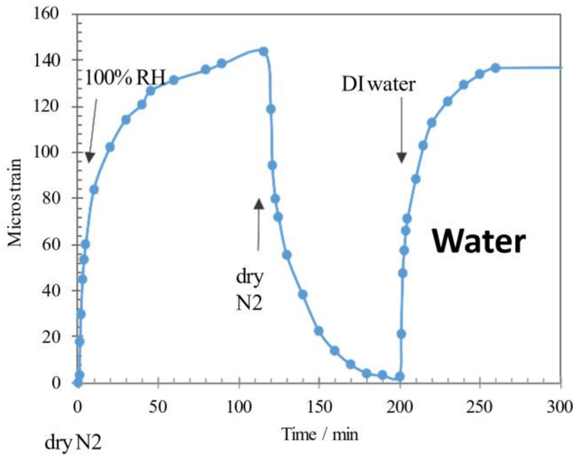
Distributed Water Condensation/Humidity Monitoring

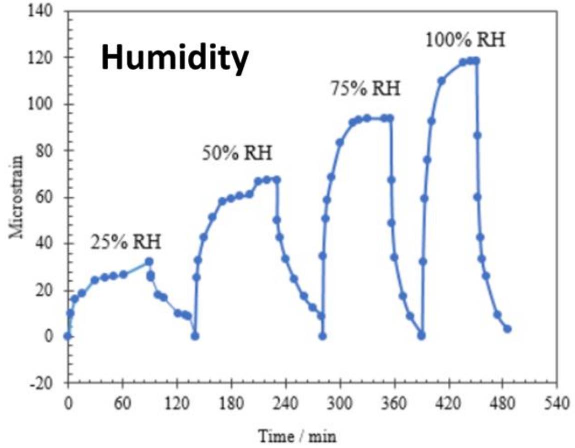
Water provides electrolytes for corrosion onset and is an indicator of potential corrosion.

Strain-based, fully distributed sensor using polymer jacketed commercially available fibers





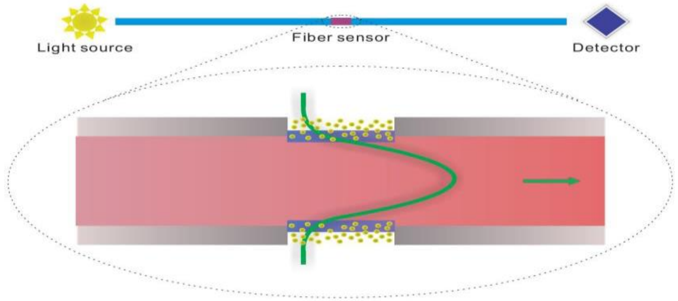




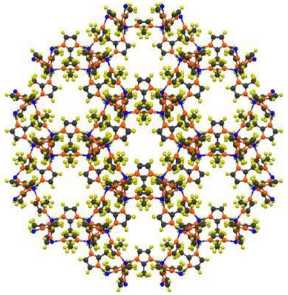
Local Humidity and Water Condensation Monitoring Due to Swelling of Polymer Jackets on Optical Fibers, as an Indicator for Corrosion.

Optical Fiber Methane Sensing

Functional Sensing Layer Integrated Fiber Optic



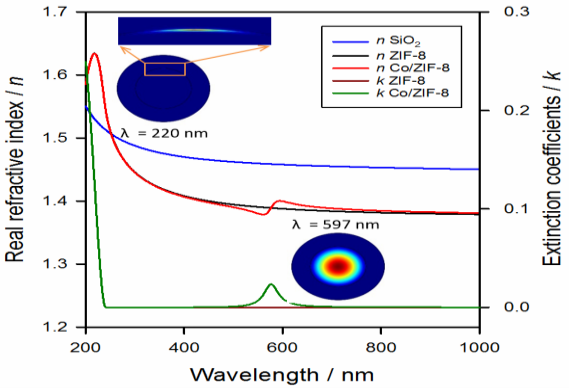
Porous Metal Organic Framework (MOF)



Micro-porous Gas Permeable Polymers

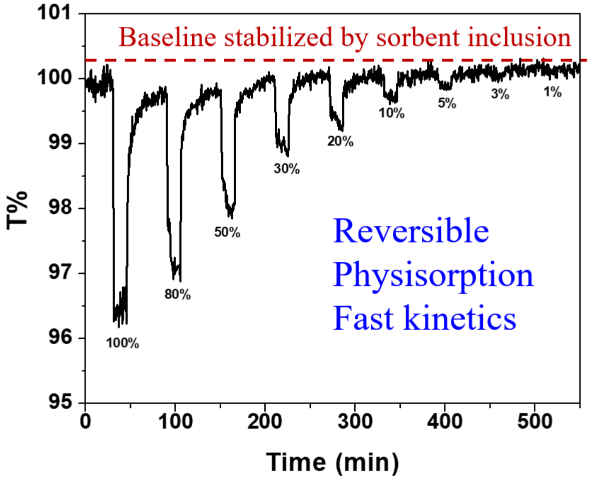
Evanescent Wave Absorption Based Sensors

