Advanced Sensors for Energy Infrastructure Monitoring

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NATIONAL ENERGY TECHNOLOGY LABORATORY

Virtual Workshop on Optical Sensors for Energy Applications
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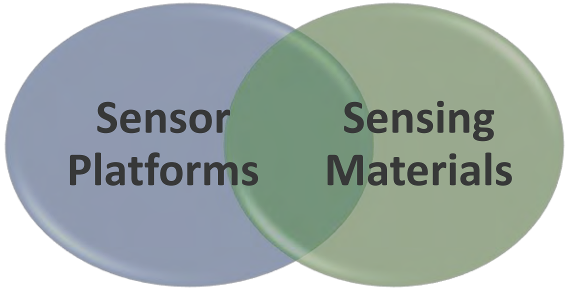
U.S. DEPARTMENT OF ENERGY

Sensor Materials for Critical Infrastructure and Extreme Environments

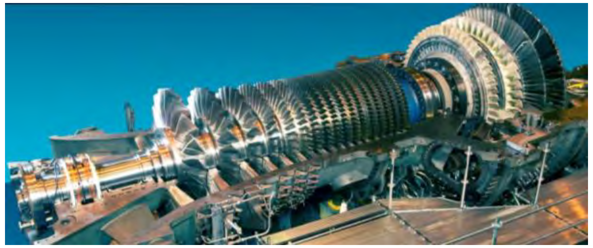
Advanced Sensors for Energy Efficiency, Safety, Resilience, and Sustainability

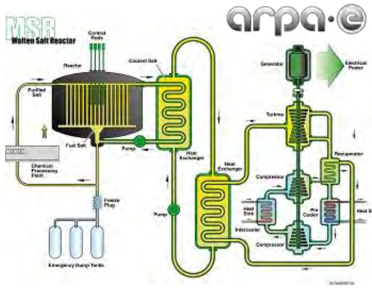
- ✓ Monitor systems and conditions
- ✓ Improve performance & efficiency
- ✓ Enhance reliability & safety
- ➢ Temp, acoustics, chemical, gas, corrosion
- ➢ Composite nano-materials, thin films & fiber optics, sensor devices development



GENERATION

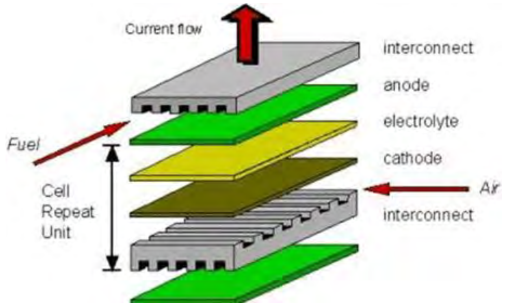
Turbines: Real-time fuel composition and combustion temperature for improved service life and efficiency





Nuclear: Core monitoring and molten salt temperatures for reactor fuel efficiency & reactor safety

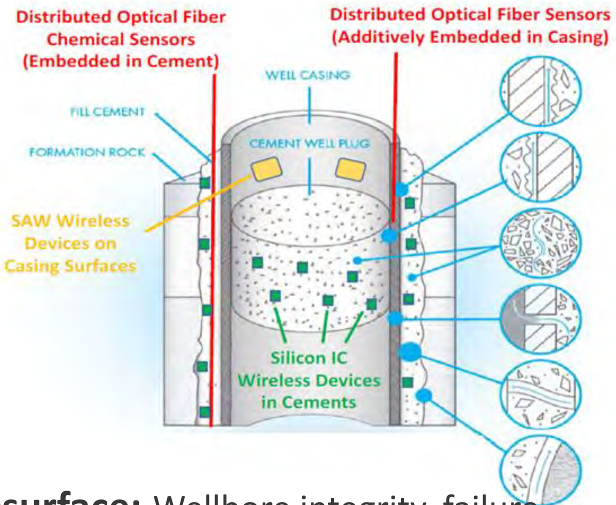
SOFCs: Fuel concentration & temperature gradients for improved lifetime and efficiency



ENERGY DELIVERY & STORAGE

Pipelines: Monitor corrosion, gas leaks, T, acoustics to predict/prevent failures. NG, H_2, CO_2

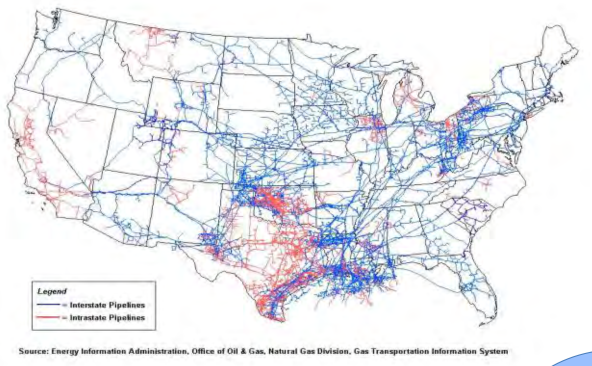
Grid: Transformer, powerline failure prediction, fault detection, state awareness



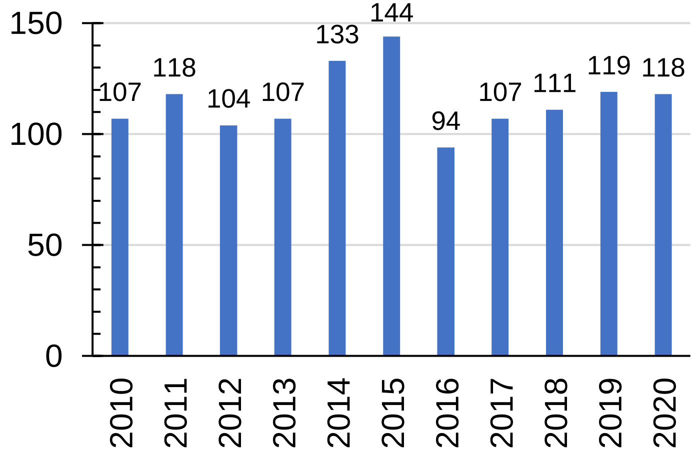
Subsurface: Wellbore integrity, failure prediction, leak detection. Geologic storage of CO_2, H_2/NG, or abandoned wells.

Reliability & Sustainability of Natural Gas Infrastructure

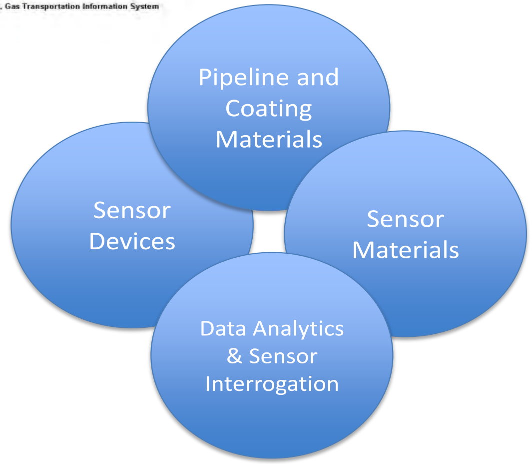
~300,000 miles of NG transmission pipelines in U.S.



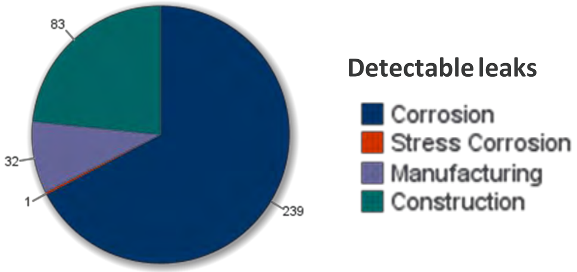
Number of natural gas transmission pipeline incidents (2010-2020)



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



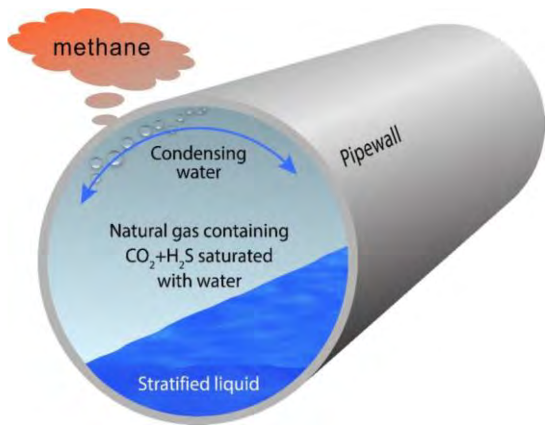
Gas Transmission Leak Sources



"Methane emissions from the transmission and storage segment accounted for ~23 percent of emissions from natural gas systems" (EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019*, published 2021).

Real-time Monitoring and Leak Detection/Mitigation for the Natural Gas Infrastructure are Increasingly Important for Reliability, Resiliency, and CH_4 emission reduction.

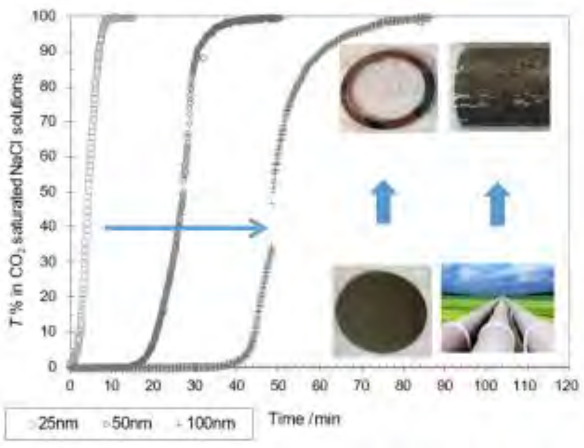
Methane Leak Monitoring and Corrosion Detection



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

Approach: Advanced Sensor Technologies

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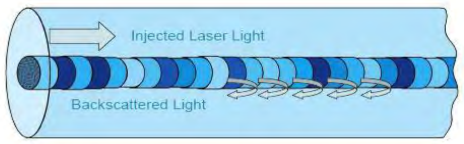
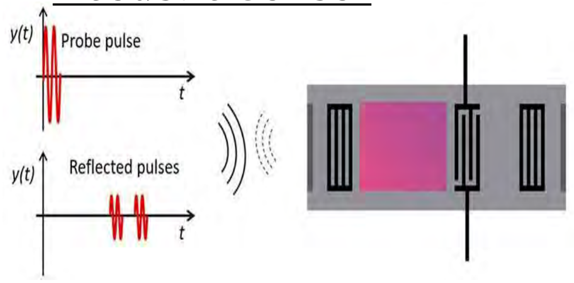
Distributed Optical Fiber Sensor

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



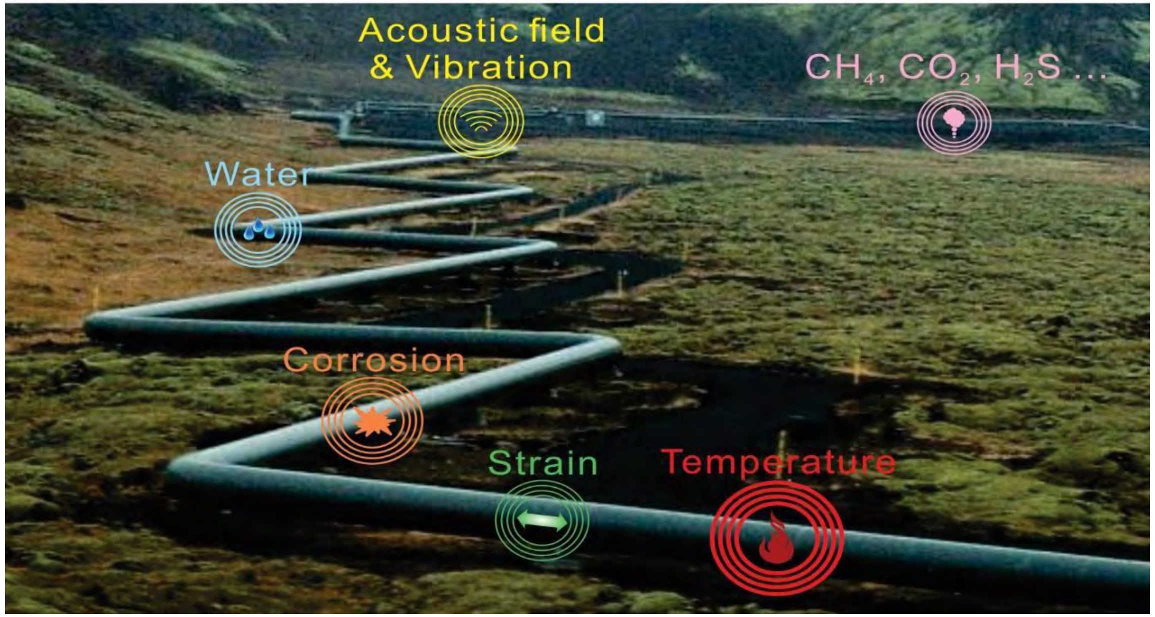
Advanced Electrochemical Sensor

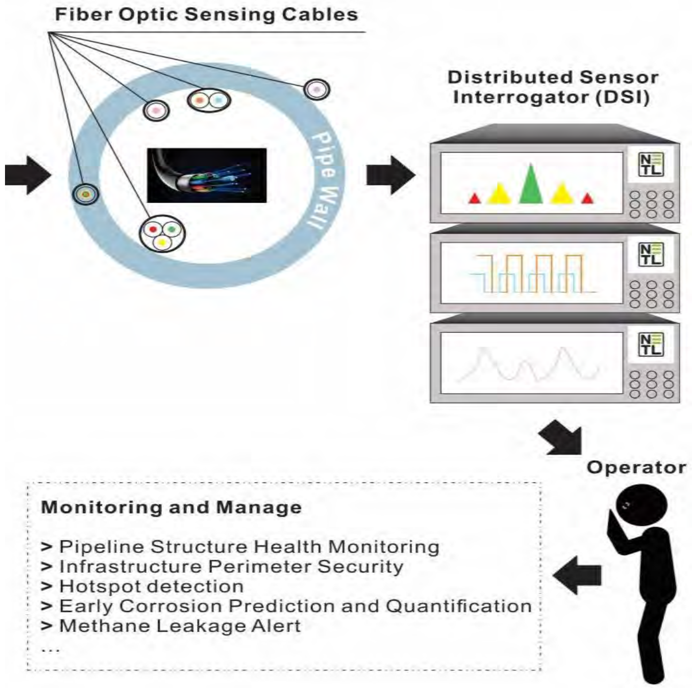
	Geospatial Attributes	Cost	Targeted Function	TRL
Distributed Optical Fiber Sensors	Linear Sensor Adjustable Distance and Resolution	Cost Per Sensor "Node" Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, H_2, etc.) Early Corrosion/pH Detection	5-6
Passive Wireless SAW Sensors	Point Sensor	Low	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, H_2, etc.) Early Corrosion/pH Detection	4-5
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 Monitoring.

