Advanced Sensors for Real-Time Monitoring of Natural Gas Pipelines

FWP-1022424, Project No.1611133

Presenter: Dr. Ruishu Wright, NETL

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

Prof. Kevin Chen, University of Pittsburgh

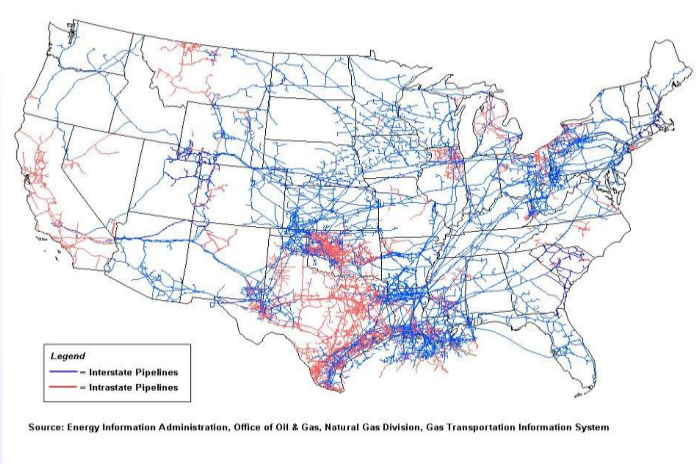
U.S. Department of Energy

National Energy Technology Laboratory

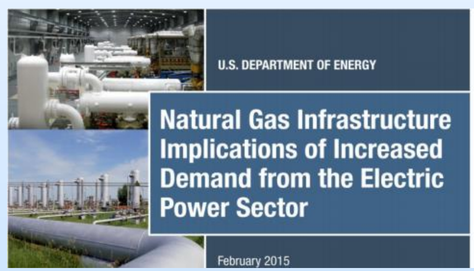
Oil & Natural Gas

2020 Integrated Review Webinar

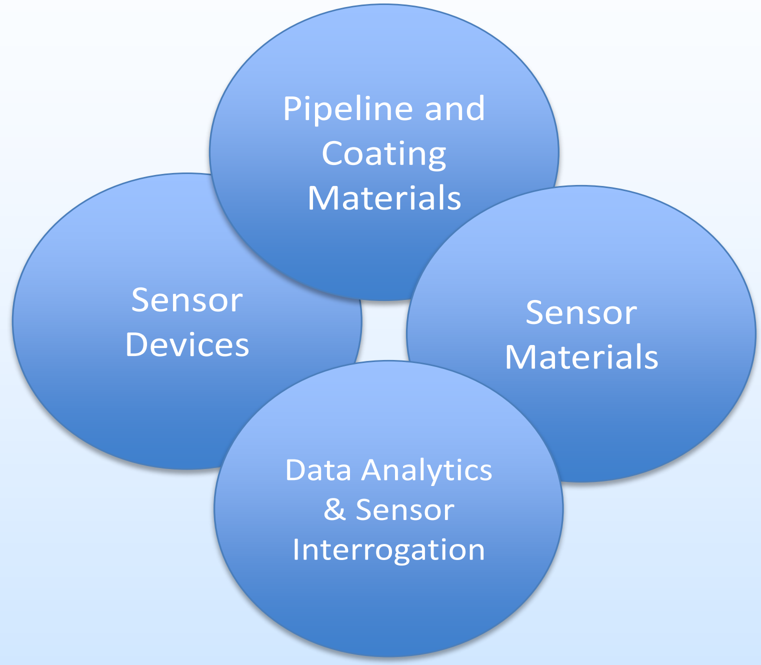
Reliability & Resiliency of Natural Gas Infrastructure



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



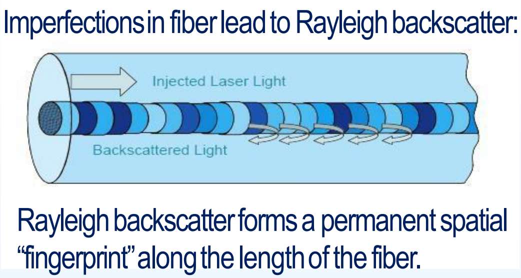
http://energy.gov/sites/prod/files/2015/02/f19/DOE%20Report%20Natural%20Gas%20Infrastructure%20V_02-02.pdf



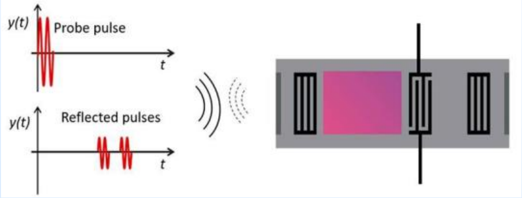
Real-time Monitoring and Leak Detection/Mitigation for the Natural Gas Infrastructure is Increasingly Important. New Sensing Technologies are Being Developed to Address these Needs.

Approach: Advanced Sensing Technologies

Distributed Optical Fiber Sensor



Passive Wireless Sensor

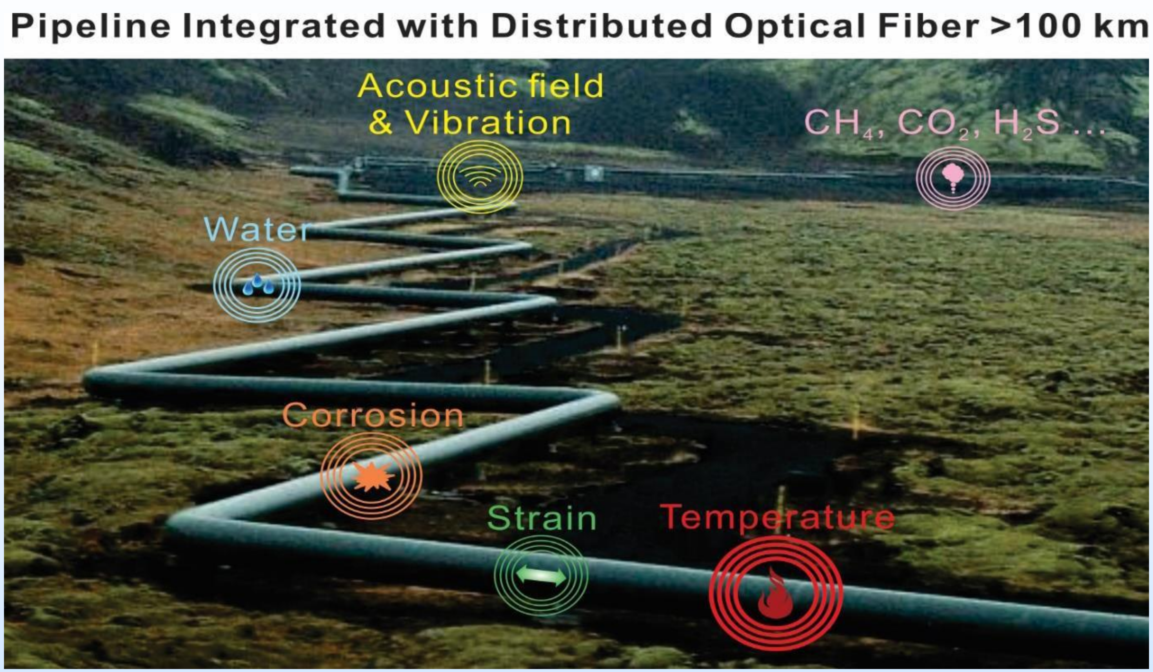


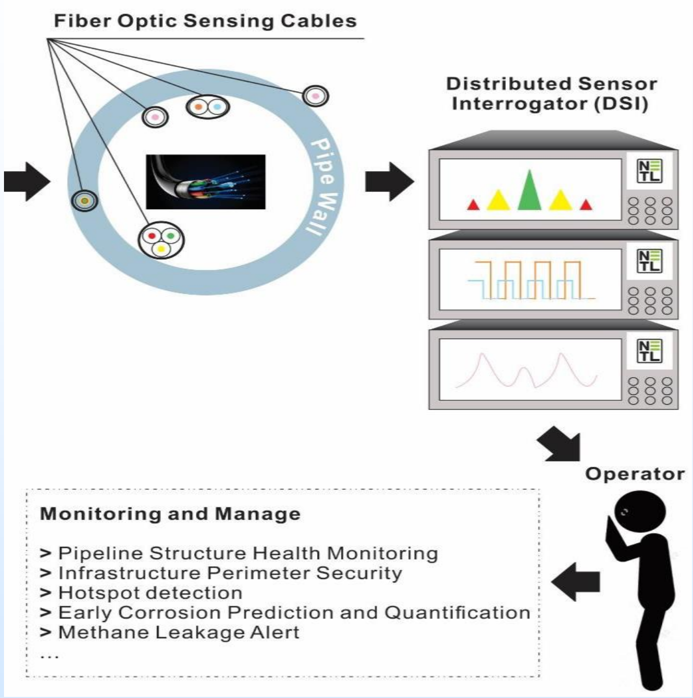
Advanced Electrochemical Sensor

	Geospatial Attributes	Cost	Targeted Function	TRL
Distributed Optical Fiber Sensor	Linear Sensor Adjustable Distance and Resolution	Cost Per Sensor "Node" Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, etc.) Early Corrosion Detection	3-4
Passive Wireless Sensor	Point Sensor	Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, etc.) Early Corrosion Detection	2-3
Advanced Electrochemical Sensor	Point Sensor	Moderate	Water Content, Corrosion Rate, T, Pitting Corrosion	5-6