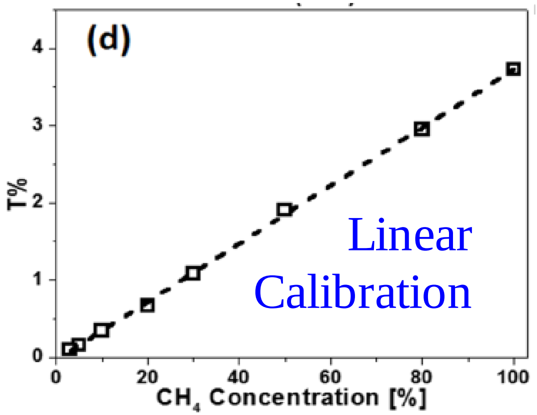
$$I_T(\lambda) = I_0 \exp[-\gamma\alpha(\lambda)CL]$$



Gas adsorption in the sensor coating causes $RI_{(coating)} > RI_{(fiber)}$, inducing optical power changes.

CH_4 Detection Limit: < 5% in N_2





Light Intensity Based Methane Sensing Technology. Integration of Fiber Optic Sensors with Engineered Porous Sensing Layers by Design.

Surface Acoustic Wave (SAW) Sensors

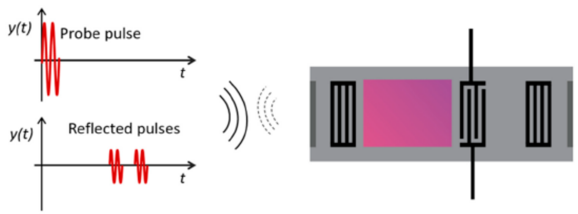
- **Passive, Wireless, Matured Devices**
- **Sensitive, Cheap Point Sensors**
- **Possible for Multi-Parameter Operation** (Temperature, Pressure, Strain, Chemical Species, Corrosion etc.)

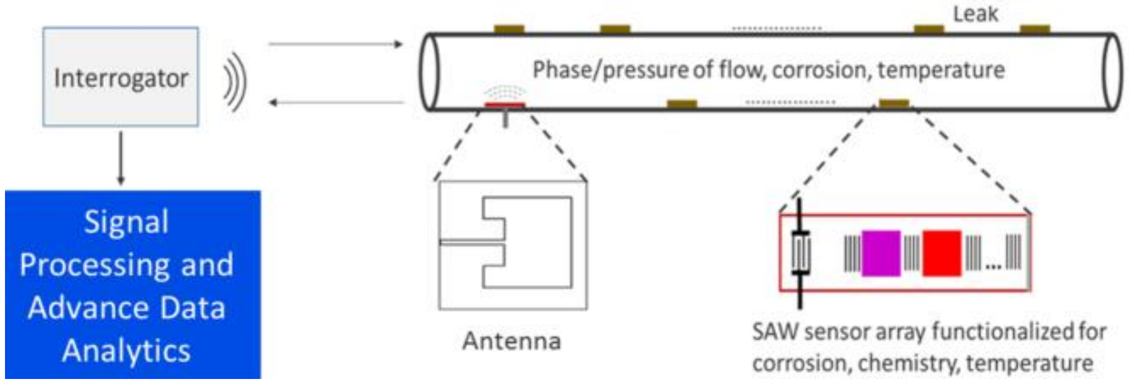
SAW Velocity (v) and Attenuation (α):

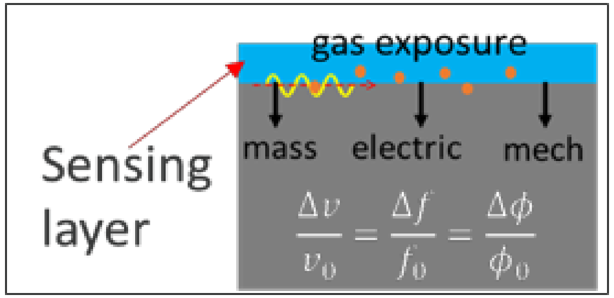
- Mass, Elasticity, Conductivity
- Environmental factors including Temperature, Pressure