Distributed Optical Fiber Sensor Network for Pipelines

Pipeline Integrated with Distributed Optical Fiber >100 km





Emphasis Within NETL Research & Innovation Center:

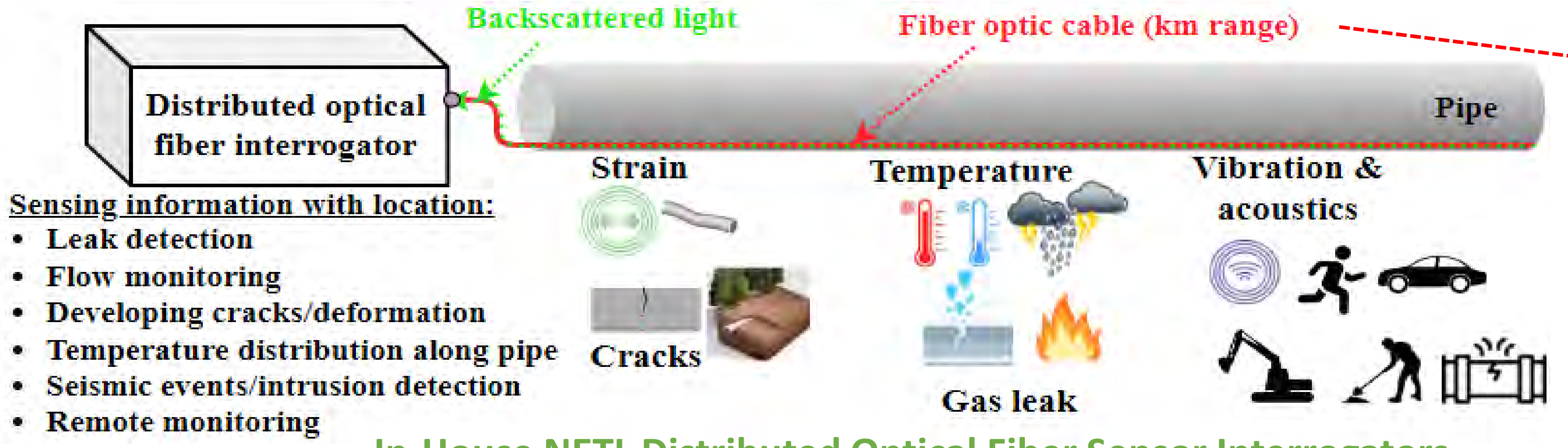
- ➢ Optimize Interrogation System (Range, Resolution, Cost)
- ➢ Early Corrosion On-Set Detection → **Predictive Signatures**
- ➢ Methane Leak Detection & In-Pipe Gas Composition Monitoring → **Direct Signatures**

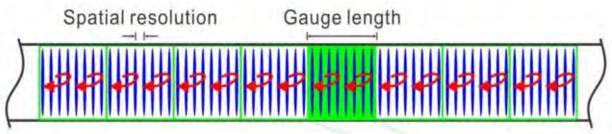
Multi-Parameter, Distributed Optical Fiber Sensor Platform to Enable Reliable and Resilient Pipelines.

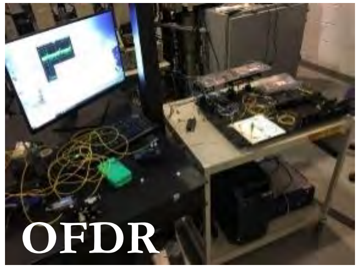
Target Metrics: >100 km Interrogation, <5 m Spatial Resolution

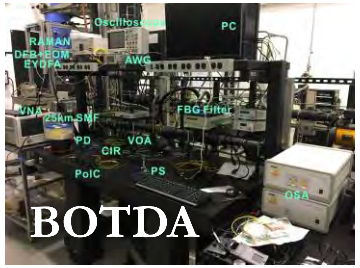
Distributed Optical Fiber Interrogator Development

Pipeline integrity monitoring based on various distributed fiber sensor systems









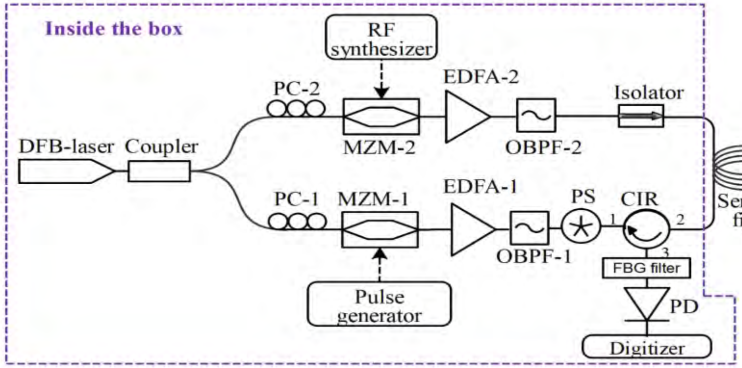
In-House NETL Distributed Optical Fiber Sensor Interrogators

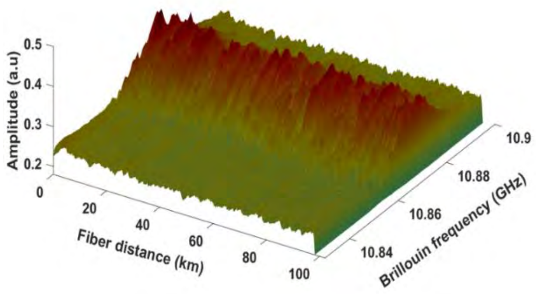
Technology	Sensing range	Spatial resolution	Measurement time	Target parameter
Rayleigh phase-OTDR	Kilometers	Meters	Seconds	Acoustic/vibrations
Brillouin- OTDA	Tens of kilometer	Centimeter to meter	Minutes	Temperature and strain
Rayleigh OFDR	Meter to kilometer	Millimeter to centimeter	Seconds	Temperature and strain

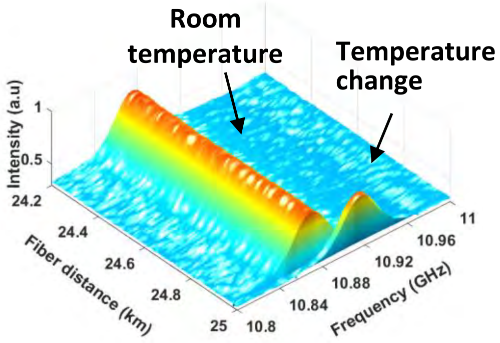
Multiple distributed optical fiber sensing platforms have been developed to enable structural health monitoring of pipeline and other infrastructure.

Ultra-long-distance Temperature and Strain Measurements

Brillouin Optical Time-domain Analysis (BOTDA)

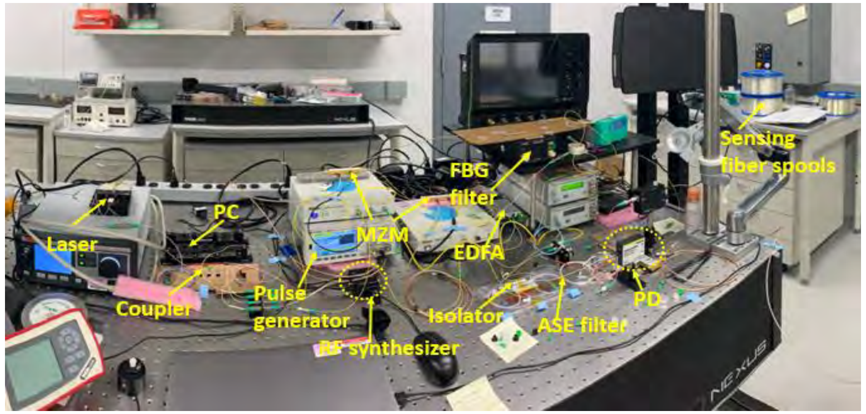


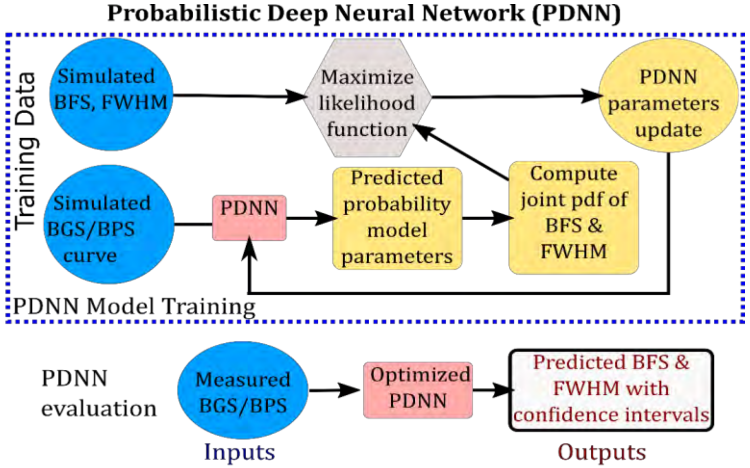




Sensing range = <150 km;
Spatial resolution = <5m;
Parameters: strain, and temperature

BOTDA experimental test-bed at NETL



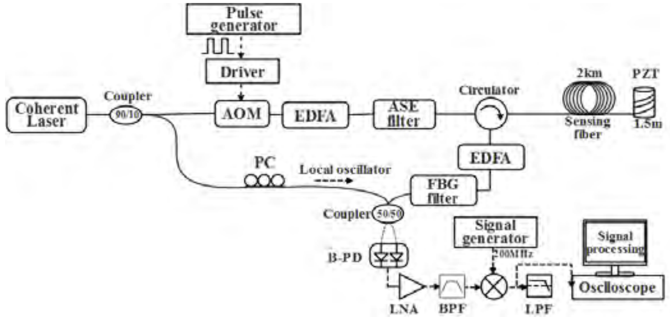


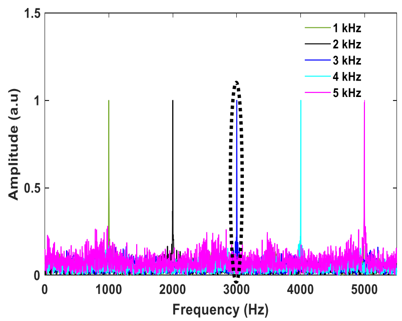
- **PDNN processes the BGS & BPS data in real-time (1 sec), compared to existing BOTDA capability (1 min)**
- Increased confidence in data: propagates noise in data as prediction uncertainty
- Better than Curving Fitting and Supervised Machine Learning

Distributed strain or T measurements inform pipeline failures and gas leaks in real-time up to 150 km.

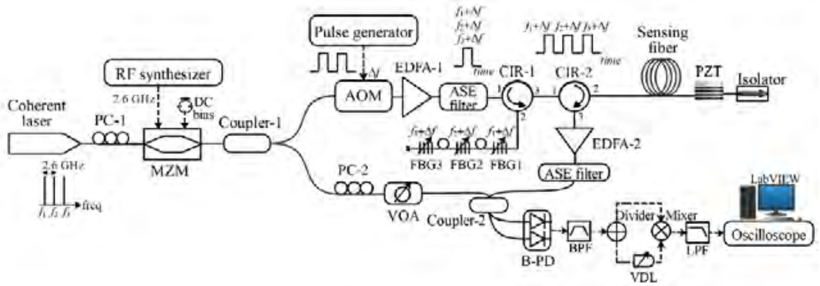
Phase-OTDR Distributed Acoustic Sensing (DAS)

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

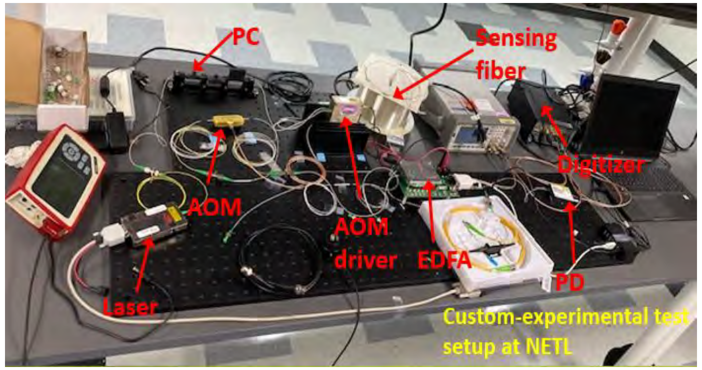




Φ-OTDR with wavelength diversity technique for enhanced Signal-to-noise ratio (SNR) Patent Filed!

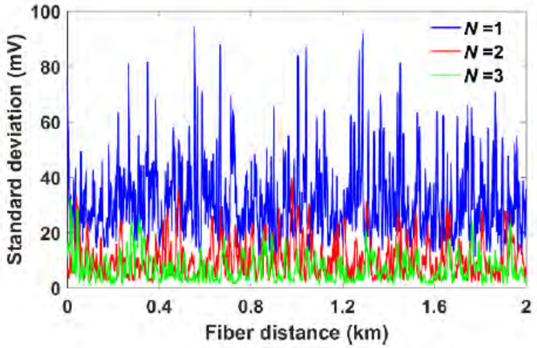


Custom-experimental test setup at NETL



Phase-OTDR interrogator box

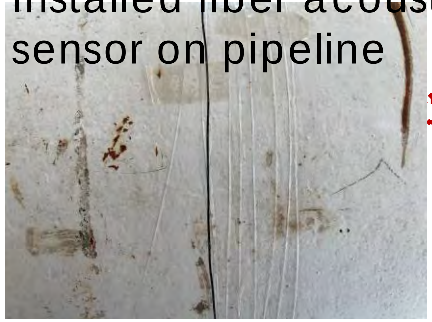
Fading noise was significantly minimized.