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

Optical Fiber Sensor Platform





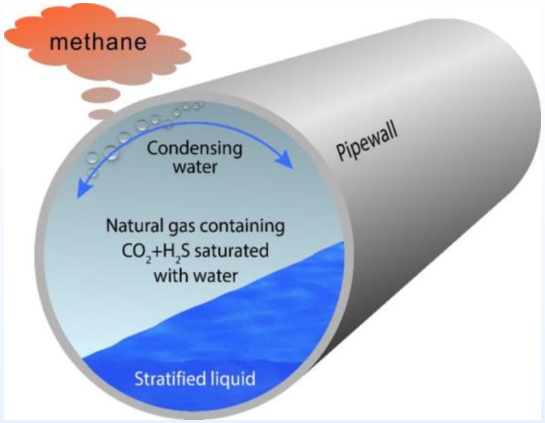
Emphasis Within NETL Research & Innovation Center:

- Optimize Interrogation System (Range, Resolution, Cost)
- Early Corrosion On-Set Detection → **Predictive Signatures**
- Methane Leak Detection & In-Pipe Gas Composition Monitoring → **Direct Signatures**

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

Target Metrics: >100km Interrogation, <1m Spatial Resolution, Cost ~$30k (<$0.30/m)

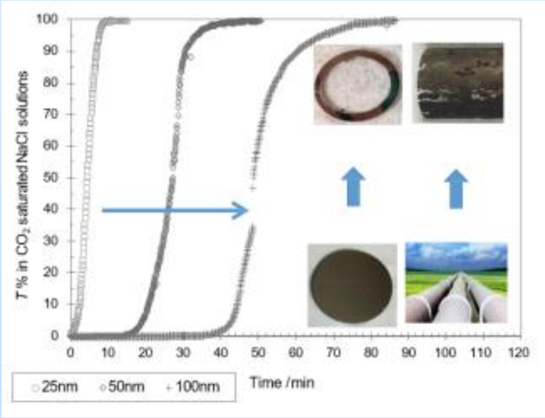
Methane Leak Monitoring and Corrosion Detection



Methane Leak Monitoring and In-pipe Gas Sensing

- ✓ Engineered Metal-organic Framework (MOFs) Layers as Sorbents
- ✓ 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)



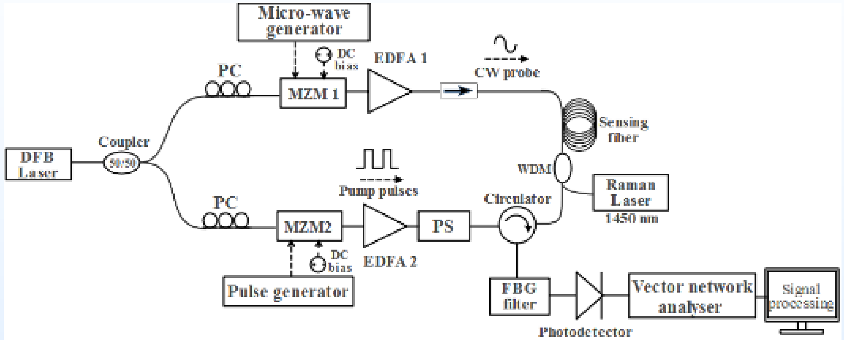
Early Corrosion On-Set Detection and Localization

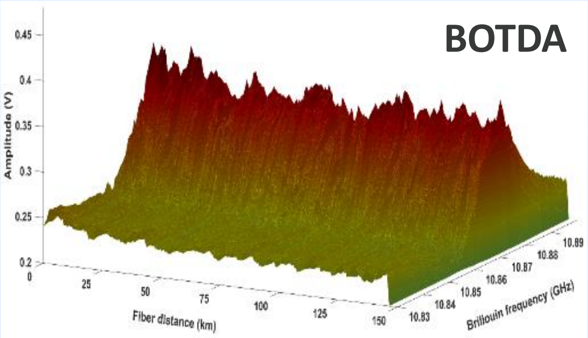
- ✓ Corrosion Proxy Sensing Materials (e.g. Fe-Based Metallic Films)
- ✓ Detection and Chemical Characterization of Condensed Water Phases (e.g. pH, dissolved CO_2, etc.)

Target Metrics: Early Corrosion On-Set Detection, < 0.1mm Thickness Reduction

Optical Fiber Distributed Interrogation

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

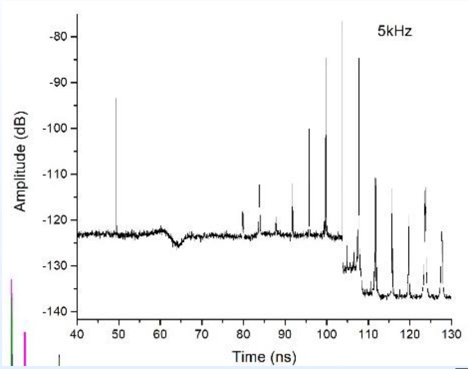


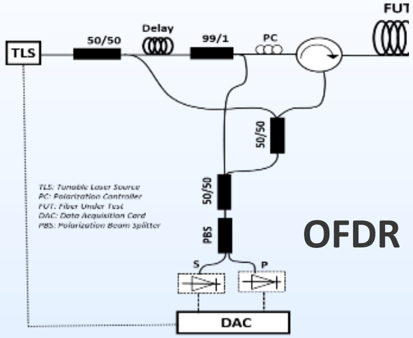


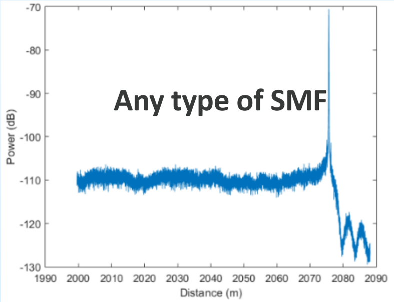
150 km SMF-28e / Metrocore Fiber / LEAF Fiber

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

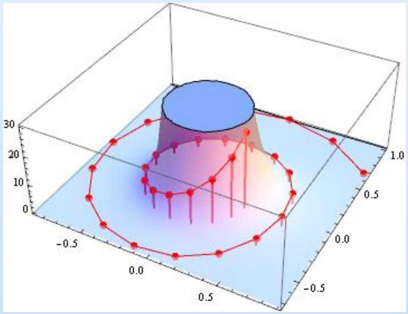
(2) Super-high-resolution temperature / strain / vibration measurement







FFT-segmented chirp-Z transform

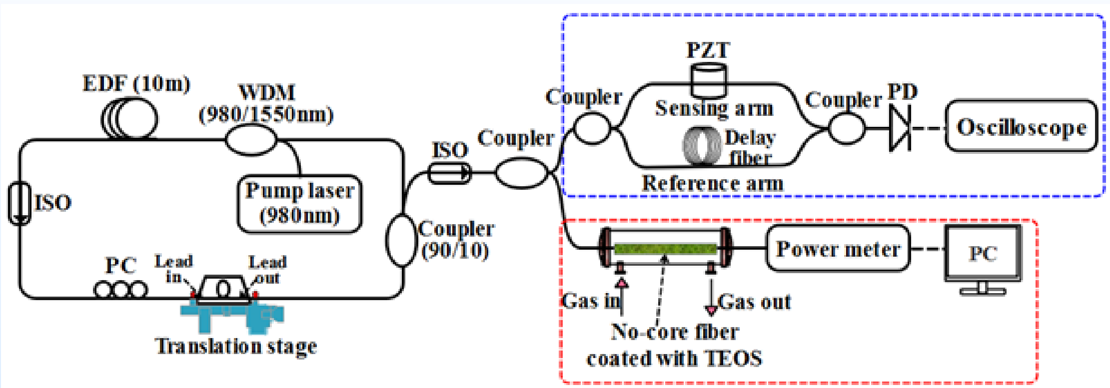


Measurement distance: ~2 km
Spatial resolution: 0.3 mm
Sensing range: 0.1 ºC / 10 με