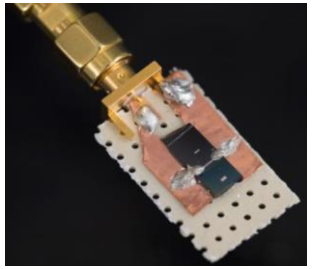
$$\Delta v = \frac{\delta v}{\delta m}\Delta m + \frac{\delta v}{\delta \sigma}\Delta \sigma + \frac{\delta v}{\delta \epsilon}\Delta \epsilon + \delta v(c, T, P)$$

$$\Delta \alpha = \delta \alpha(\sigma, \epsilon, c, T, P)$$









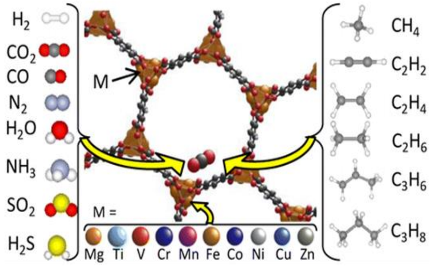
<u>Target Metrics</u>: Small (~5x5 cm^2), Low Cost (< \$1.00 /device + antenna installed)

Ubiquitous Wireless Sensors can be Deployed External and Internal to the Pipeline

Wireless SAW Sensors for Gas Sensing

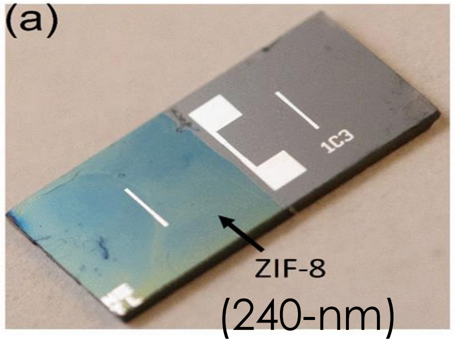
NATIONAL ENERGY TECHNOLOGY LABORATORY

Wireless CO_2, CH_4 Sensing

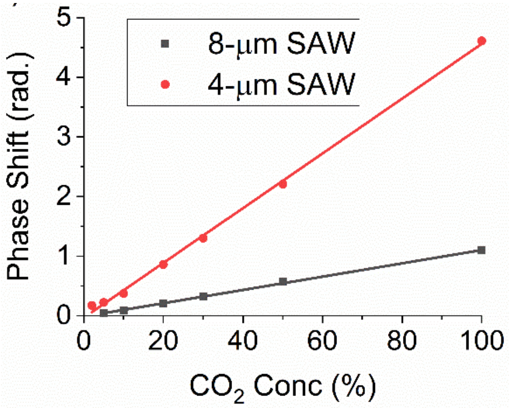


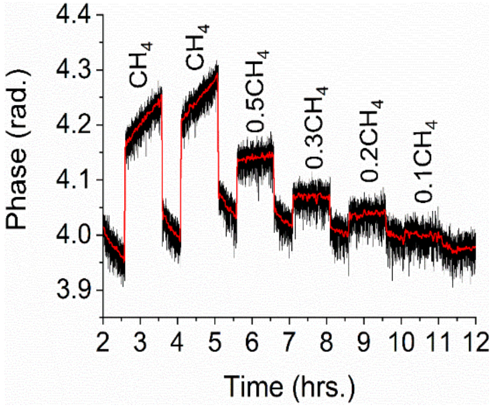
Lee et al., Chem. Mater. 27, 668, (2015)

Nanoporous Sensing Materials

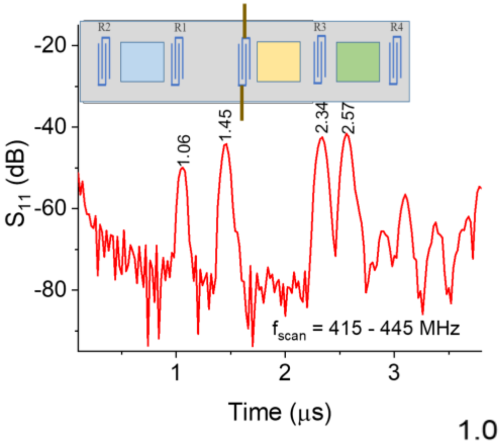


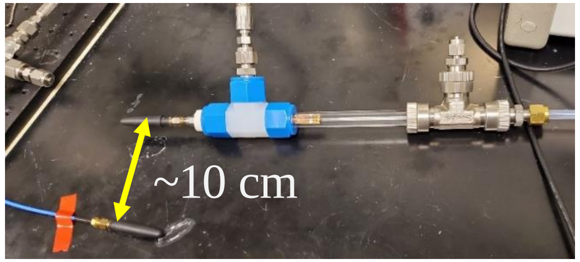
(240-nm)