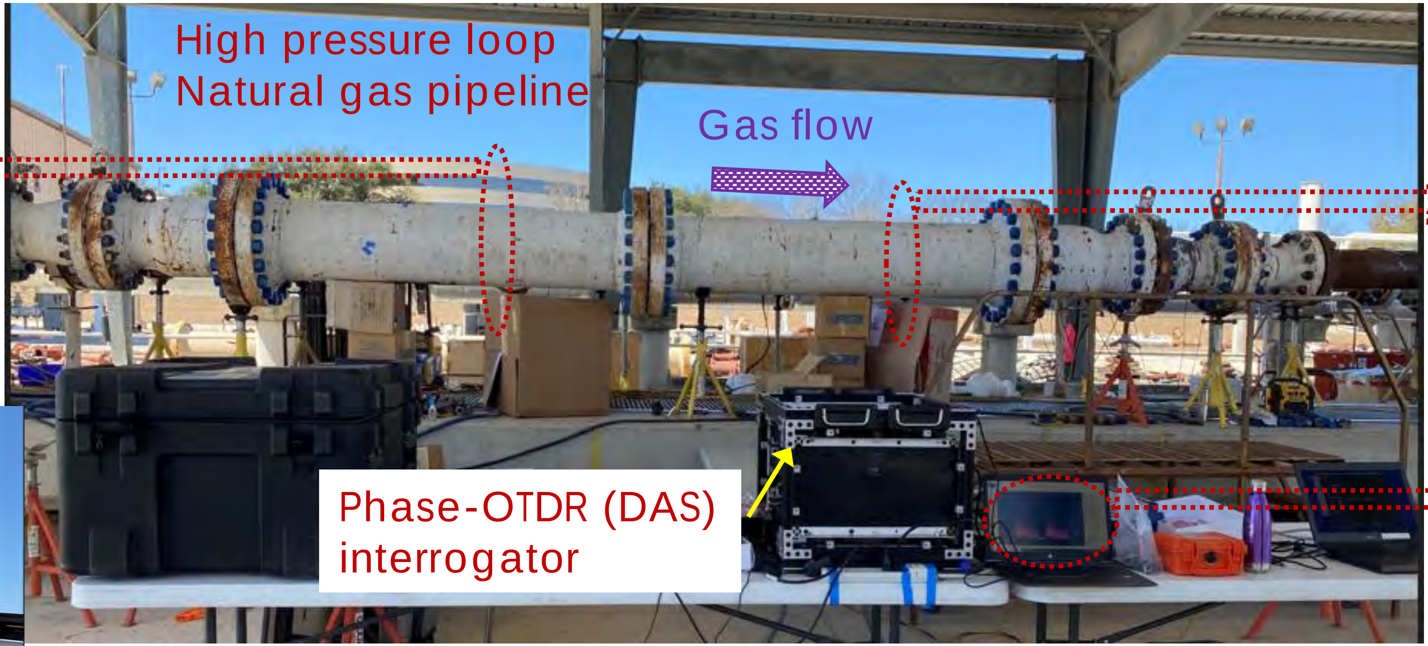


- Novel Approach to improve SNR in **phase-OTDR** for distributed measurements of acoustic waves and vibration.
- Portable Prototype of NETL Custom phase-OTDR/DAS

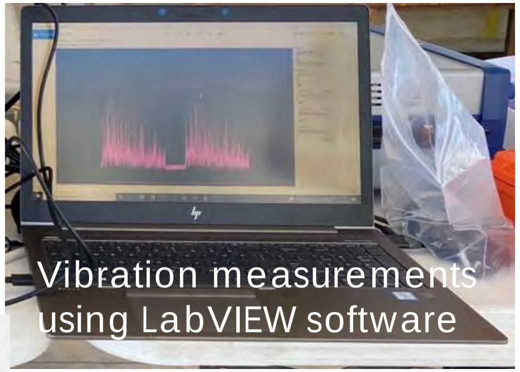
Pilot-scale test of phase-OTDR distributed acoustic sensing in a high-pressure natural gas pipeline

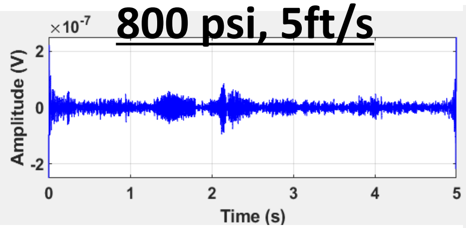
Installed fiber acoustic sensor on pipeline

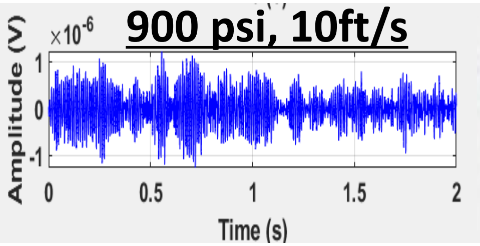


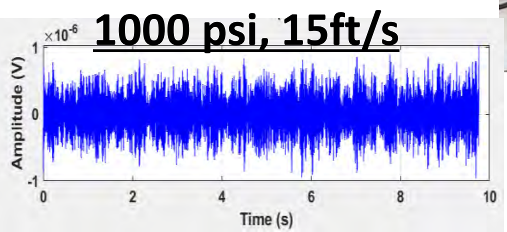


Installed fiber acoustic sensor on pipeline

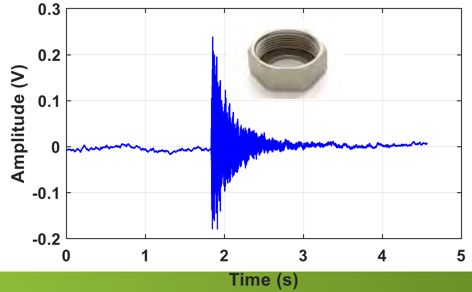




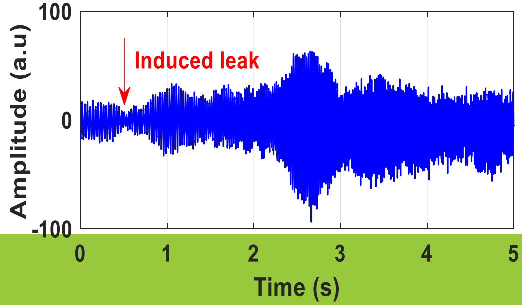




Drop a Stainless Steel Hex Nut on pipe



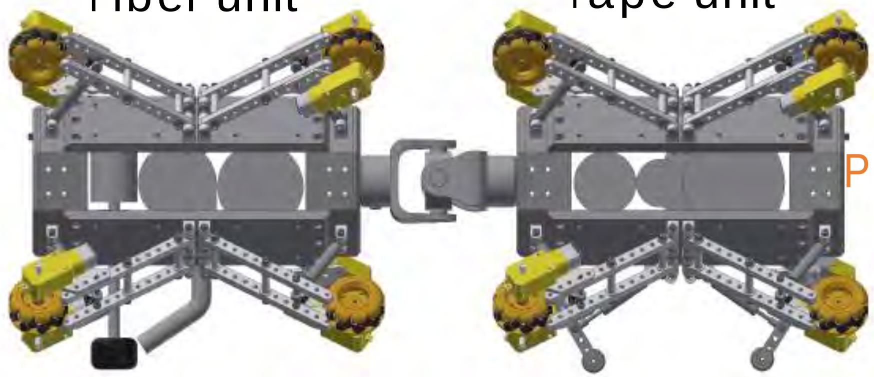
- **Flow rate monitoring**
- **Leak detection**
- **Third party intrusion detection**



In-line Robotic Fiber Optic Deployment Tool

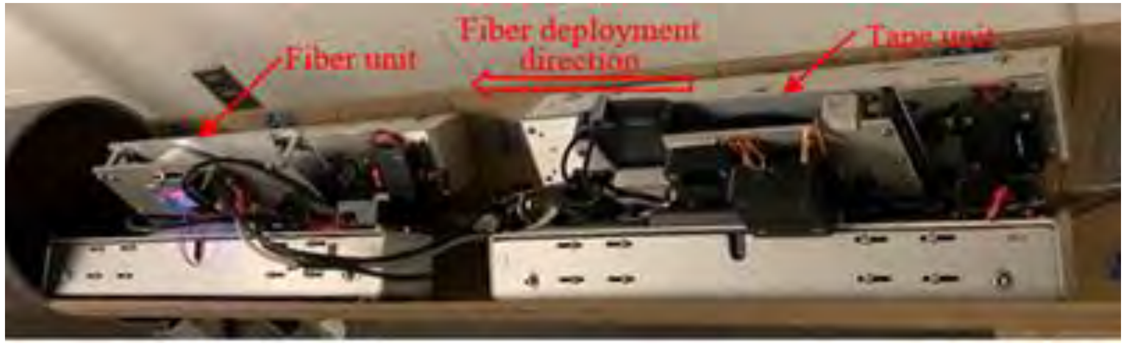
Internal fiber deployment for retrofitting existing pipelines

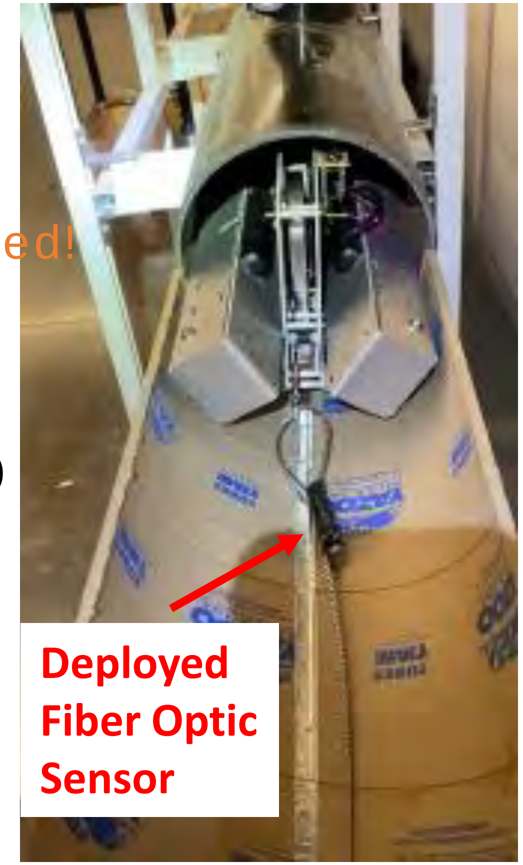
Fiber unit Tape unit

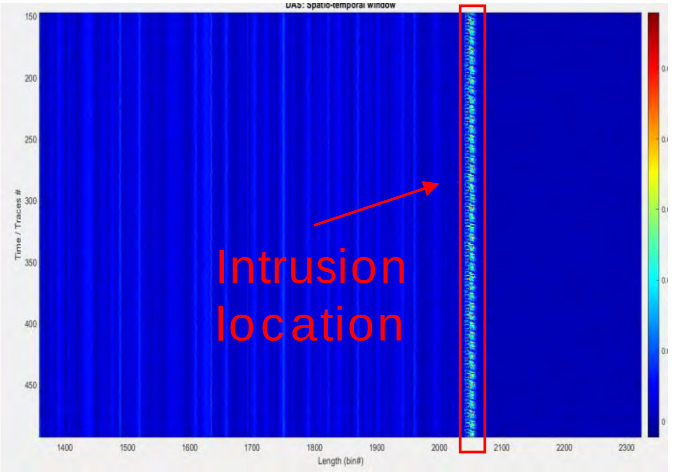


Patent Filed!

Automated Robotic Fiber Optic Deployment Tool (FODT)





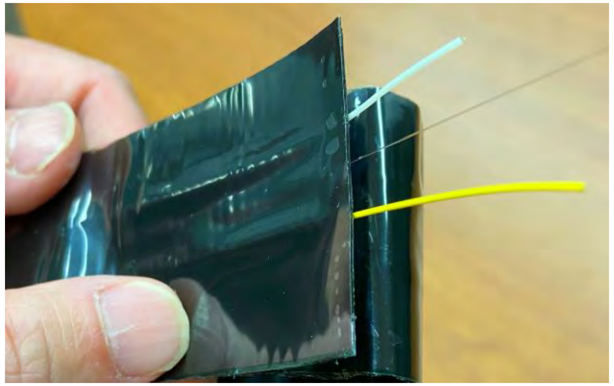


- **UPitt has developed a Robotic Fiber Optic Deployment Tool (FODT) supported by ARPA-E.**
- **Through collaboration, distributed acoustic sensing using NETL interrogator was demonstrated in a steel pipe.**

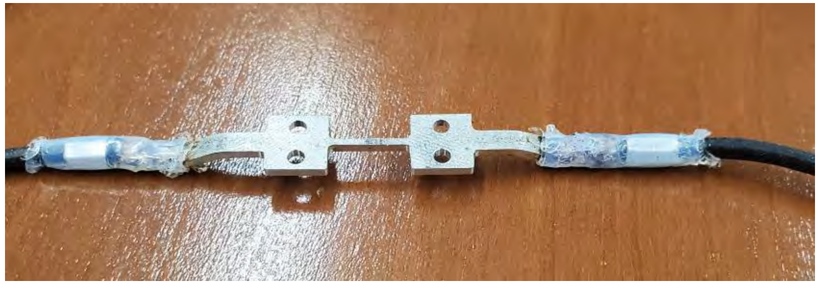
In Collaboration with Prof. Ohodnicki, UPitt

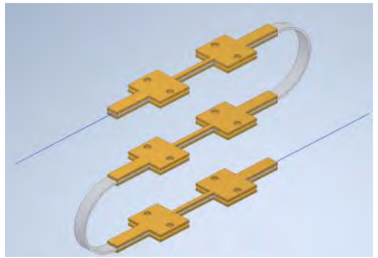
Smart Tape of Optical Fiber Sensors

Smart Tapes for Pipeline Deployment

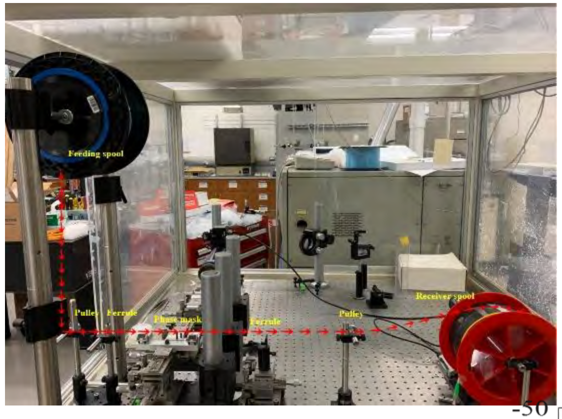


Fiber Packaging Technology: up to 400 ^{o}C

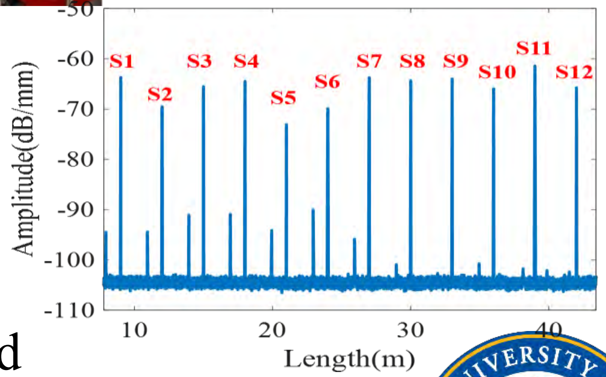




Rapid reel-to-reel sensor fabrication of low-cost Rayleigh-enhanced sensors



Patent!