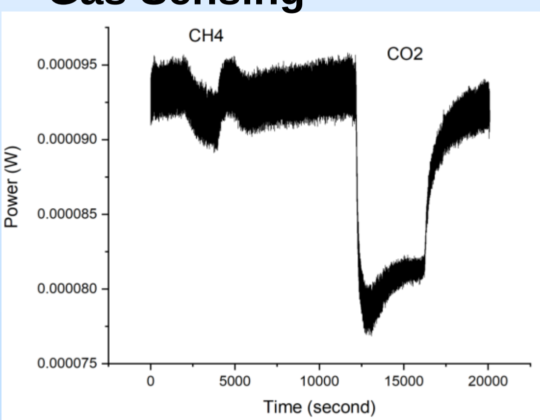
A Number of Different Optical Backscattering Methods were Employed to Enable Distributed Measurements of Temperature, Strain, and Vibration.

Optical Fiber Distributed Interrogation

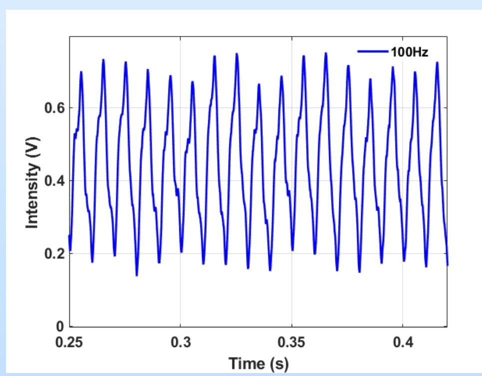
(3) Simultaneous CO_2 detection and vibration monitoring based on a tunable fiber ring laser



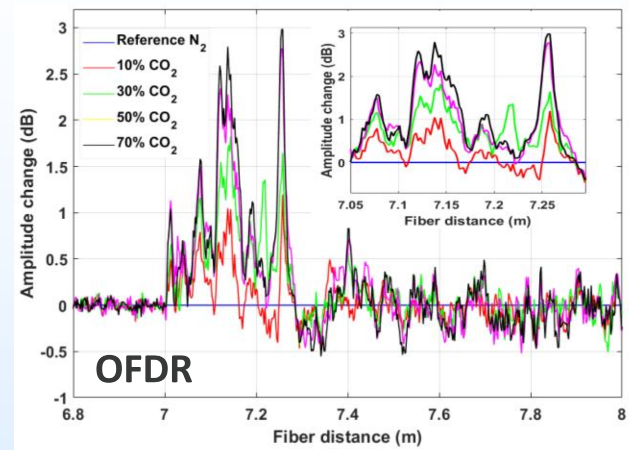
Gas Sensing

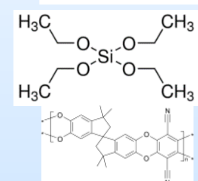


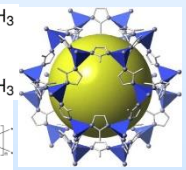
Vibration Sensing



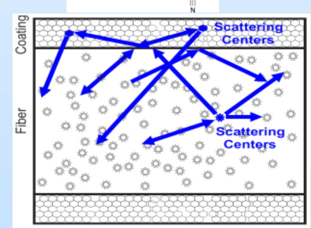
(4) Distributed CO_2 / N_2 Detection







Functional Material (TEOS, MOF, polymer) Coated Fiber



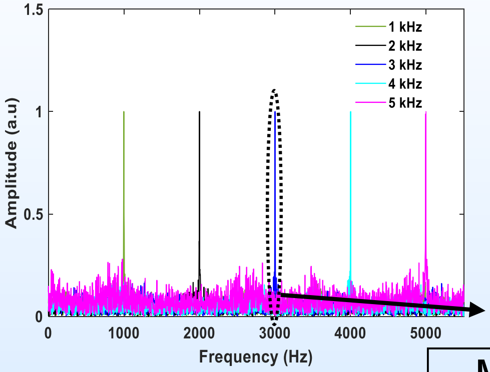
Rayleigh Scattering due to inhomogeneities in both fiber and its coating layer.

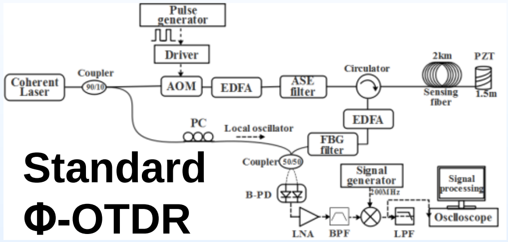
Measurement distance: 2 km
Spatial resolution: 1 cm
Sensing resolution: 10% CO_2/N_2

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

Optical Fiber Distributed Interrogation

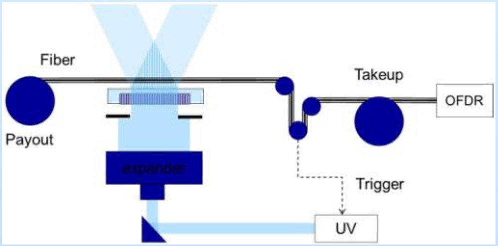
(5) Ultrasonic acoustic wave / vibration monitoring



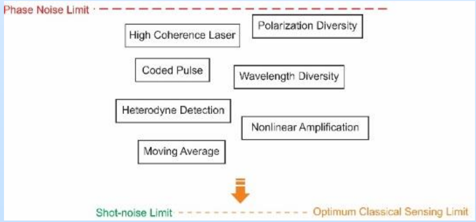


Standard Φ-OTDR

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

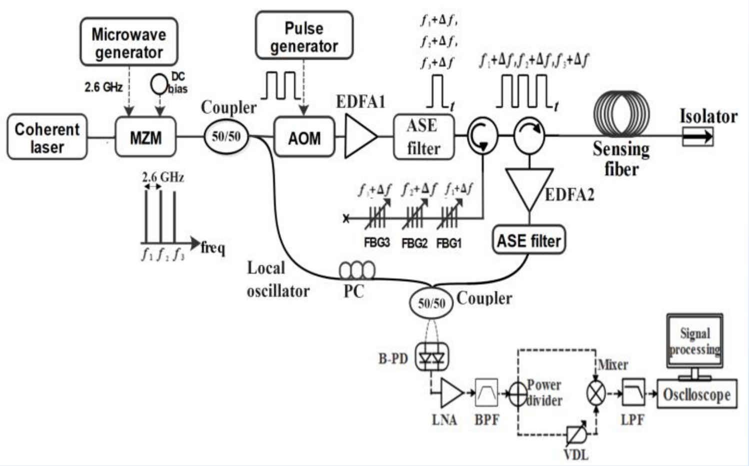


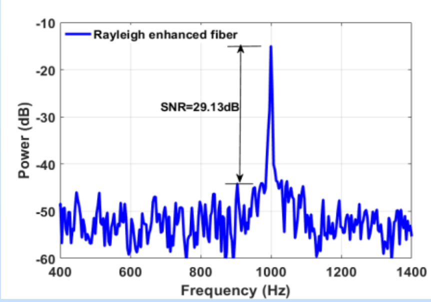
Acoustic-sensing Fiber / High NA Fiber / Fs-laser Fiber