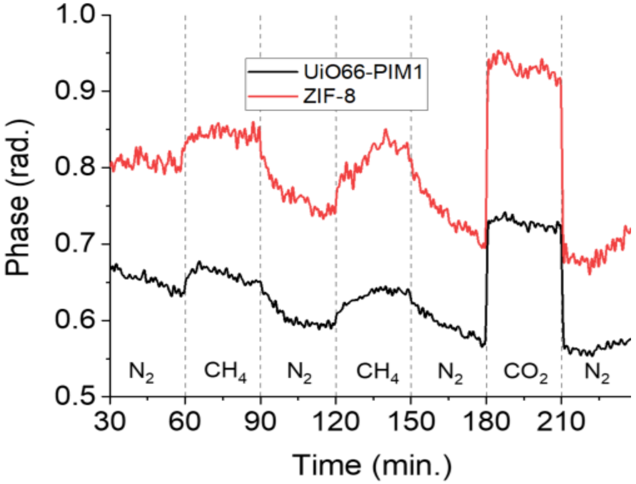




SAW Sensor Array for Multiple Gases: CH_4 and CO_2



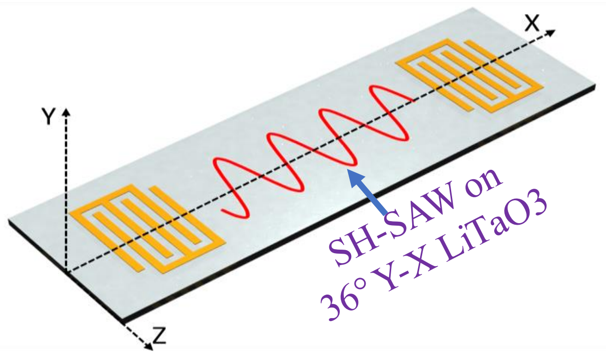


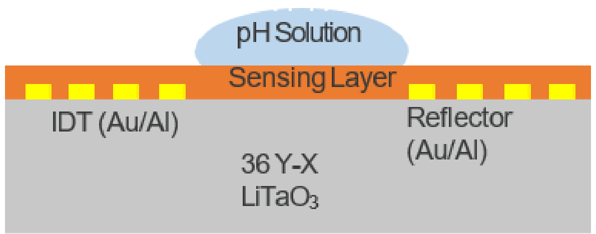


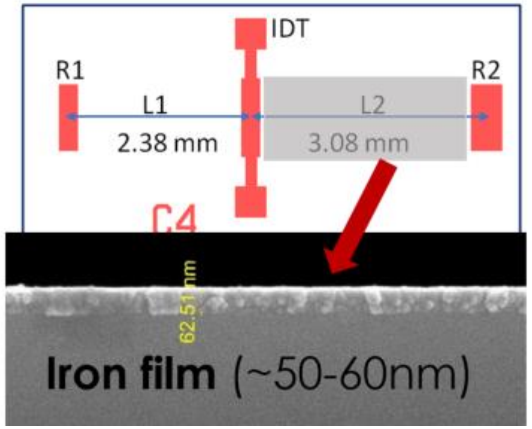
- **Successful Demonstration of Wireless SAW Gas Sensor**
- **Sensor Array Devices were successfully fabricated and functionalized for simultaneous monitoring of CH_4 and CO_2**