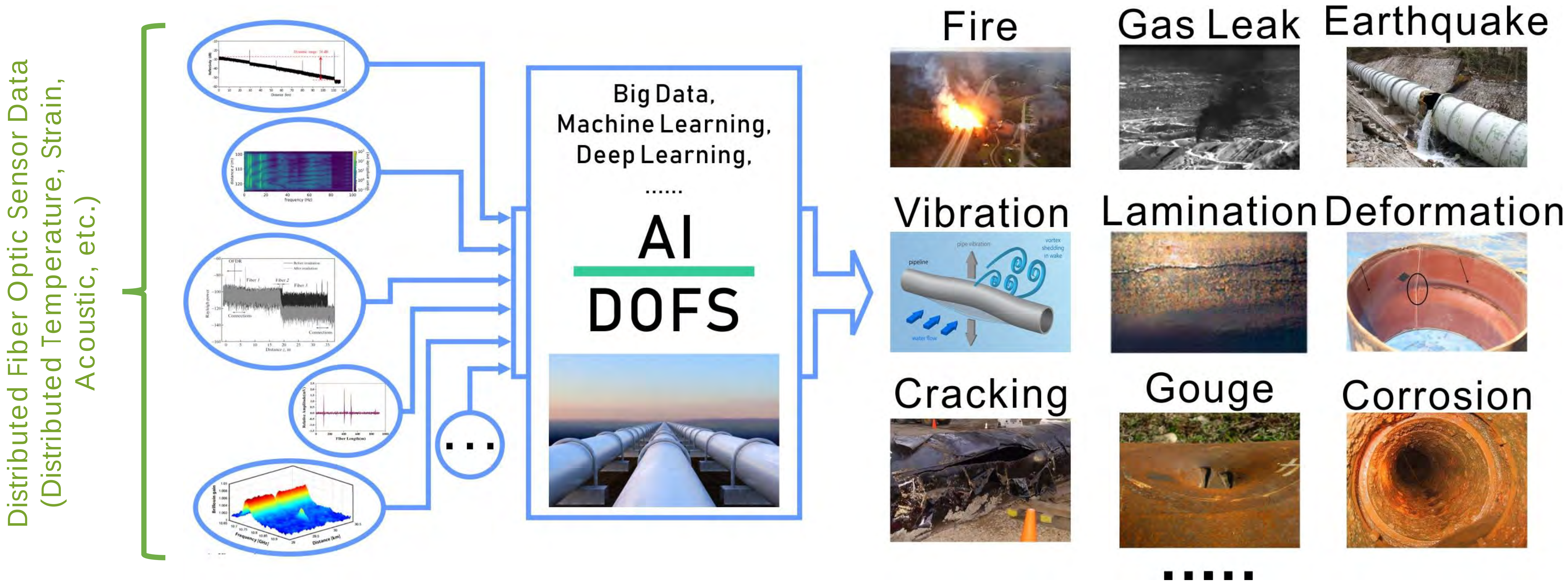


- Smart tapes for pipeline deployments: three sensors for vibration, temperature, and acoustic measurements;
- Easy to apply onto pipelines;
- Great potential for at least 10x cost reduction in Rayleigh-enhanced sensing fibers.

In Collaboration with Prof. Chen, UPitt

AI-Enhanced Distributed OFS Network

Fiber Optic Based Distributed OFS Technology Integrated with Advanced Analytics Including Pattern and Feature Recognition Can Convert Large Data Sets to Actionable Information.



Physics Based Modeling + AI For Pipeline monitoring

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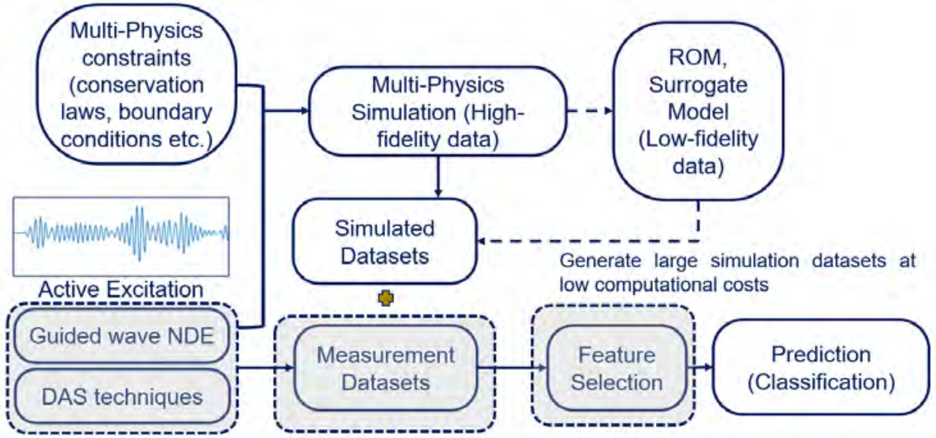
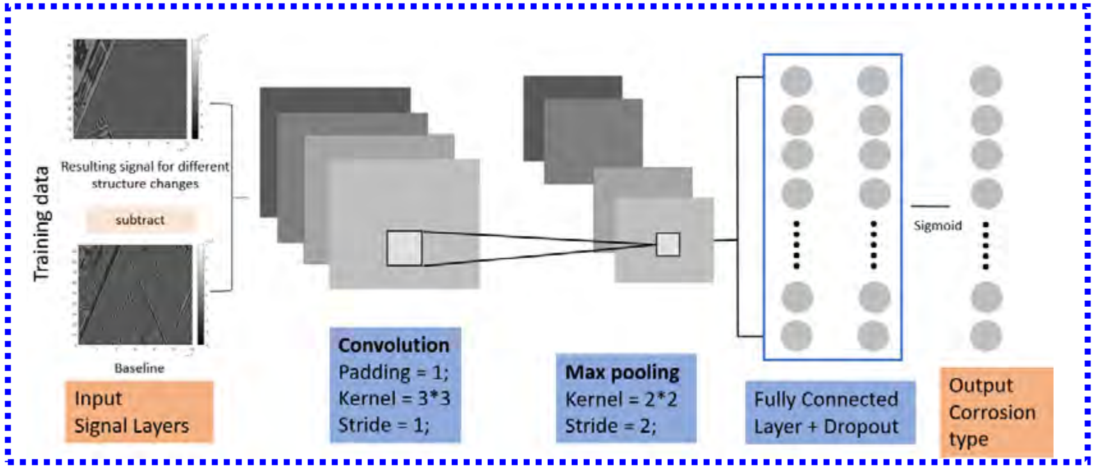
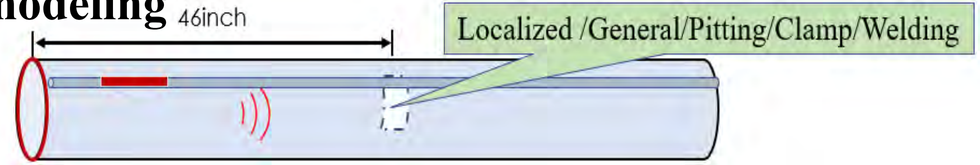
Scheme



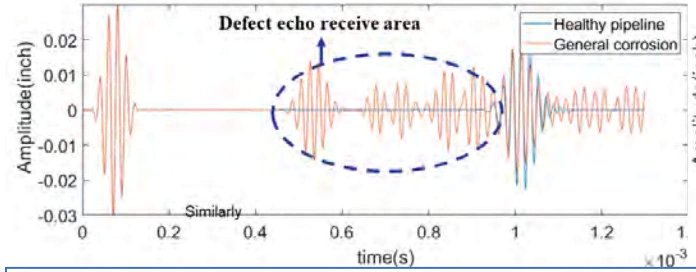
CNN framework:



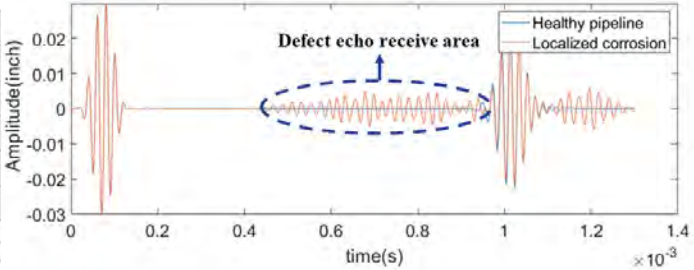
Multi-physics modeling



General corrosion



Localized corrosion



The general corrosion has a larger signal reflection area and a higher amplitude of defect echo signal for the same wall thickness reduction than localized corrosion.

Confusion matrix:

Actual \ Predicted	Clamp	Local	General	Pitting	Welding
Clamp	98.02	1.05	0.45	0.23	0.25
Local	0.17	98.67	0.76	0.21	0.19
General	0	0	98.6	0.8	0.6
Pitting	0.2	3.52	0.61	95.1	0.53
Welding	0.22	0.36	0.08	0.3	99.04

Pipeline defect classification based on CNN framework.

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In Collaboration with Prof. Ohodnicki, UPitt

Corrosion Sensing and Early On-Set Detection

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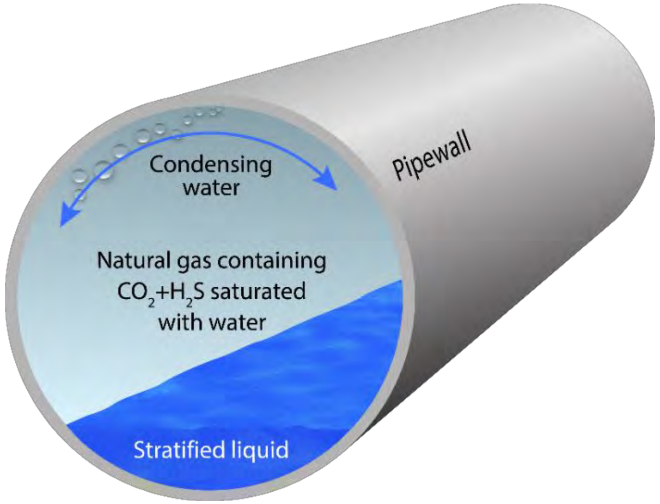
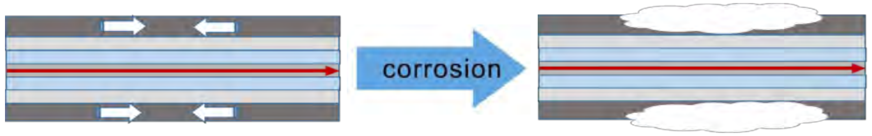
Metallic film coated optical fibers

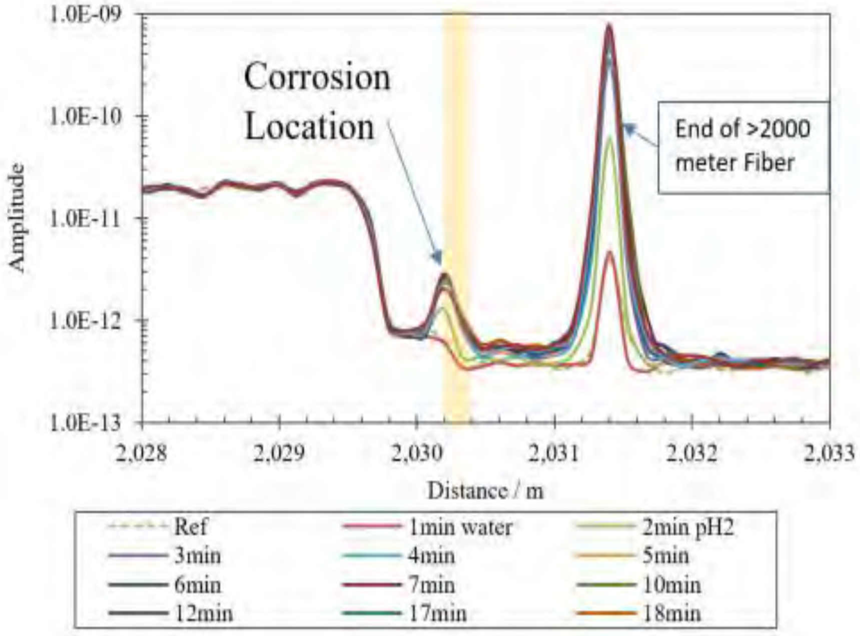
Patent!

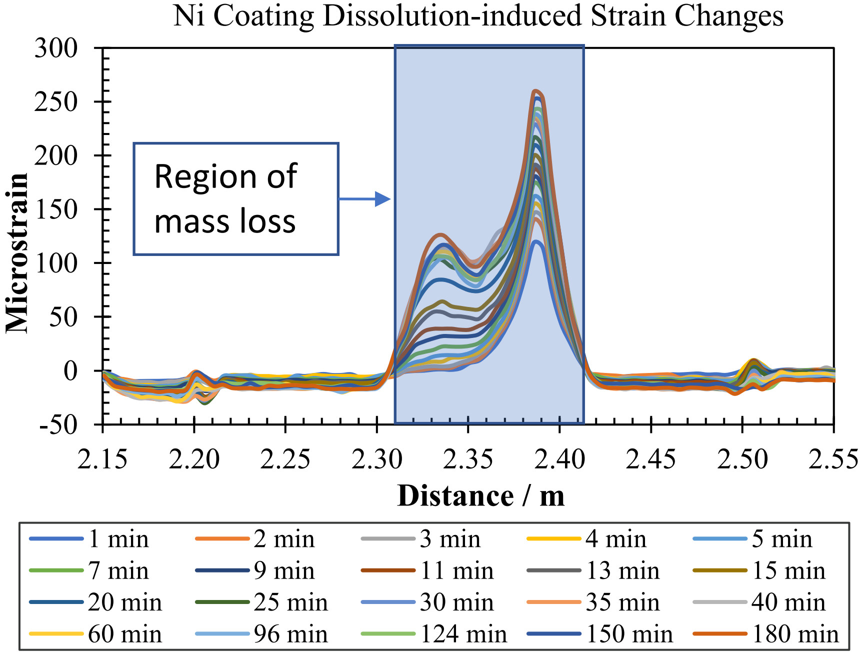


Optical Power Based

Strain Based





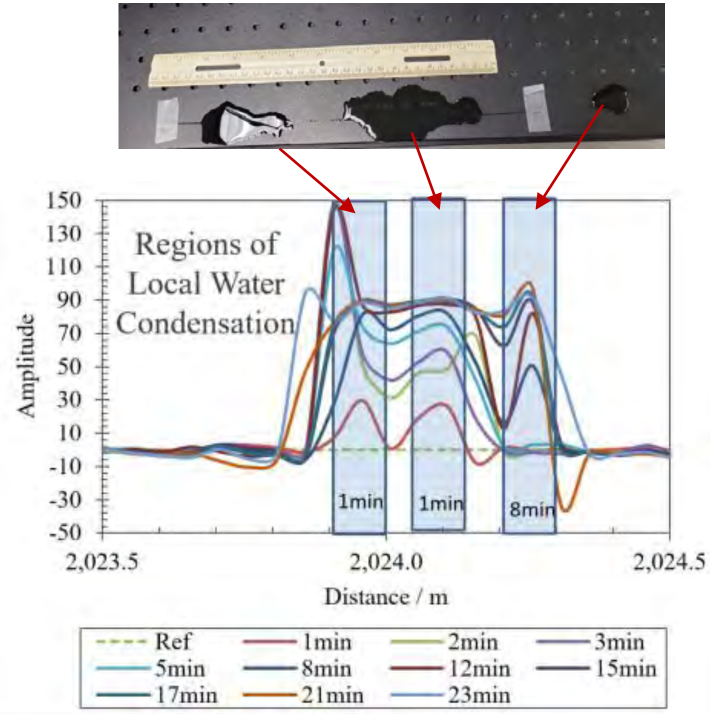


Corrosion can be detected and located along the optical fiber, which enables distributive corrosion monitoring for long-distance infrastructure.