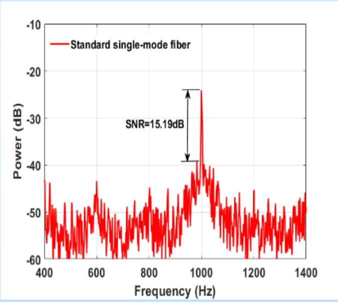


Noise reduction techniques

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



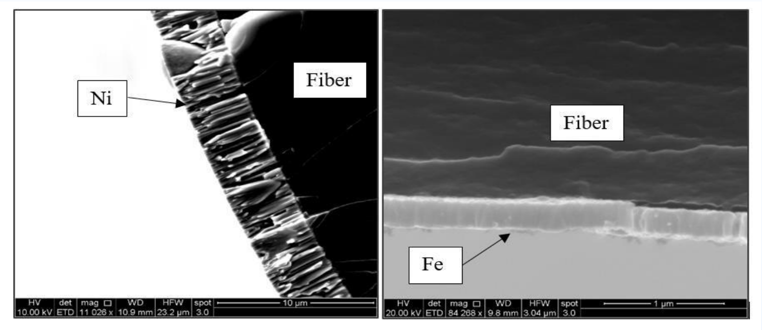


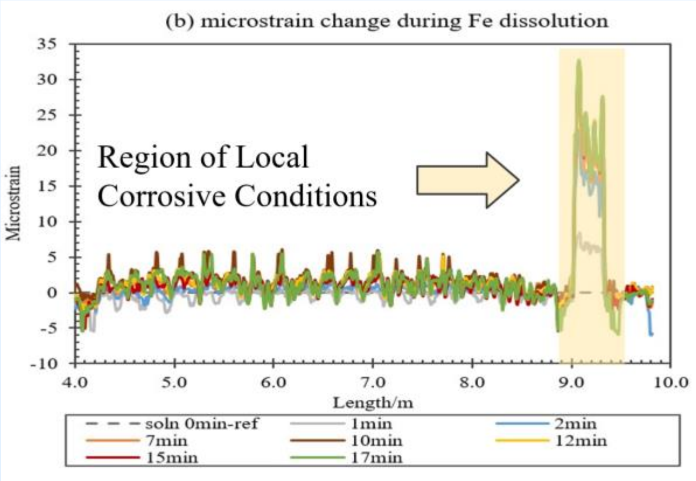


Different Optical Backscattering Methods were Employed to Enable Distributed Measurements of Acoustic Waves and Vibration. Novel Methods to Improve SNR.

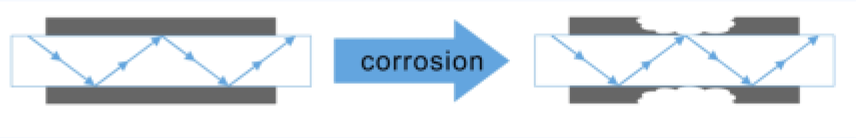
Distributed Corrosion Onset Monitoring

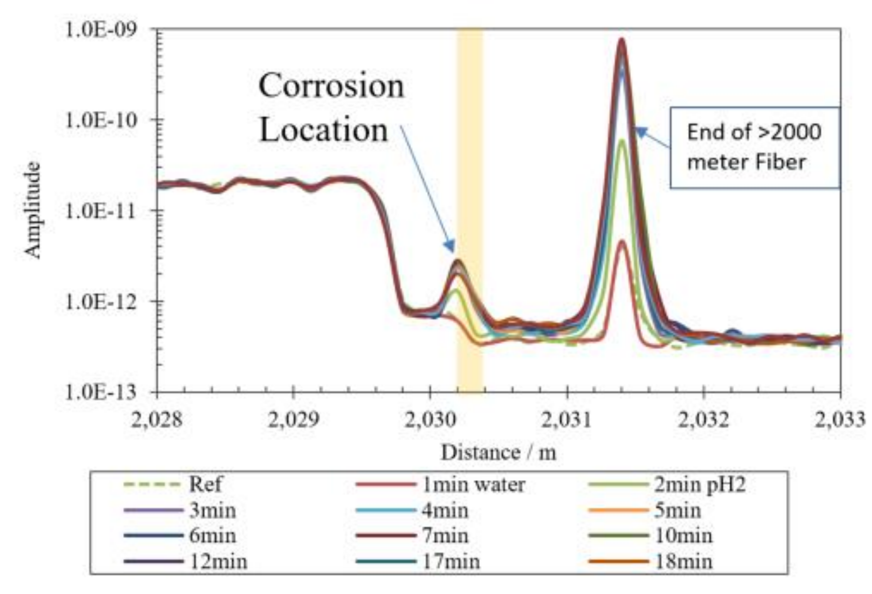
Strain: Thick Metallic Films on Fiber Exterior, fully distributed signals





Power variation: Thin Film Corrosion Proxy-Coated Optical Fiber (e.g. iron films)



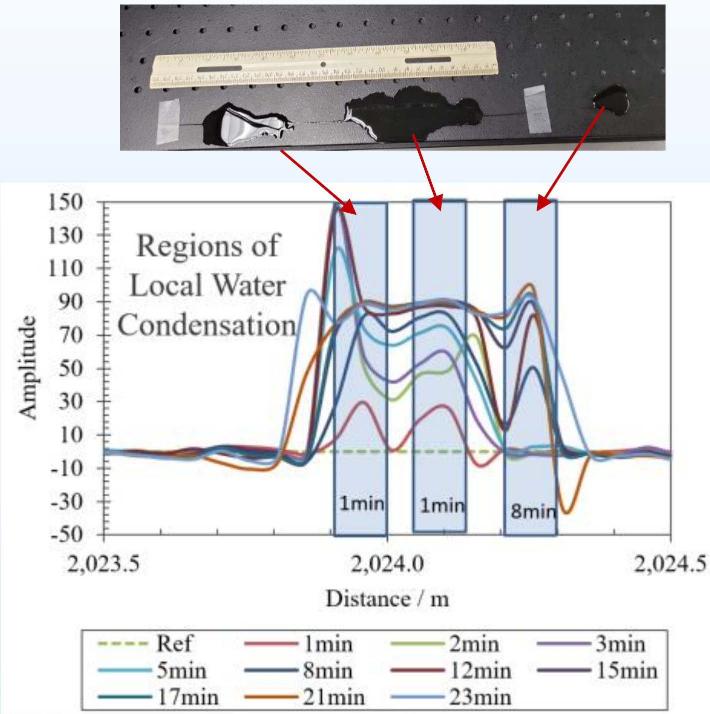


<u>**Approach #1: Metallic Films as Corrosion Proxy**</u>

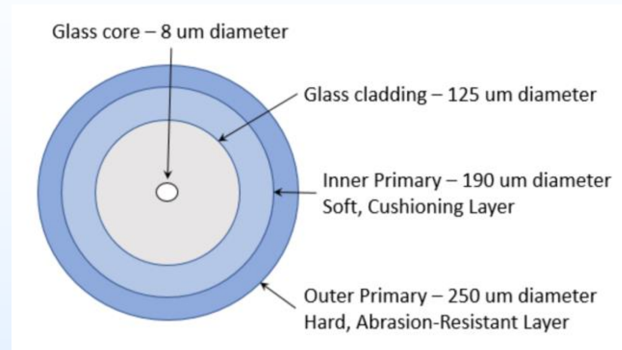
Monitoring Stress/Power on Fiber as a Function of Time and Location (km-range, 10 cm spatial resolution)

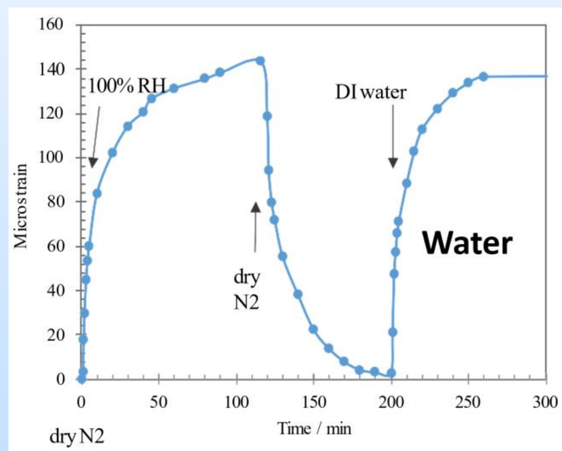
Distributed Water Condensation/Humidity Monitoring

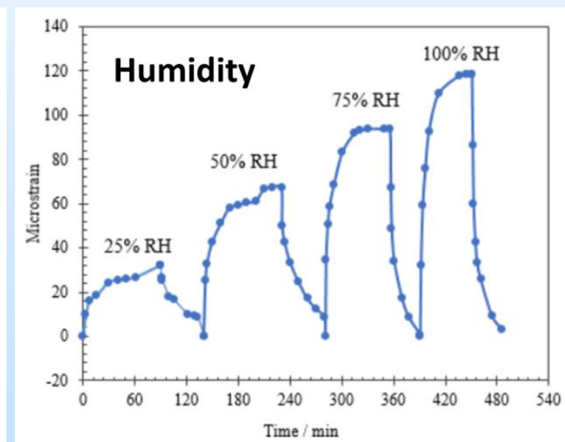
Water provides electrolytes for corrosion onset and is an indicator of potential corrosion.