SAW Sensors for Liquid Applications

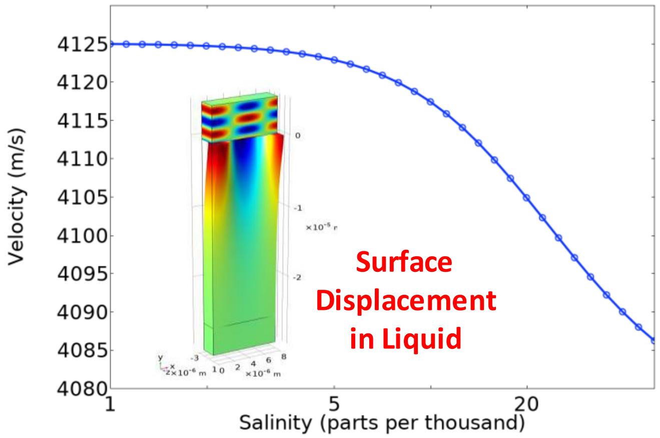
Shear Horizontal Surface Acoustic Waves



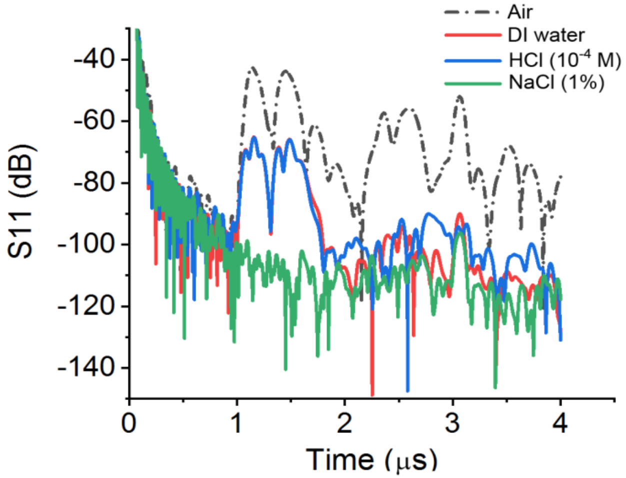


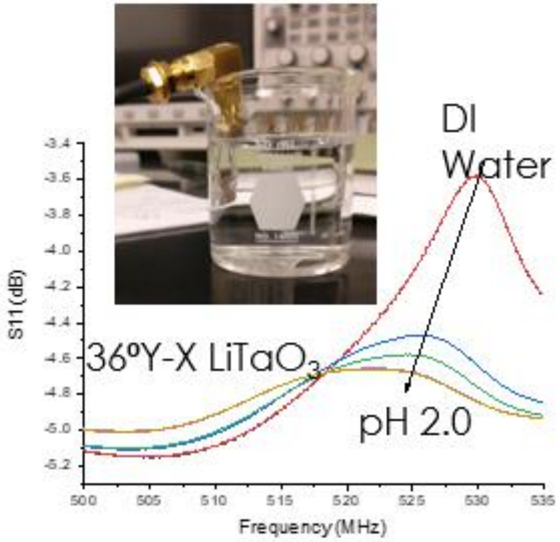


Simulation



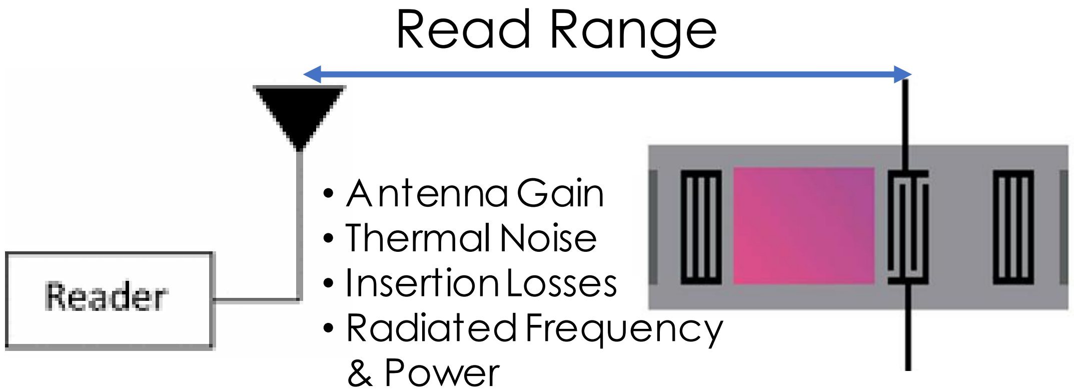
Experiment





SAW Sensors were Developed for Liquid Phase Application and Demonstrated their Capability for Monitoring Iron Film Corrosion in low pH (Acidic) Solutions.

Enabling Telemetry for SAW Devices and Pipelines



- Antenna Gain
- Thermal Noise
- Insertion Losses
- Radiated Frequency & Power

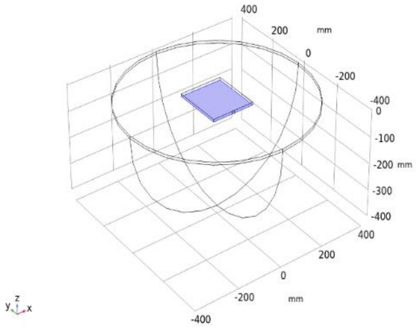
- Telemetry of wireless and passive SAW sensors is similar to radar operation.