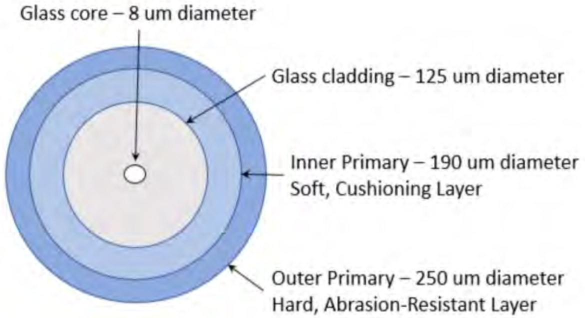
Distributed Water Condensation/Humidity Monitoring

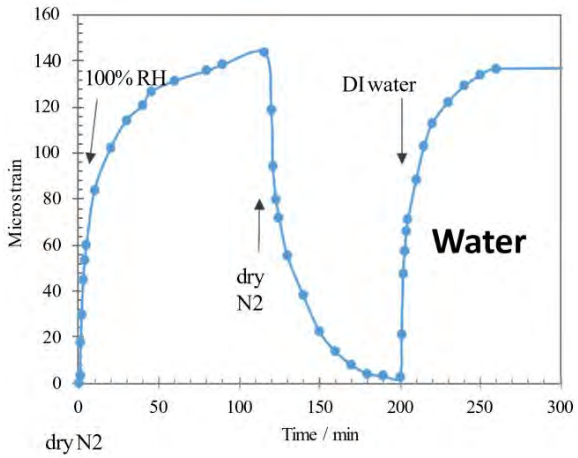
Water provides electrolytes for corrosion onset and is an indicator of potential corrosion.

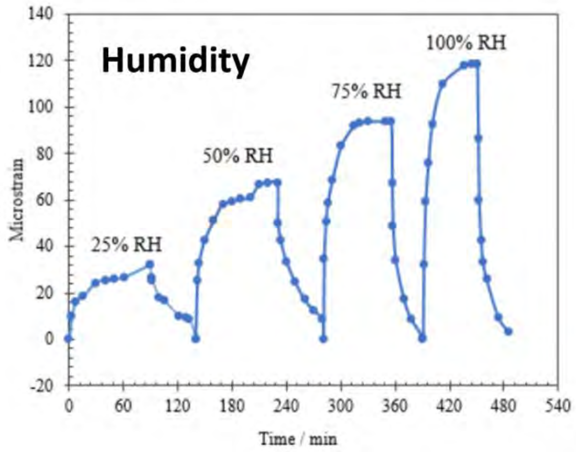
Patent Filed!



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





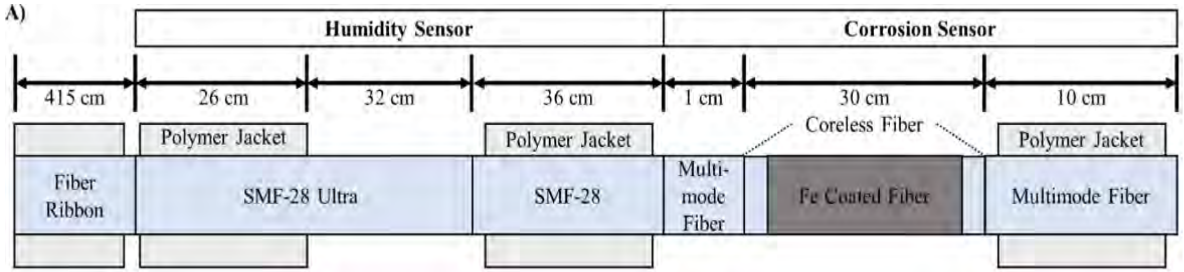


Local Humidity and Water Condensation Monitoring Due to Swelling of Polymer Jackets on Optical Fibers, as an Indicator for Corrosion.

Early Field Test of Distributed OFS Sensor Inside a High-Pressure Natural Gas Pipeline (1000 psi)

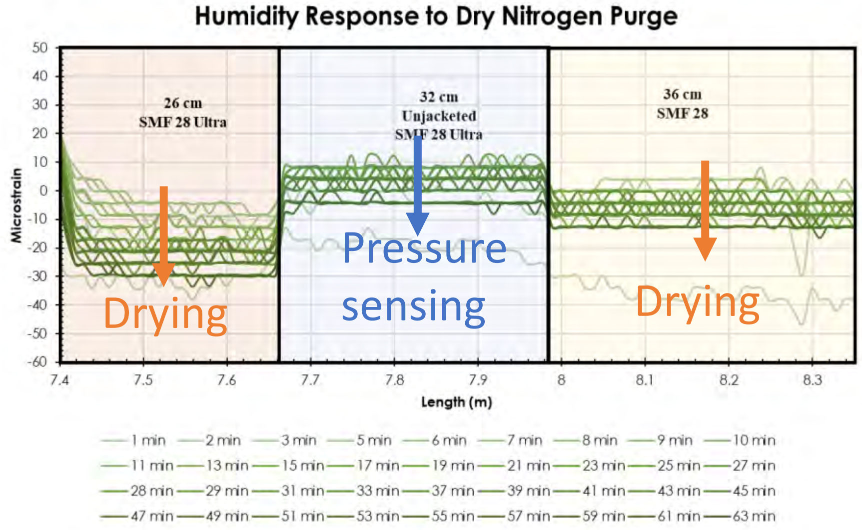
NATIONAL ENERGY TECHNOLOGY LABORATORY

A single optical fiber with multiple functions

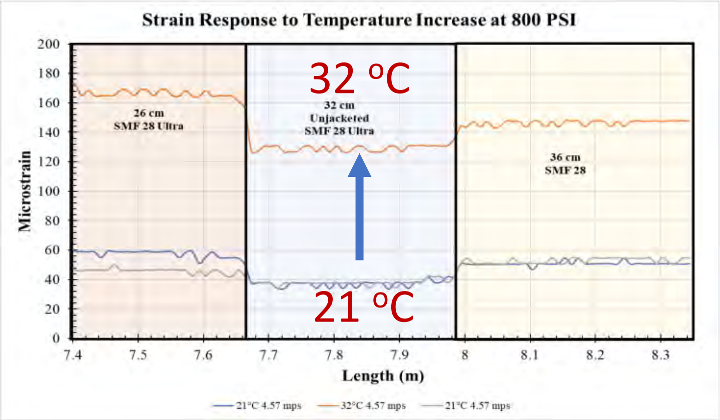


- **Pressure, Temperature monitoring**
- **Water content monitoring**
- **Corrosion monitoring**

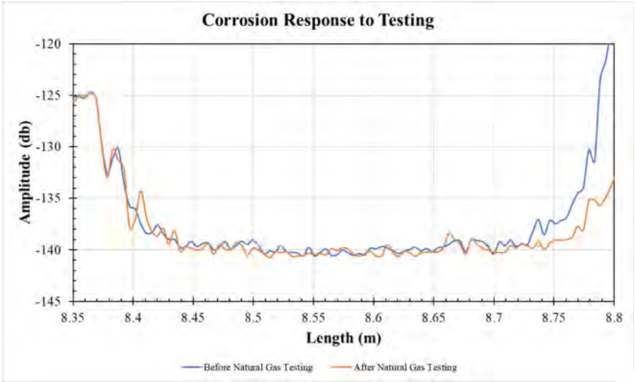
Pressure and Humidity Sensing



Gas Temperature Sensing

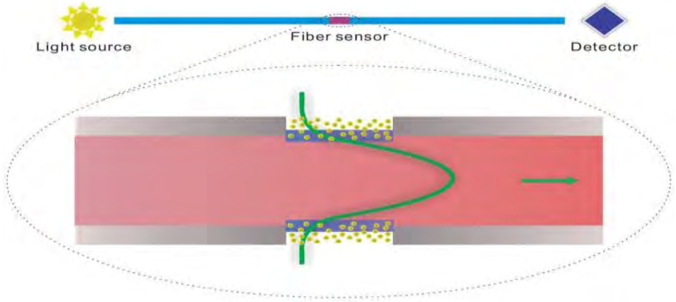


No significant corrosion was detected

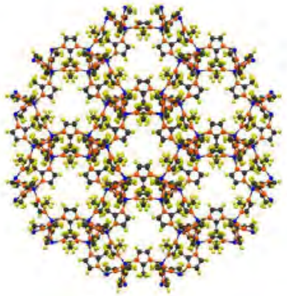


Optical Fiber Methane Sensing

Functional Sensing Layer Integrated Fiber Optic



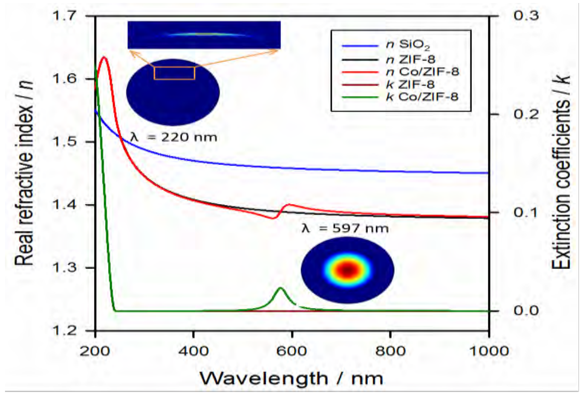
<u>Porous Metal Organic Framework (MOF)</u>



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

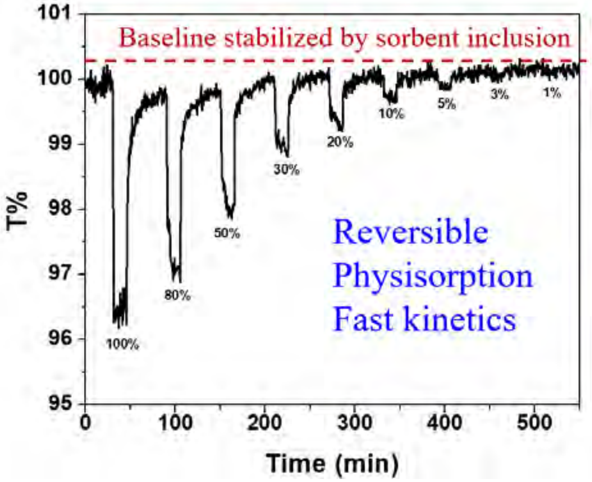
Evanescent Wave Absorption Based Sensors

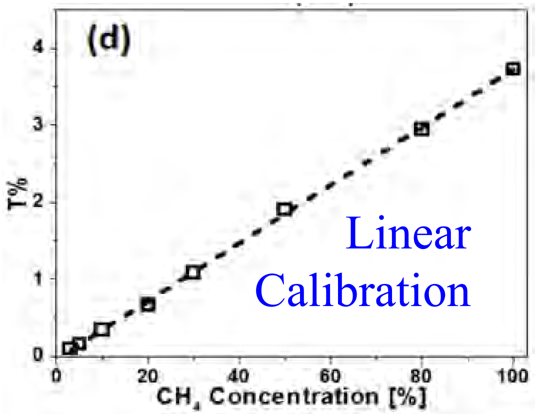
$$I_T(\lambda) = I_0 \exp[-\gamma\alpha(\lambda)CL]$$



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

CH_4 Detection Limit: < 5% in N_2



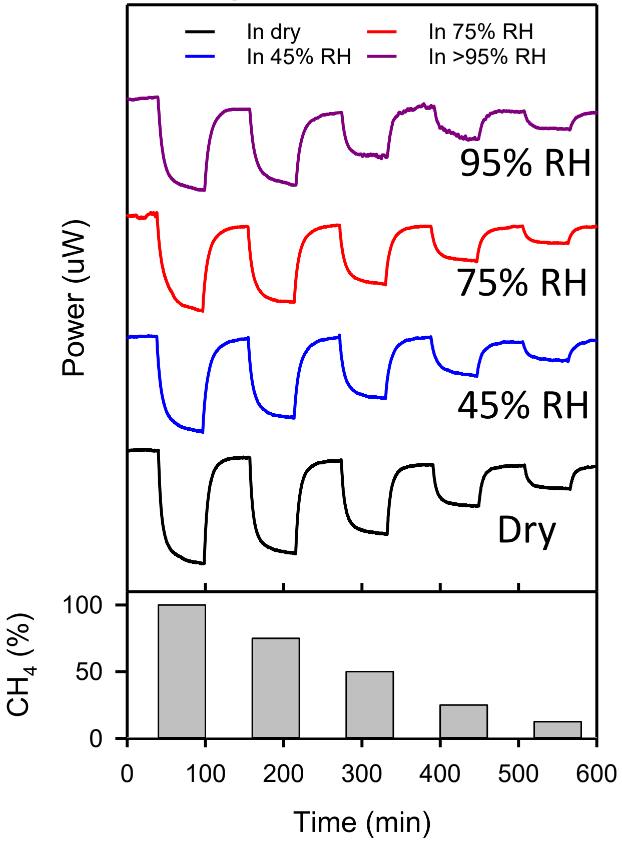


- **Light Intensity Based Methane Sensing Technology.**
- **Integration of Fiber Optic Sensors with Engineered Porous Sensing Layers by Design.**

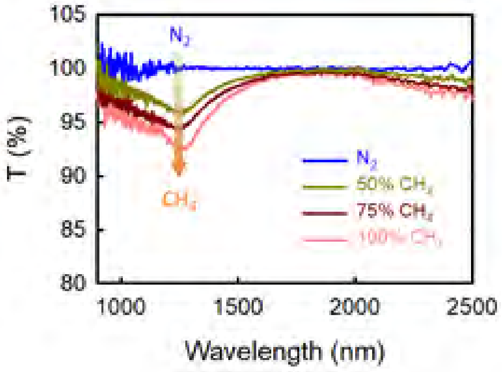
Optical Fiber Methane Sensor in Humid Conditions and Scale-up

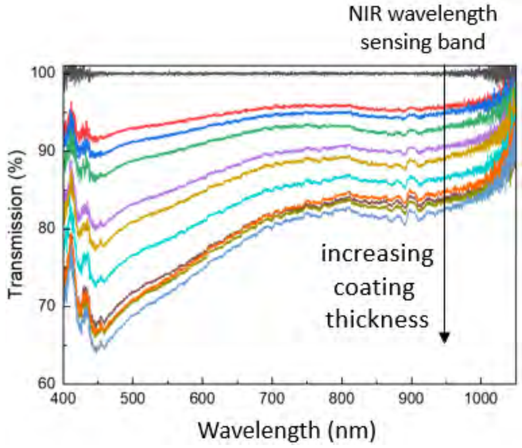
NATIONAL ENERGY TECHNOLOGY LABORATORY

Humid conditions, at visible wavelength 630nm Patent Filed!