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





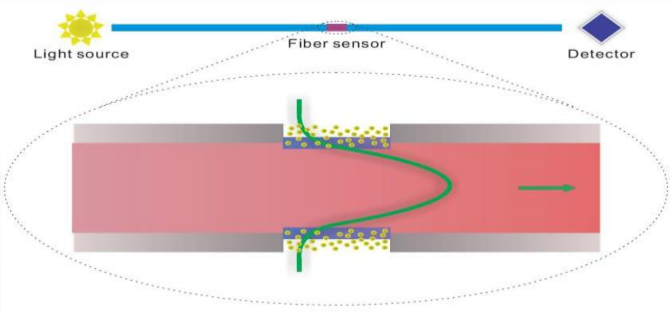


Approach #2: Corrosive Environment Monitoring

Local Humidity and Water Condensation Monitoring Due to Swelling of Polymer Jackets on Optical Fibers

Distributed Methane Monitoring

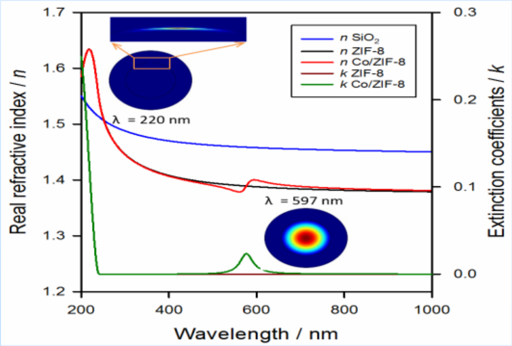
Functional Sensing Layer Integrated Fiber Optic



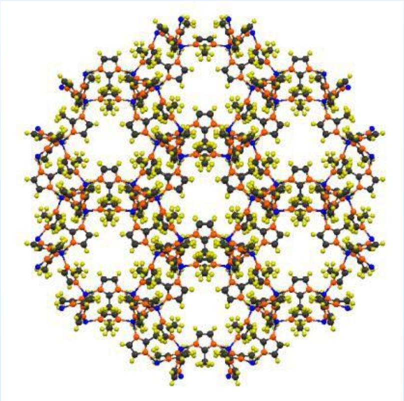
Evanescent Wave
Absorption Based Sensors

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

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



<u>Porous Metal Organic Framework (MOF)</u>



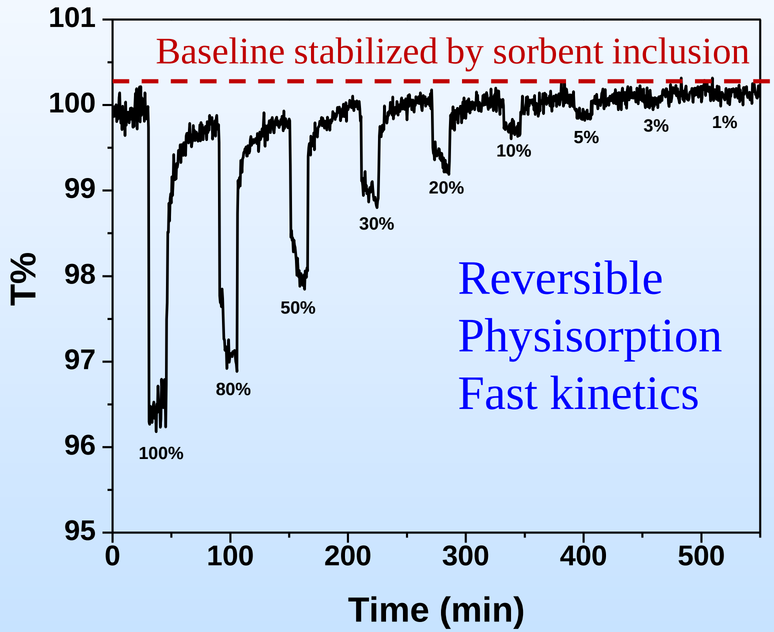
<u>Micro-porous Gas Permeable Polymers</u>

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

Distributed Methane Monitoring: Materials by Design

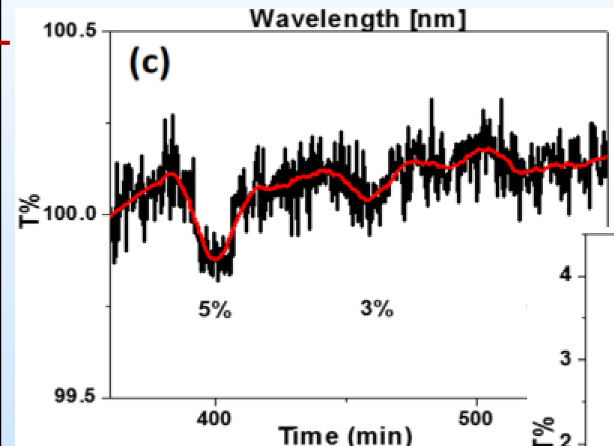
<u>Mixed Matrix of Polymer Crosslinked with Sorbent</u>

- Stabilize polymer against aging
- Good diffusion rate for CH_4
- CH_4 detection below 5% in N_2

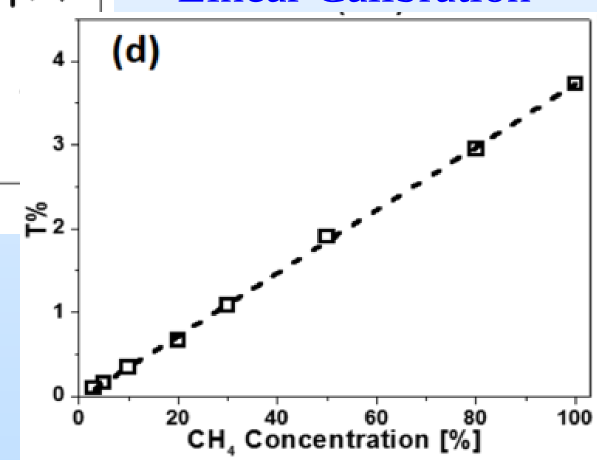


Reversible Physisorption
Fast kinetics

CH_4 Detection Limit: < 5% in N_2



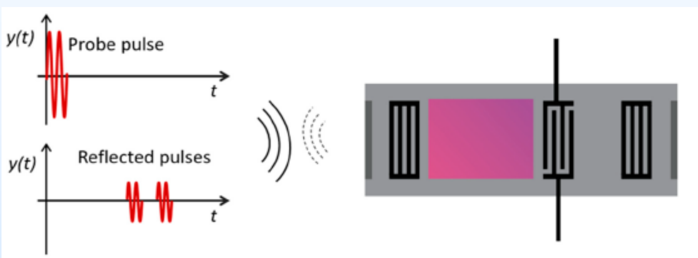
Linear Calibration



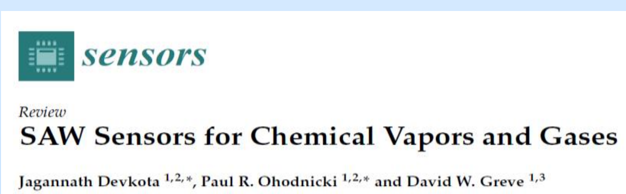
Successful Demonstration of CH_4 Sensing using a Polymer/Sorbent Composite Coated Fiber Optic, Scalable through a Reel-to-Reel Coating Process.

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.)