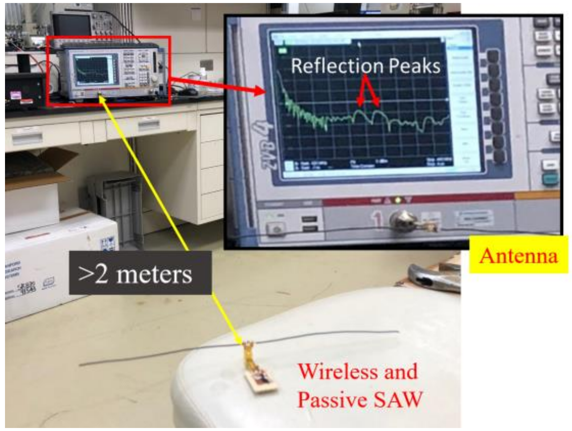
$$\text{Read Range}(r) = \frac{\lambda . W}{4\pi} \sqrt[4]{\frac{P_t G_r^2 G_t^2}{A.kTB.SNR}}$$

- Low loss SAW devices and higher the radiated power to improve the range.

Wireless Coupling:

SAW Device + EM Radiator/Receiver



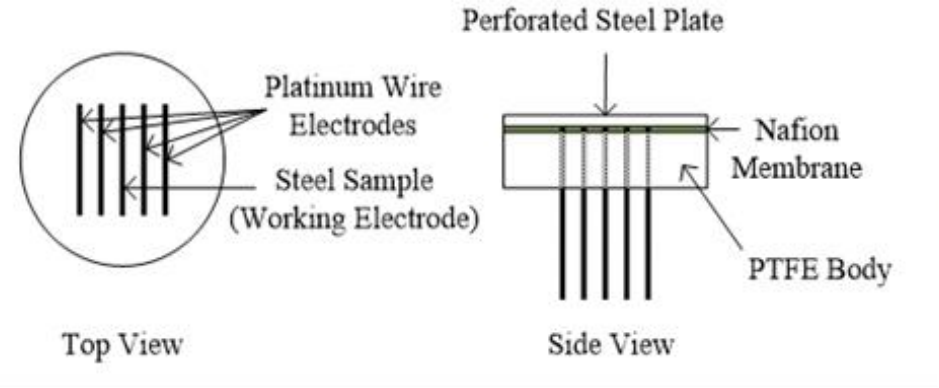


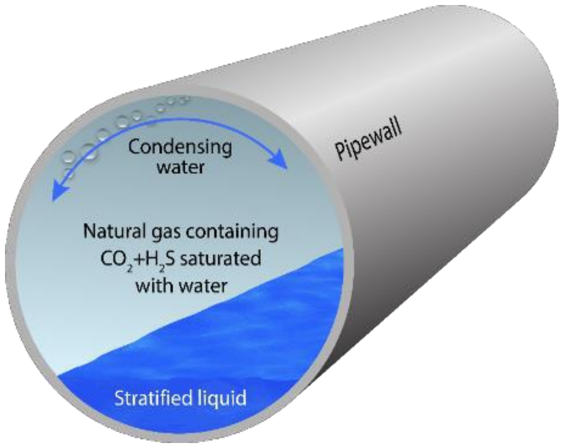
Long Range Telemetry and Interrogation

Wireless Interrogation of SAW Sensors Inside Metal Pipe from >1m was Demonstrated.

Various Approaches have been Designed and Demonstrated to Achieve Wireless Interrogation of SAW Sensors in Pipelines.

Advanced Electrochemical Sensor (AES)





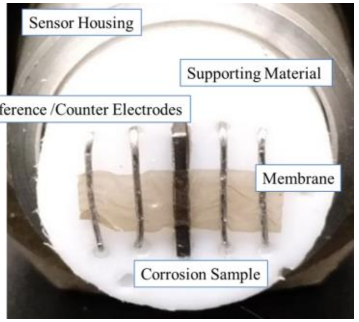
- **Most of EC sensors are designed for bulk aqueous streams, but are usually not suitable for measurements in non-aqueous phases**
  - Conductivity is typically too low in gas phases such as natural gas
    - Example of chemical composition of natural gas: 7 lb/MMscf H_2O: +3 vol% CO_2+48 ppmv H_2S+3 vol% O_2 *[source: GRI Internal Corrosion Direct Assessment of Gas Transmission Pipelines Methodology]*
  - Corrosion degradation is of electrochemical nature