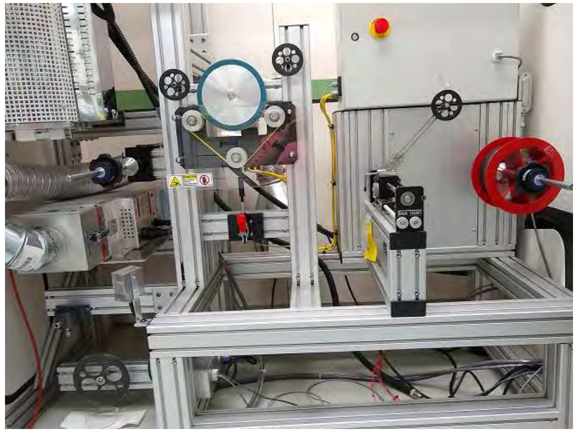


Optimize coating for near infrared CH_4 sensing



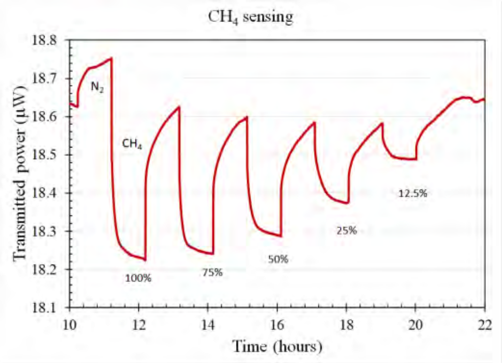


Early-stage reel-to-reel coating



NETL reel-to-reel fiber coating capability

CH_4 sensing with R-to-R coating



- Successful demonstration of optical fiber methane sensor in humid conditions up to 95% relative humidity (RH)
- Tune the wavelength to NIR range to be readily compatible with commonly used distributed OFS interrogators,.
- Demonstrated early-stage reel-to-reel coating of methane sensing materials onto optical fibers.

Surface Acoustic Wave (SAW) Sensors

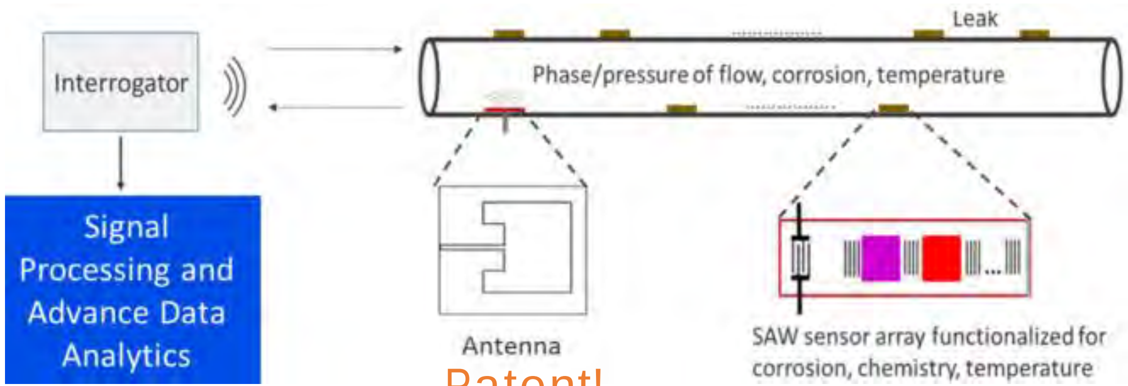
- Passive, Wireless, Matured Devices
- Sensitive, Cheap Point Sensors
- Possible for Multi-Parameter Operation (Temperature, Pressure, Strain, Chemical Species, Corrosion etc.)

SAW Velocity ($\boldsymbol{v}$) and Attenuation ($\boldsymbol{\alpha}$):

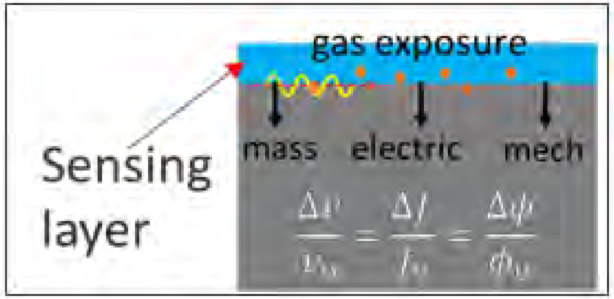
- Mass, Elasticity, Conductivity
- Environmental factors including Temperature, Pressure

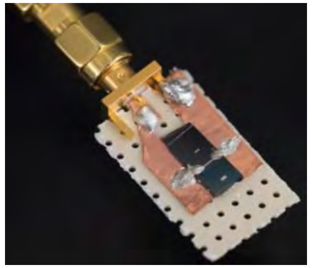
$$\Delta v = \frac{\delta v}{\delta m}\Delta m + \frac{\delta v}{\delta \sigma}\Delta \sigma + \frac{\delta v}{\delta \epsilon}\Delta \epsilon + \delta v(c, T, P)$$

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



Patent!





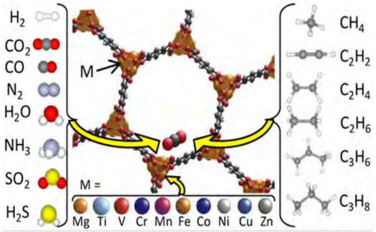
<u>Target Metrics</u>: Small (~5x5 cm^2), Low Cost (< $1.00 /device + antenna installed)

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

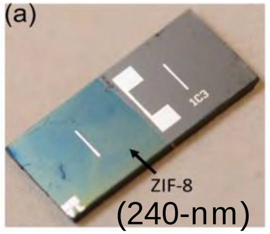
Wireless SAW Sensors for Gas Sensing

NATIONAL ENERGY TECHNOLOGY LABORATORY

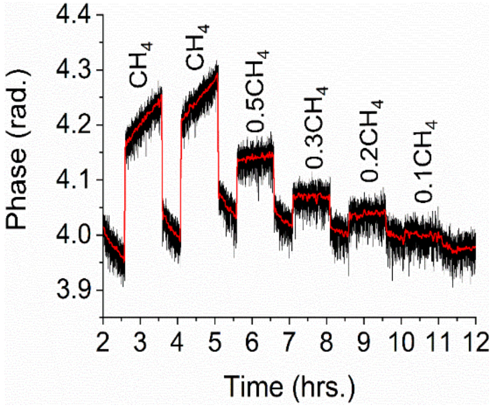
Wireless CO_2, CH_4 Sensing



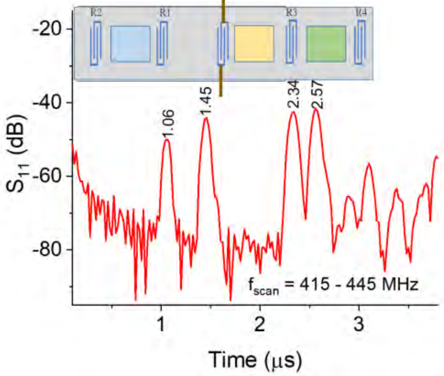
Lee et al., Chem. Mater. 27, 668, (2015)

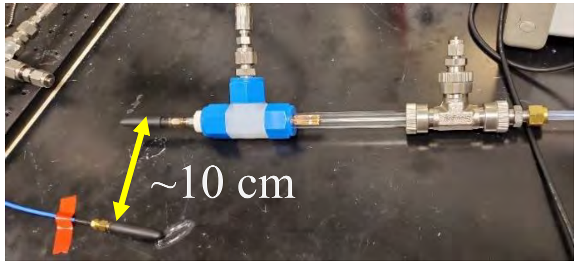


Nanoporous Sensing Materials

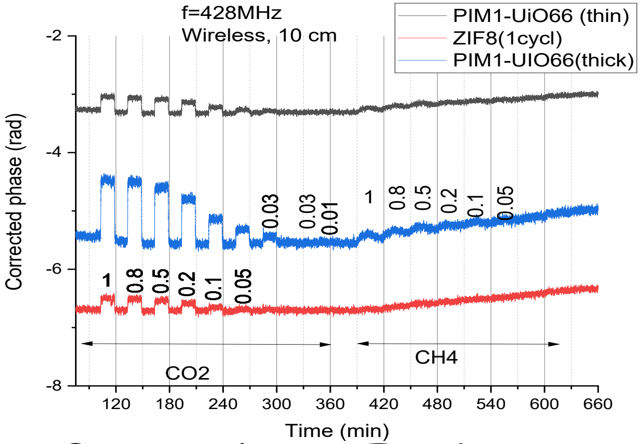


SAW Sensor Array for Multiple Gases: CH_4 and CO_2

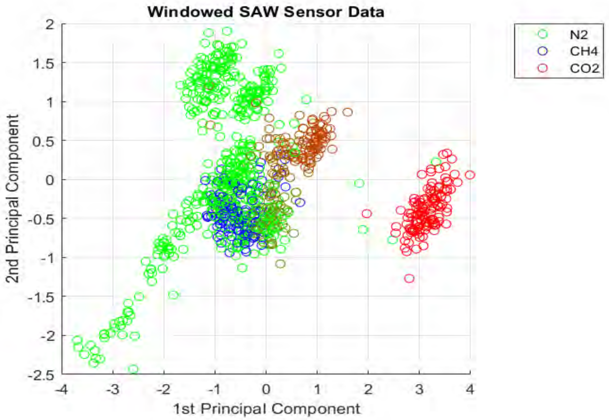




Patent Filed!



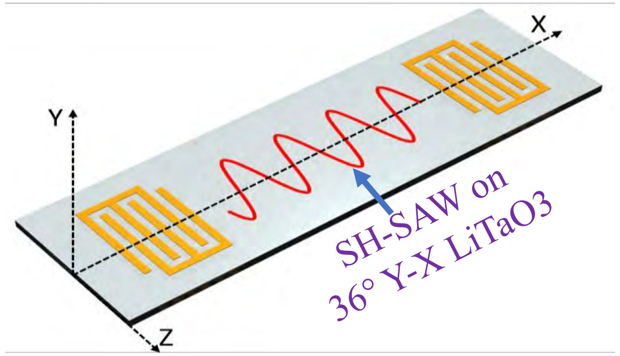
PCA Analysis of Sensor Data

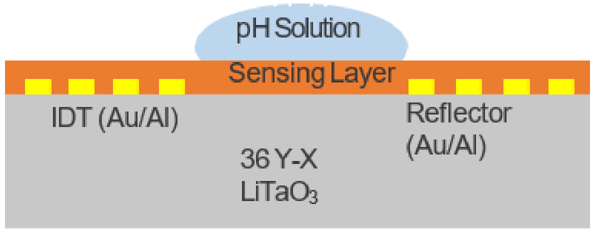


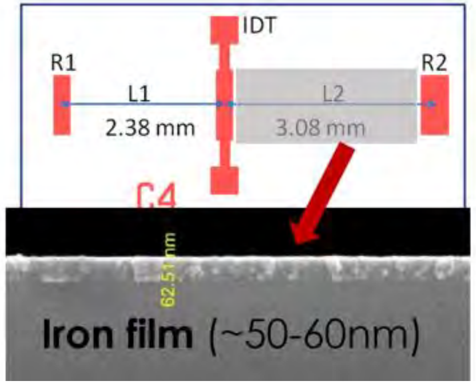
- **Wireless detection of gas components using a Sensor Array Device was demonstrated**
- **Advanced data analytics method was applied for classification of multi-element sensor array data for simultaneous monitoring of multiple gases.**

SAW Sensors for Liquid Applications

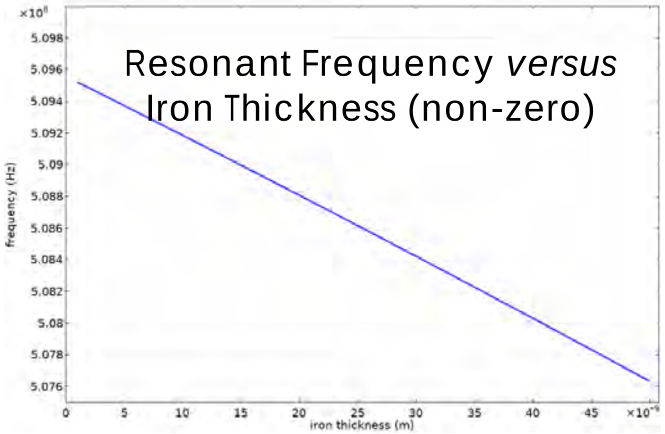
Shear Horizontal Surface Acoustic Waves

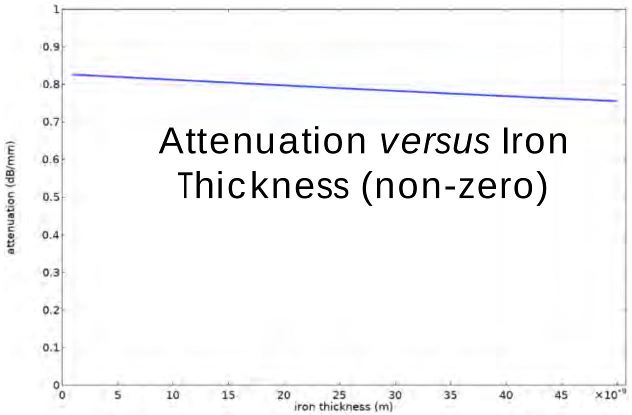




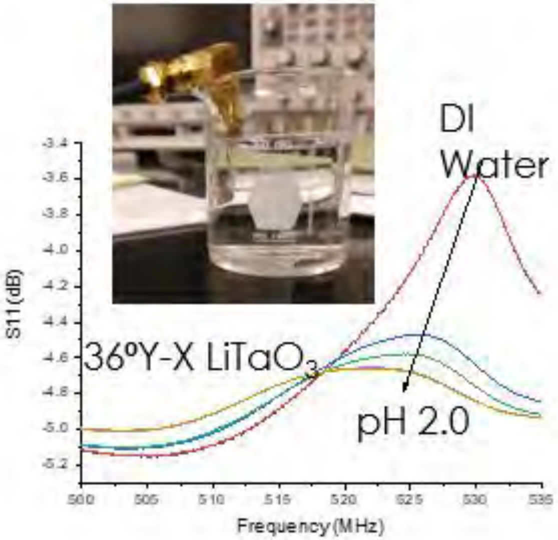


Simulation (finite element analysis)



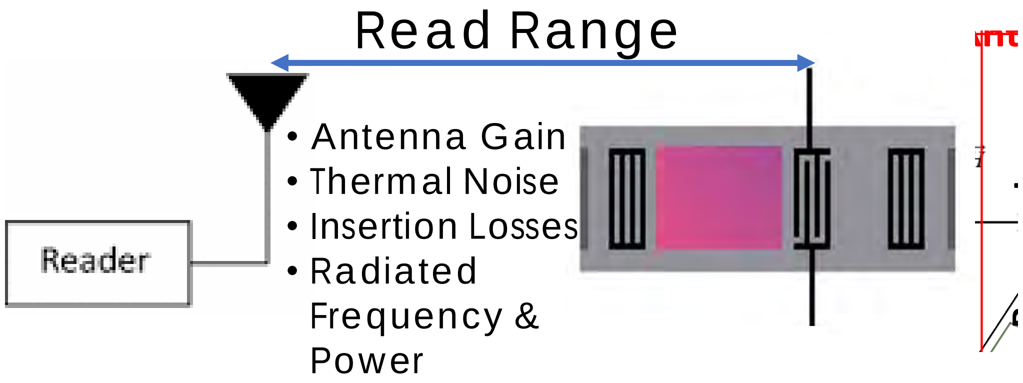


Experiment



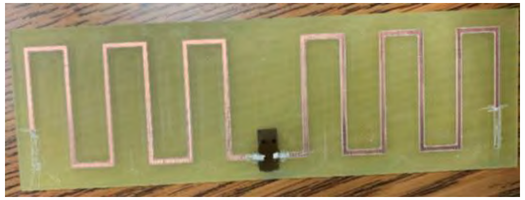
SAW Sensors were developed for liquid phase application and Demonstrated the capability for monitoring iron film corrosion in low pH (acidic) solutions via both simulation and experiments.