Reflective Delay Line SAW Device


sensors

Review

SAW Sensors for Chemical Vapors and Gases

Jagannath Devkota [1,2,*], Paul R. Ohodnicki [1,2,*] and David W. Greve [1,3]

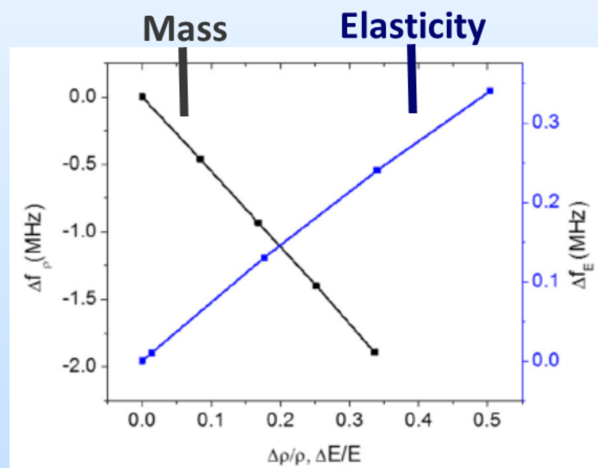
Sensors **2017**, *17*, 801; doi:10.3390/s17040801

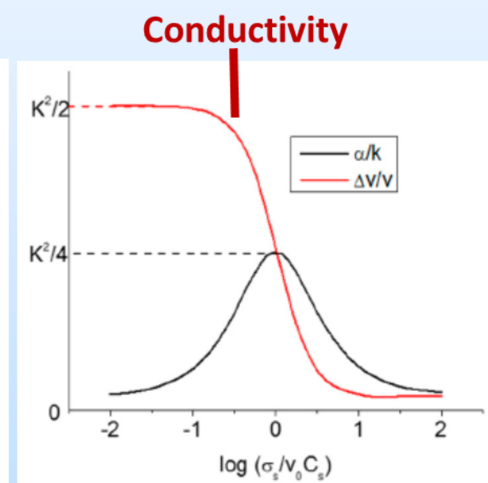
SAW Velocity (v) and Attenuation (α):

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

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

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



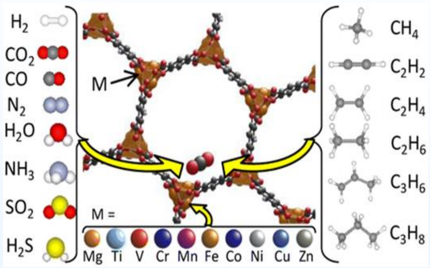


<u>Target Metrics</u>: Small (~5x5 cm²), Low Cost (< $1.00 /device + antenna installed)

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

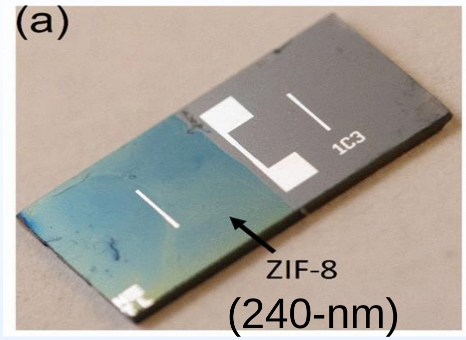
Wireless SAW Sensors for Gas Sensing

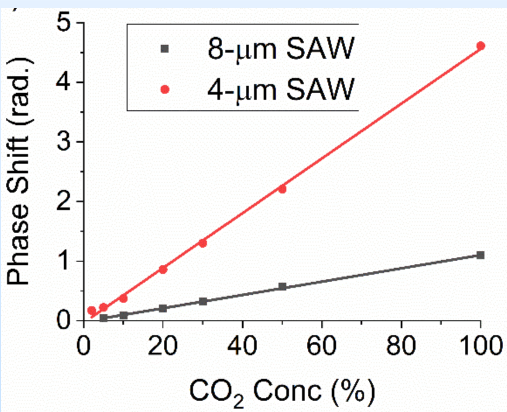
Wireless CO_2, CH_4 Sensing

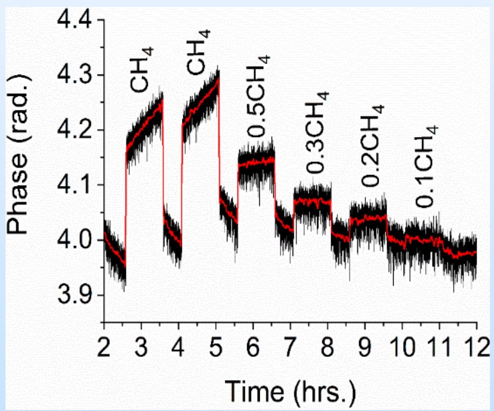


Lee et al., Chem. Mater. 27, 668, (2015)

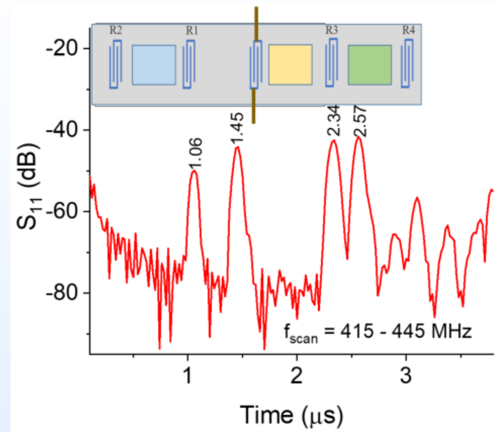
Nanoporous Sensing Materials

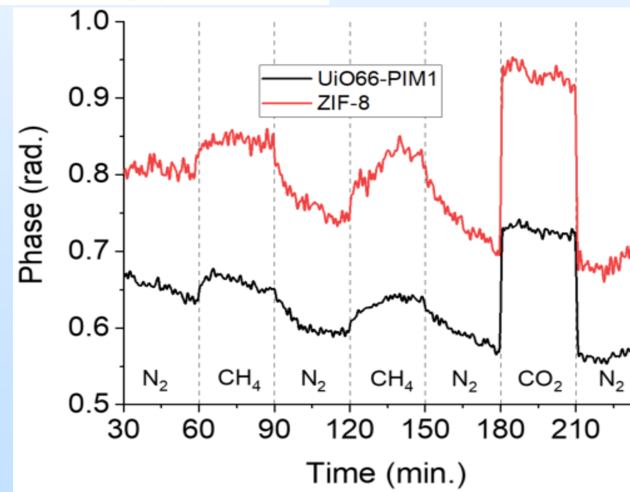






SAW Sensor Array for Multiple Gases: CH_4 and CO_2

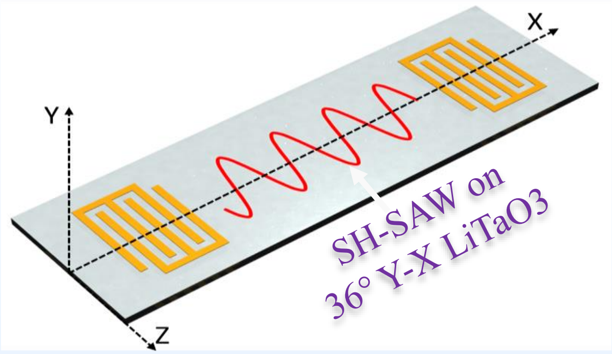


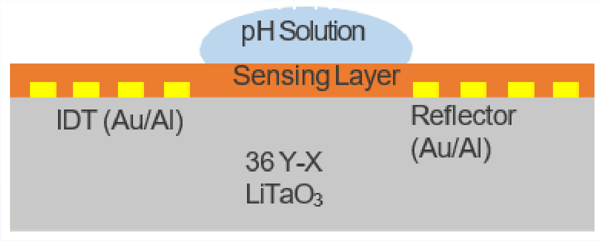


- Successful Demonstration of Wireless SAW Gas Sensor
- Sensor Array Devices were successfully fabricated and functionalized for simultaneous monitoring of CH_4 and CO_2