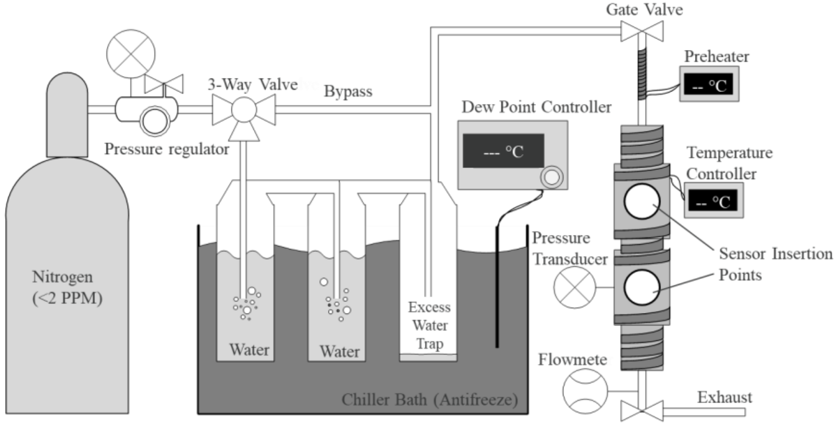
Integration of Ion-conducting Membrane Makes AES Capable of Real-Time In-Situ Monitoring of Water Content, Steel Corrosion Rate, and Pitting / Localized Corrosion Parameters Inside Natural Gas Pipelines.

AES for Water Content & Corrosion Rate Monitoring

NATIONAL ENERGY TECHNOLOGY LABORATORY

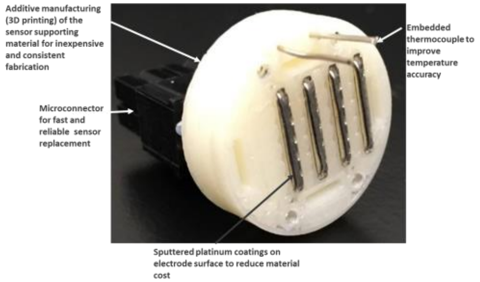
1st Gen. Membrane-based AES prototype for measuring water content and corrosion rate using <u>High-Pressure Flow-Through Electrochemical Test System</u>

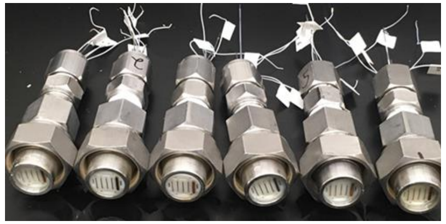




Estimated material, manufacturing, and operation cost is reduced from $1000 to $100 per sensor from 1st to 2nd Gen.

2nd Gen. Membrane-based AES prototype fabricated via sputtering and additive manufacturing, with embedded thermocouples.





2nd generation AES during testing in water-saturated natural gas at CEESI multi-phase flow facility.

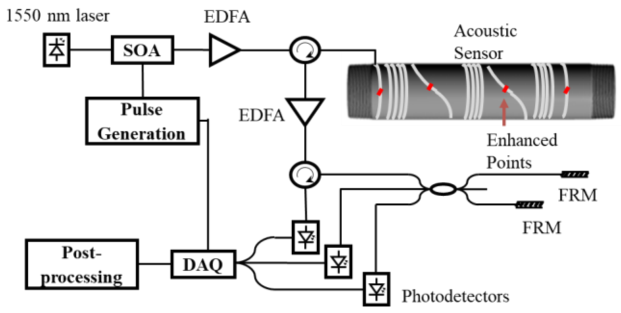
Electrochemical testing equipment is in weather-proof container.

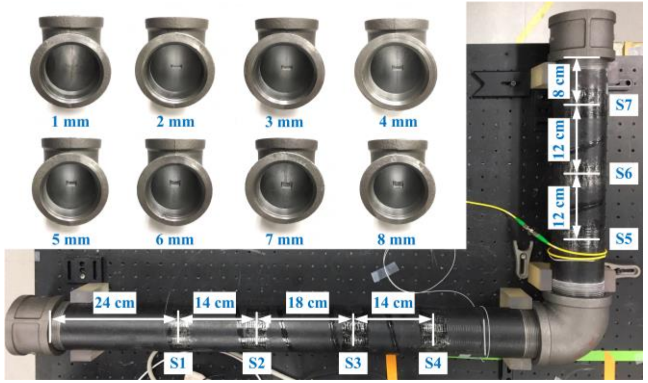
- ✓ ***AES easy to install by facility operators***
- ✓ ***Capable of remote data collection***
- ✓ ***Successfully monitored increased humidity and corrosion rate in wet natural gas***

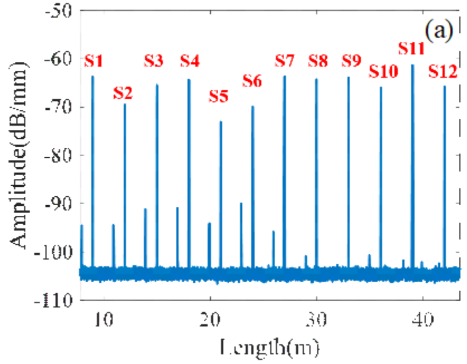
AI-Enhanced Fiber Optic Sensors for Pipe Defect Detection