Enabling Telemetry for SAW Devices and Pipelines



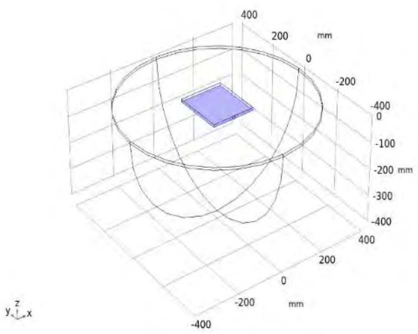
- Telemetry of wireless and passive SAW sensors is similar to radar operation.
- Low loss SAW devices and higher the radiated power to improve the range.

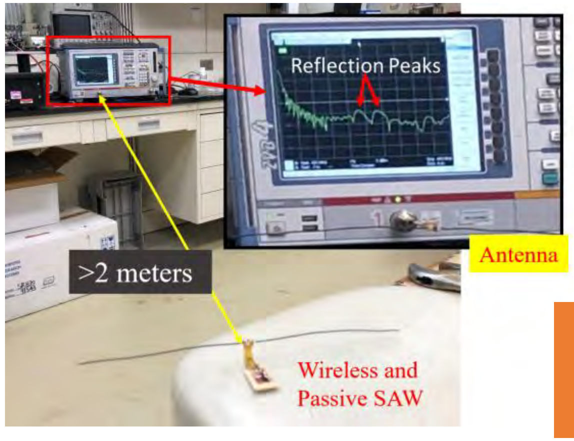
Antenna Design and Fabrication:


Compact Meander Dipole

Wireless Coupling:

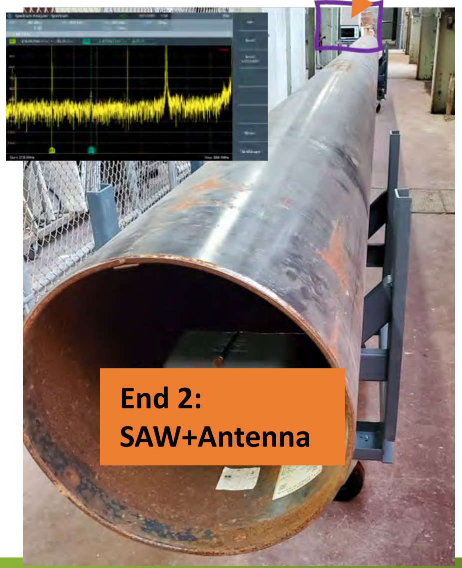
SAW Device + EM Radiator/Receiver





Long Range Telemetry and Interrogation

Wireless Interrogation of SAW Sensors Inside Metal Pipe for 12 meters (40 ft) was Demonstrated in the lab.



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

Field demonstration of Electromagnetic(EM) Wave Propagation Inside a steel Pipe

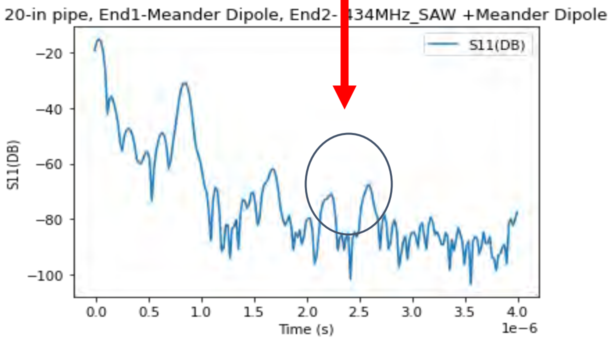
NATIONAL ENERGY TECHNOLOGY LABORATORY

- 230 ft long straight pipes with various diameters

- Curved pipes with flanges

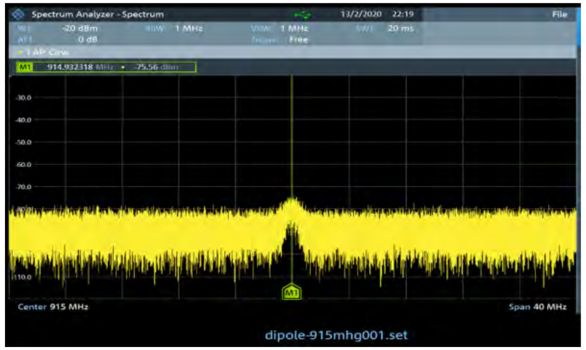
Successful antenna communication (434 MHz in 20'' OD)

Wireless communication of SAW sensor with antenna



Successful antenna communication (856 MHz in 10'' OD)

Curved 8'' OD pipe (915 MHz)

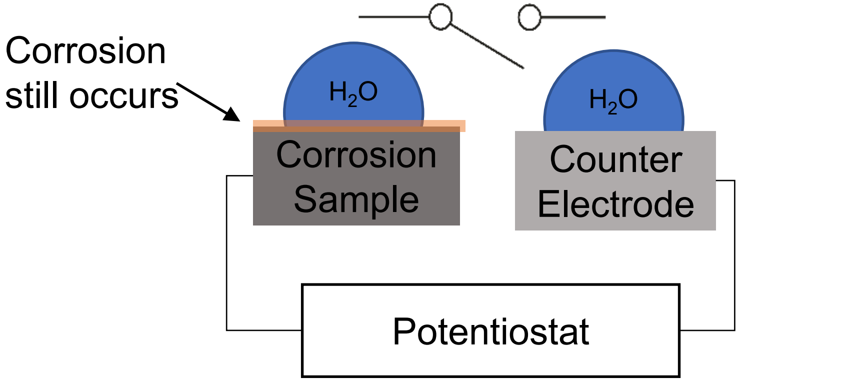


Successful demonstration of wireless RF propagation inside ~70 m long steel pipes

Advanced Electrochemical Sensor (AES)

Traditional electrochemical sensors

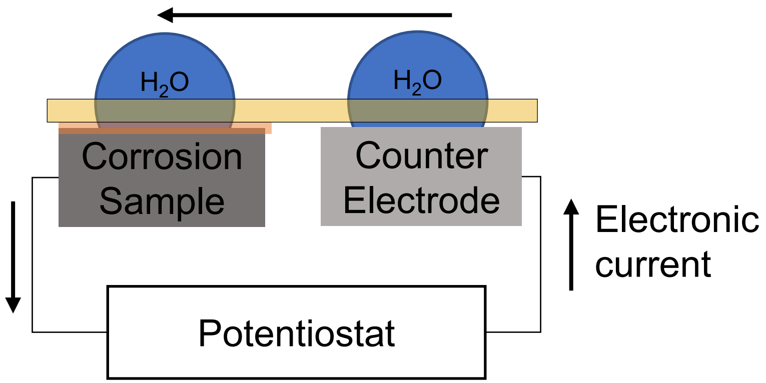
✕ No ionic current path (open circuit error)



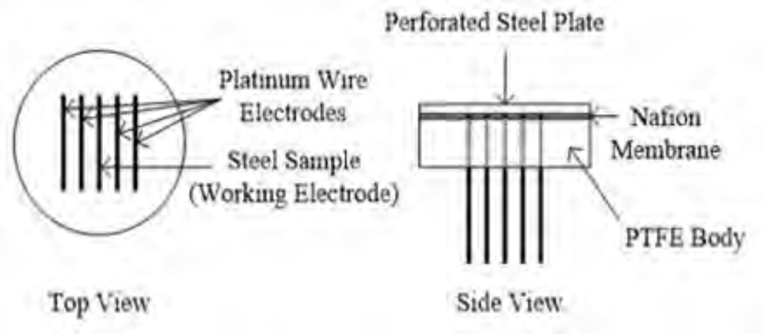
✕ No electrochemical monitoring

Advanced electrochemical sensor

✓ Ionic current provided by membrane



✓ Electrochemical monitoring

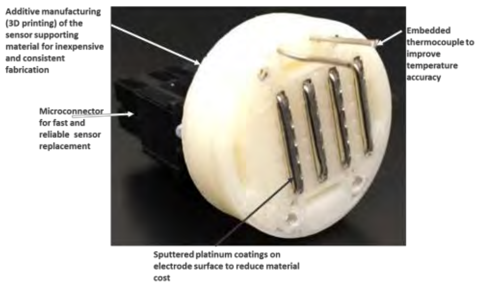


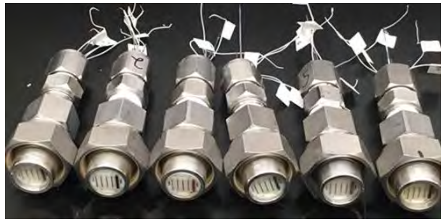
Integration of Ion-conducting Membrane Makes AES Capable of Real-Time In-Situ Monitoring of Water Content, Steel Corrosion Rate, and Pitting / Localized Corrosion Parameters Inside Natural Gas Pipelines.

PennState

AES for Water Content & Corrosion Rate Monitoring

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



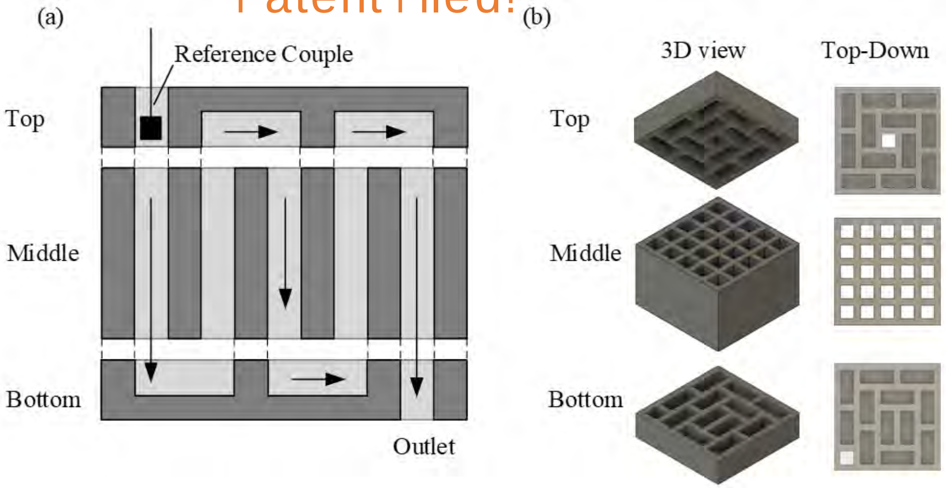


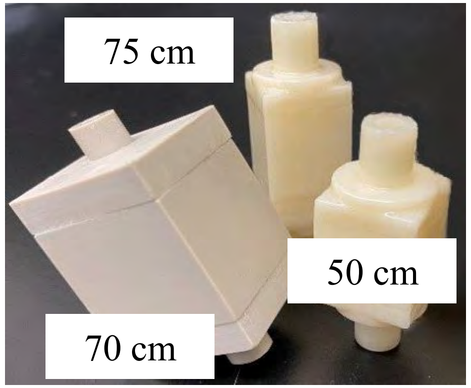
2nd generation AES during testing in water-saturated natural gas at CEESI multi-phase flow facility in 2020.

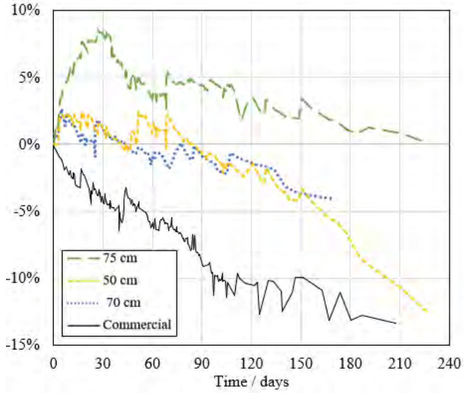
Electrochemical testing equipment is in weather-proof container.

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

Patent Filed!