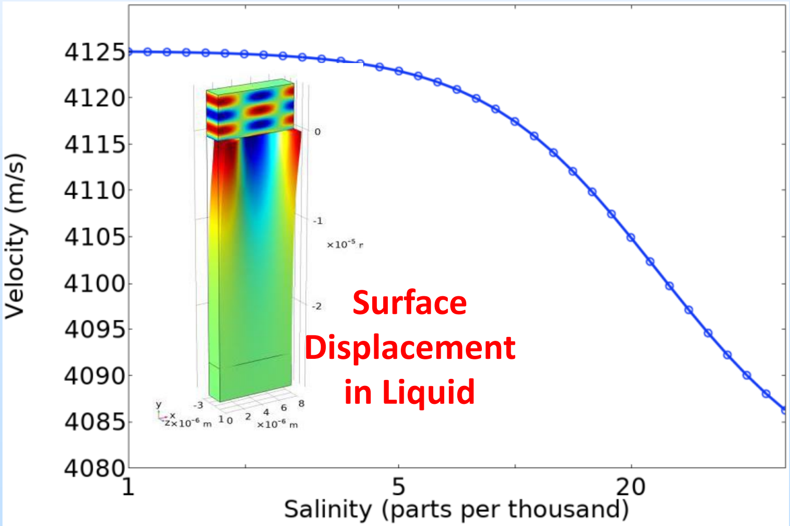
SAW Sensors for Liquid Applications

Shear Horizontal Surface Acoustic Waves

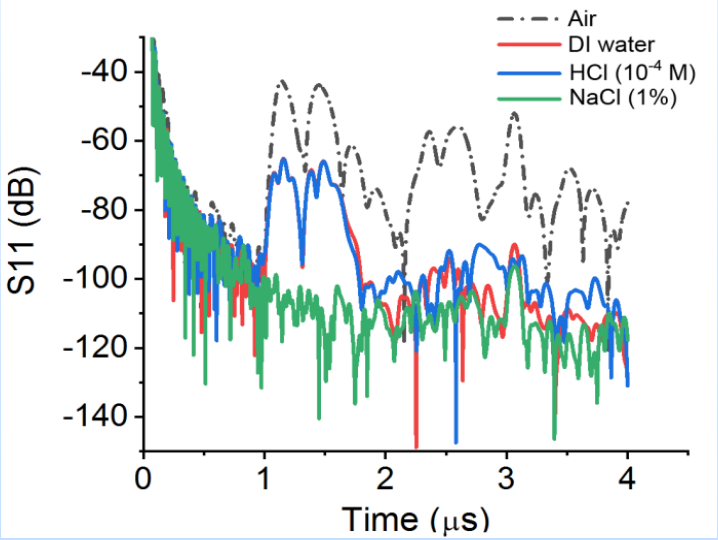




Simulation

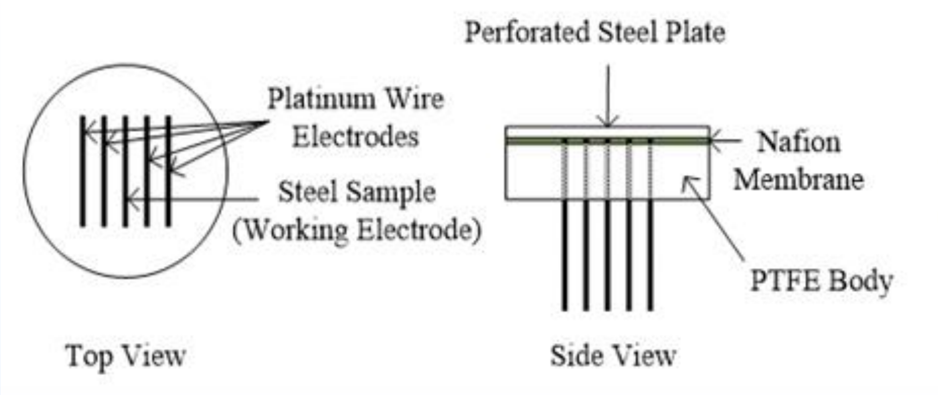


Experiment

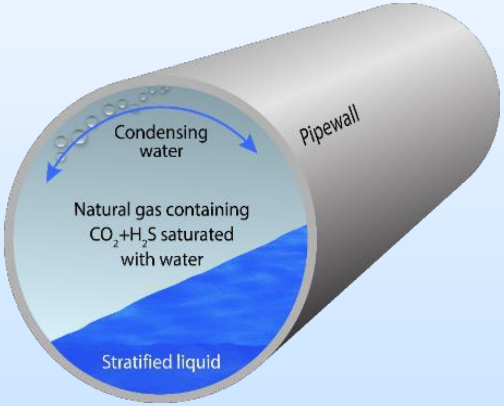


SAW Device Modeling and Experiments as Proof of Concept for Aqueous Phase Operation. Demonstrated Velocity Change and Attenuation with Various Salinities and pH.

Advanced Electrochemical Sensor (AES)



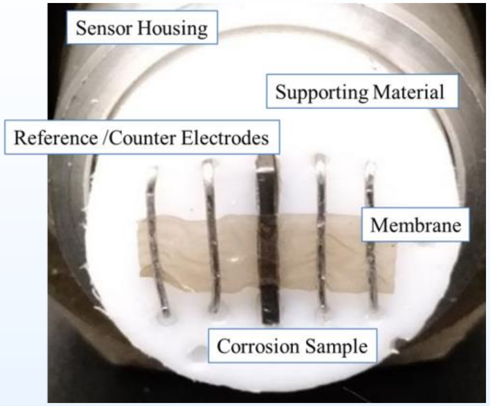
- **Electrochemical sensors are commonly used to measure and monitor many process properties**
  - E.g. dissolved oxygen, pH, redox potentials, corrosion rates
- **Most of these sensors are designed for bulk aqueous streams, but are usually not suitable for measurements in non-aqueous phases**
  - Conductivity 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 the electrochemical nature

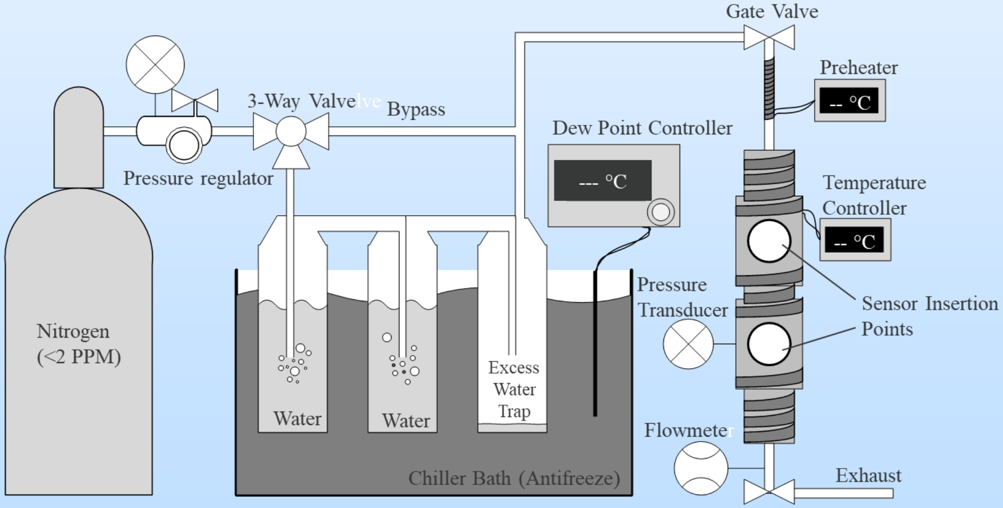


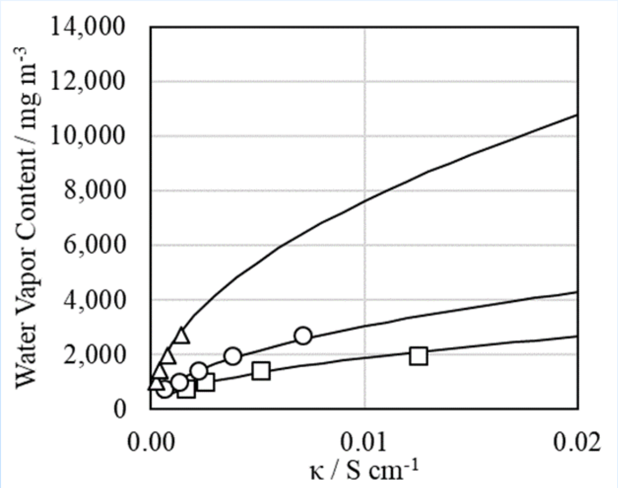
Integration of Ion-conducting Membrane in Advanced Electrochemical Sensor (AES) will Make AES Capable Of Monitoring in Real-Time In-Situ Water Content, Temperature, Steel Corrosion Rate and Pitting / Localized Corrosion Parameters Inside Natural Gas Pipeline.