NATIONAL ENERGY TECHNOLOGY LABORATORY

Distributed Acoustic Sensing (DAS) System with Enhanced Fiber Sensors



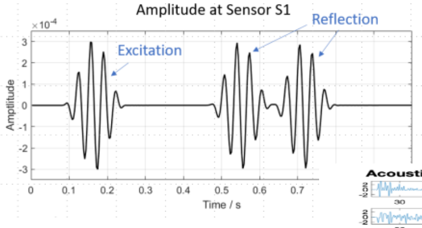




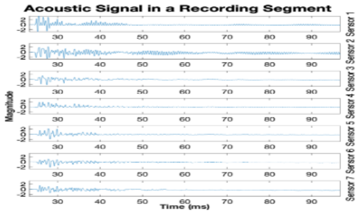
8-in OD Steel Pipe

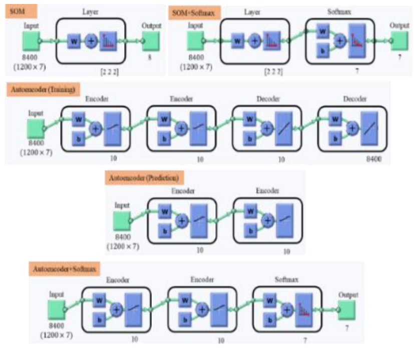
Deep Neutral Network Machine Learning to Identify Pipe Defects

Simulated



Sensor Data





Magnetostriction Acoustic Actuator: 20-30kHz

Sensors Wrapped around the Pipe

Distributed Acoustic Sensing Technology with Advanced Data Analytics to Identify, Classify, and Quantify Various Defects and Features along the Pipe.

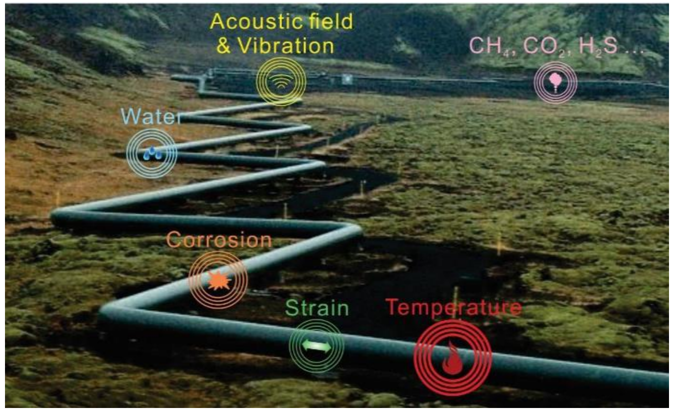
UNIVERSITY OF PITTSBURGH

Key Accomplishments and Outcomes

- Multiple Custom Low-cost Optical Fiber Interrogators Have Been Developed for Distributed Monitoring of Various Parameters, up to >150 km.
- New CH_4 Sensitive Coatings with Improved Hydrophobicity Have Been Developed for Humid Conditions and Applied for Optical Fiber-based and SAW Sensors.
- Optical Fiber Based Water Condensation and Corrosion Sensors Have Been Demonstrated for >2 km
- Passive Wireless SAW Sensors Have Been Demonstrated for Simultaneous Sensing of Multiple Gases and for Corrosion Monitoring in Liquid Phase. Wireless Telemetry Methods are Developed.
- Successful First Field Test of Advanced Electrochemical Sensor (2^{nd} Gen) for Water Content, T and Corrosion Rate Monitoring and Published the Field Test Data.
- Artificial Intelligence (AI)-Enhanced Distributed Optical Fiber Sensing for Pipeline Defect Identification.

<u>Project Outcomes to Date:</u>

- 11 Provisional / Non-Provisional Patent Applications
- >17 Published Scientific Manuscripts
- 4 Published Major Literature Reviews
- >36 Conference Proceedings Published
- >45 Presentations at Technical Conferences



Acknowledgement and Disclaimer

Acknowledgement

Program Manager: Christopher Freitas (HQ)

Technology Manager: Jared Ciferno (NETL)

Technical Portfolio Lead: Natalie Pekney (NETL)

This work was performed in support of the U.S. Department of Energy's Fossil Energy Oil & Natural Gas Research Program. The Research was executed through the NETL Research and Innovation Center's Natural Gas Infrastructure FWP. Research performed by Leidos Research Support Team staff was conducted under the RSS contract 89243318CFE000003.

Disclaimer

Contact Info

Ruishu.Wright@netl.doe.gov

NETL Resources

VISIT US AT: **www.NETL.DOE.gov**

@NETL_DOE

@NETL_DOE

@NationalEnergyTechnologyLaboratory