AES for Water Content & Corrosion Rate: Lab Test

Phase 1: Development of 1st Generation Membrane-based AES prototype for measuring water content and corrosion rate in humid nitrogen at elevated pressure and elevated temperature using <u>High-Pressure Flow-Through Electrochemical Test System for two AES</u>





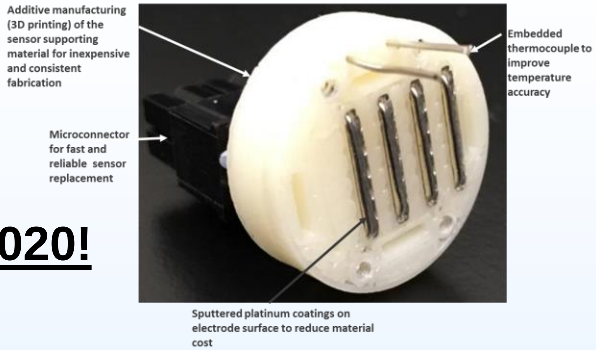


Water vapor content-conductivity data in N_2 streams at 689 kPa and a flow rate of 3.4 m^3/h at 30 °C (□), 40 °C (○) , and 60 °C (Δ).

<u>1st Generation AES:</u> Estimated material, manufacturing, and operation cost, which includes instrumentation and data collection, is $1000 per sensor.

AES for Water Content & Corrosion Rate: Field Test

<u>Phase 2</u>: Development of 2nd Generation Membrane-based AES prototype fabricated via sputtering and additive manufacturing, with embedded thermocouples.



<u>Successful 1st Field Test in August, 2020!</u>

- Colorado Engineering Experiment Station (CEESI) operators installed the AES prototypes safely and without any problem in the pipe spool with connections to the experimental data acquisition equipment.
- Successfully monitored corrosion rate and environmental conductivity in dry and wet natural gas.

Natural Gas: 1000 psi; flow rate 15 ft/s; T=70 °F, 20 hours

- Conductivity: ~0.04 (top/bottom) S/cm
- Corrosion rate: 0.001 (top) to 0.003 (bottom) mm/y

Wet Natural Gas: flow rate 60 ft/s; T=95 °F, 70 hours

- Conductivity: ~15 (top) to 20 (bottom) S/cm
- Corrosion rate: ~0.1 (top) to ~0.3 (bottom) mm/y

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

Electrochemical testing equipment is in weather-proof container.

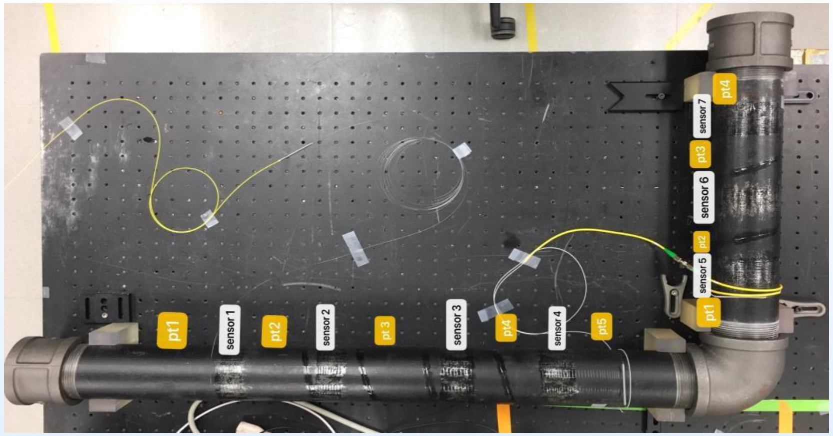
✓ ***AES easy to install by facility operators***

✓ ***Capable of remote data collection***

<u>2st Generation AES:</u> Estimated material, manufacturing, and operation cost, which includes instrumentation and data collection, is $100 per sensor.

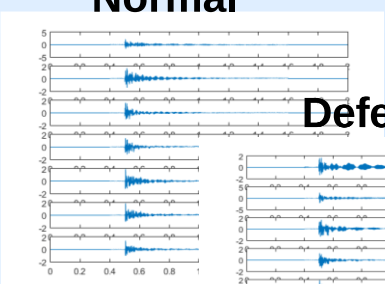
AI-Enhanced Fiber Optics for Pipe Defect Detection

Defect Distribution in Metallic Structures

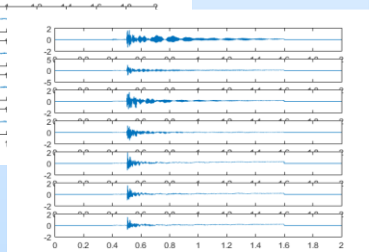


Various Types of Defects to Classify

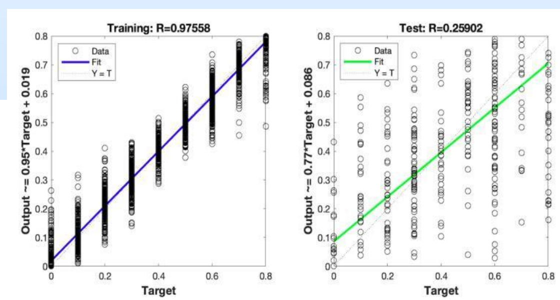
Normal



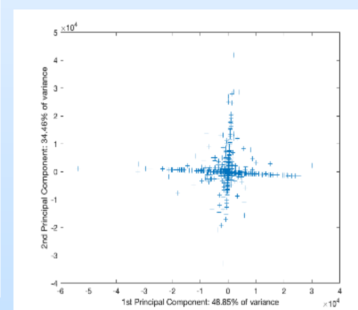
Defective



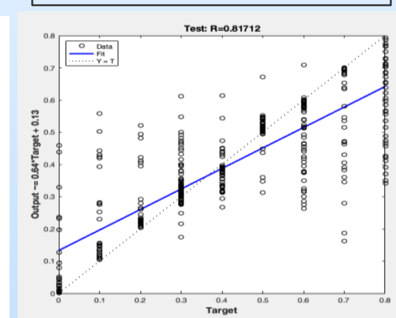
Linear Regression



Principal Components



Shallow Neural Network



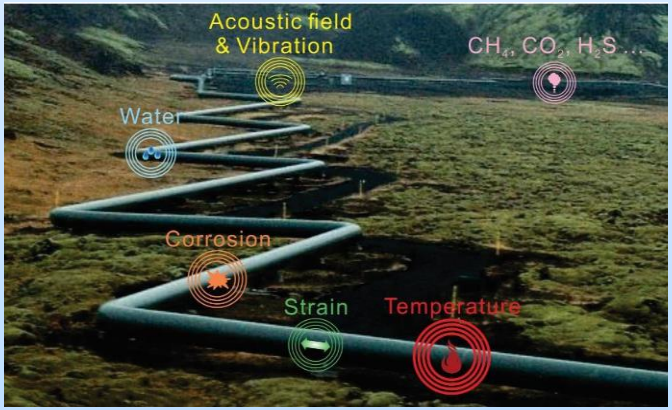
Distributed Acoustic Sensing Technology with Advanced Data Analytics to Identify, Classify, and Quantify Various Defects at the Joint of Two Metallic Tubular Structures.

Key Accomplishments and Outcomes

- Multiple Custom Low-cost Optical Fiber Interrogator Hardware Has Been Developed for Various Applications
- New CH_4 Sensitive Coatings Have Been Optimized and Applied for Optical and Wireless Sensors
- Optical Fiber Based Humidity and Early Corrosion Onset Sensors Have Been Demonstrated for >1km
- Passive Wireless SAW Sensors Have Been Demonstrated for Simultaneous Sensing of CH_4 and CO_2
- Successful First Field Test of Advanced Electrochemical Sensor (2nd Gen) for Water Content, T and Corrosion Rate Monitoring
- Artificial Intelligence (AI)-Enhanced Distributed Optical Fiber Sensing for Pipeline Defect Identification. First Field Test is Planned in EY20.

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

- 8 Provisional / Non-Provisional Patent Applications
- >10 Published Scientific Manuscripts
- 4 Published Literature Reviews
- >30 Conference Proceedings Published
- >35 Presentations at Technical Conferences



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Appendix

Technology Development and Deployment

EY2019 | EY2020 | EY2021 | EY2025

- **Advanced Electrochemical Sensor**

1st Generation Prototype Wired

2nd Generation Wired and Wireless, Low Cost, 1000 psi

3rd Gen. Wired and Wireless, Compact

Commercial

1st Field Validations

2nd Field Validations

Technology Transfer

- **Distributed Optical Fiber Sensor**
- **Passive Wireless Sensor**

Early Stage Technology Development

Multi-parameter, Technology Scaling up

Prototype Deployment & Telemetry Optimization

Commercial

1st Field Validations

2nd Field Validations

Technology Transfer

Sensing Platforms Under Development Have Complementary Technology Readiness Levels and Will be Matured for Commercialization.