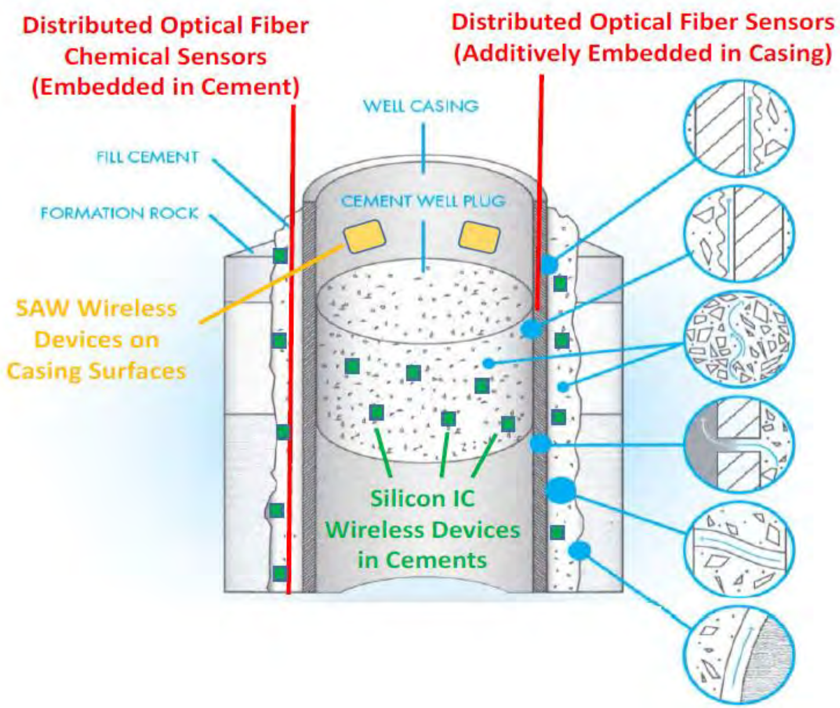


New solid-state reference electrodes (SSRE) outperformed commercial probes in multi-month testing

PennState

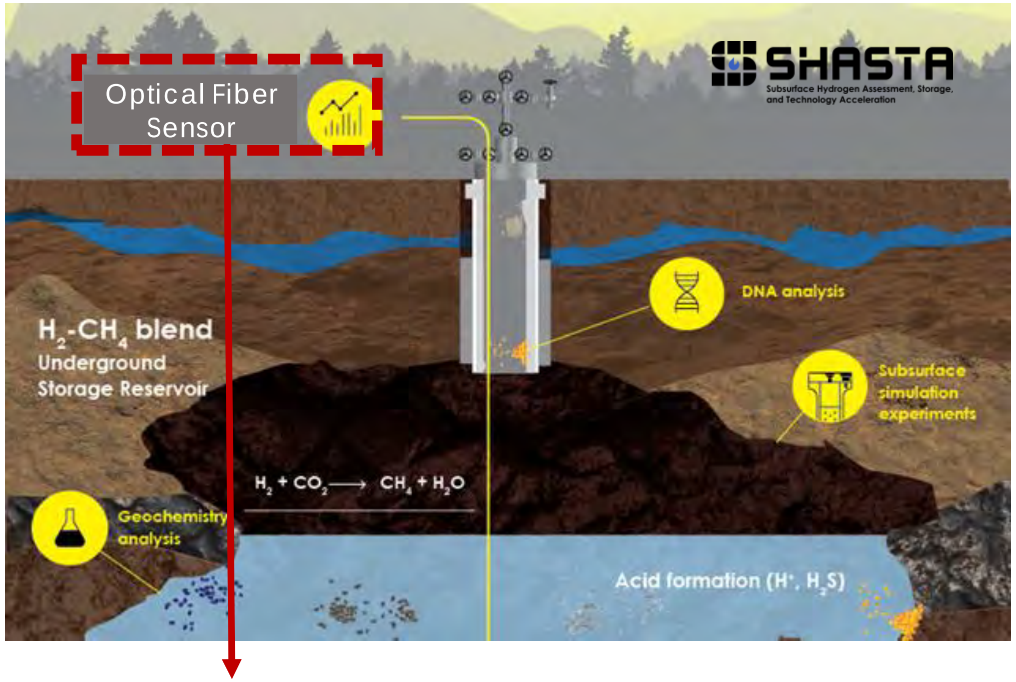
Sensor Technologies for Subsurface CO_2 or H_2-NG Storage

Wellbore Integrity Monitoring (SubTER)



A suite of technologies functionalized for chemical sensing of high priority parameters (**pH, corrosion** onset, etc.).

H_2-NG Subsurface Storage Wells (SHASTA)



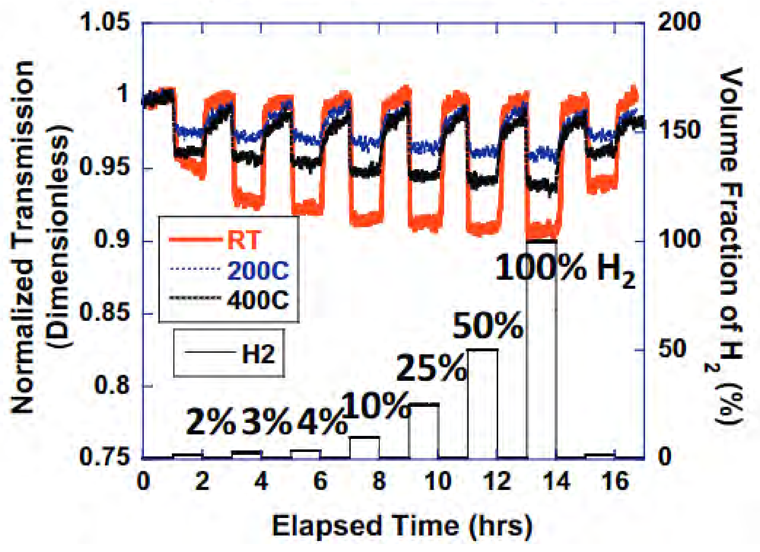
- Subsurface **H_2, CH_4, and pH** monitoring
- Gas Leak and Wellbore Integrity Monitoring

- Challenging harsh conditions in subsurface require reliable and durable sensor technologies.
- Applicable to abandoned wells, geothermal wells, and aquifer.

Optical Fiber Hydrogen Sensor

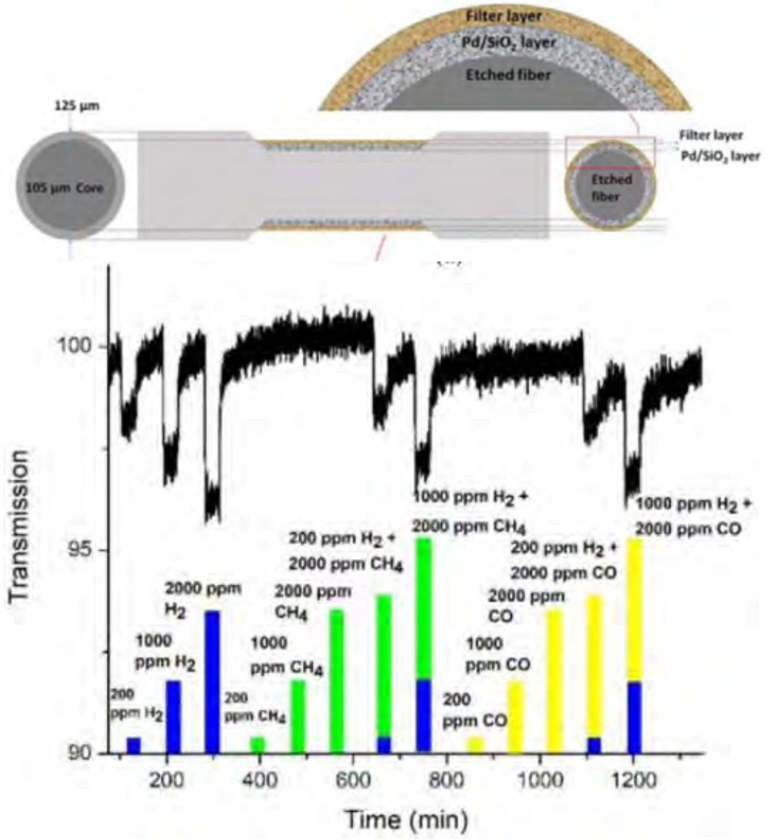
Pd Nanoparticle-Incorporated SiO_2 Thin Film coated Optical Fiber Sensor

H_2 Sensing from RT to 400 °C



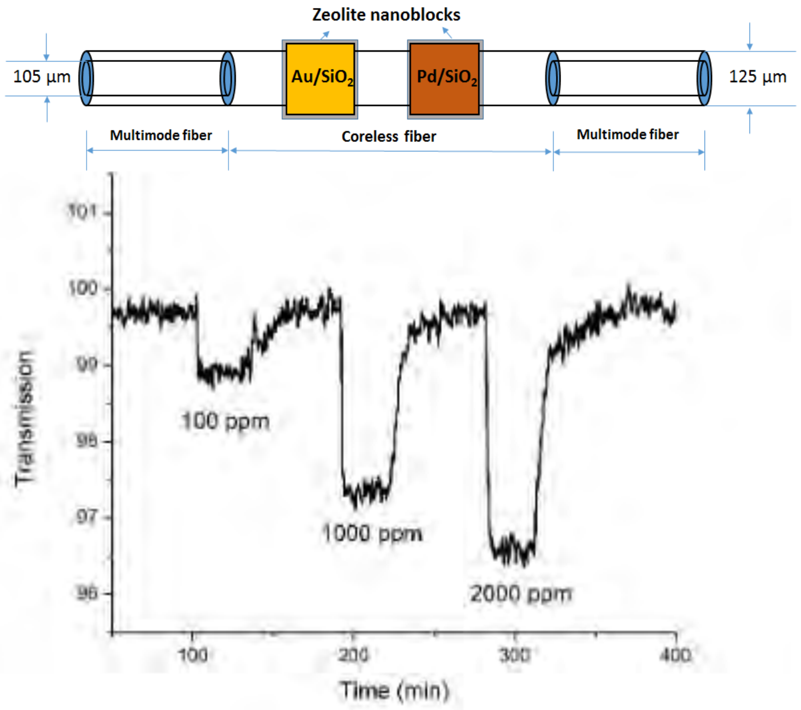
Ref: Ohodnicki et al, Sensors and Actuators B 214 (2015)159–168.

Selective H_2 Sensing with nano-filter layer



Ref: Sun et al, IEEE Sensors Letters, Vol. 1, No. 5, October 2017.

Multi-parameter sensing of H_2 and Temperature

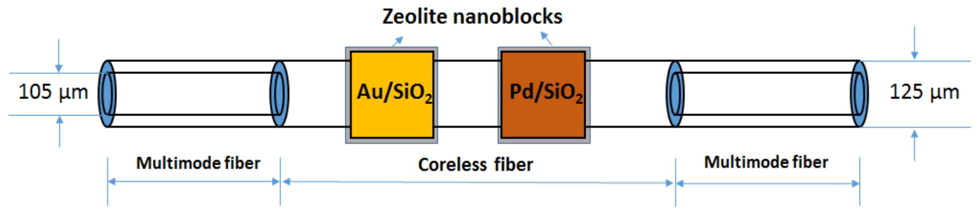


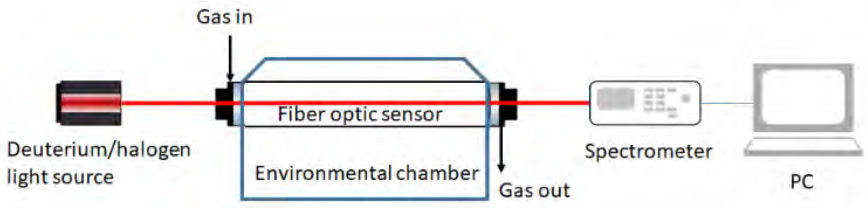
Ref: Sun et al, Proc. SPIE 10654, Fiber Optic Sensors and Applications XV, 1065405 (14May 2018);

Simultaneous Detection of H_2 and Temperature

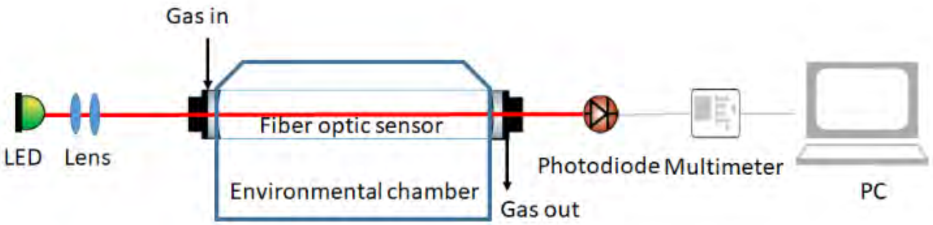
NATIONAL ENERGY TECHNOLOGY LABORATORY

Functionalized Optical Fiber Sensor for H_2 and T

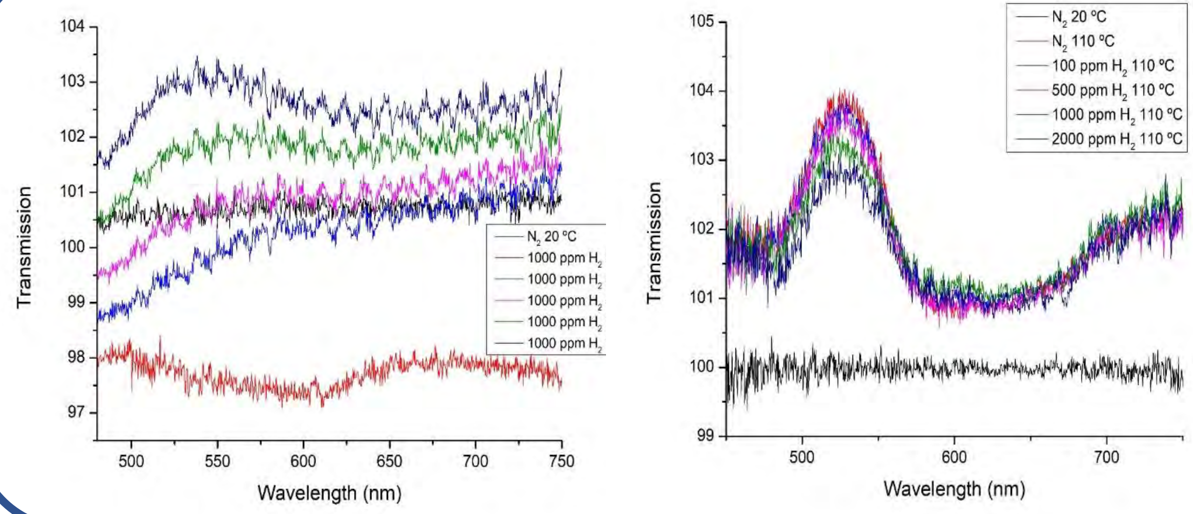




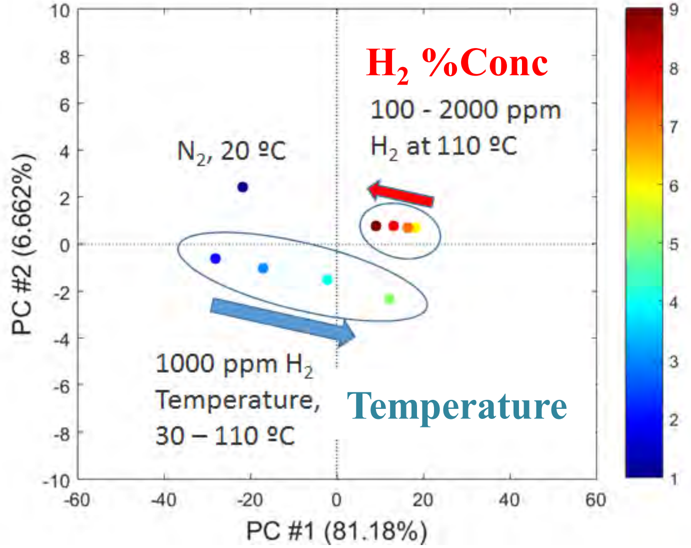
Low-cost Optical Fiber Sensor Design



Simultaneous detection of H_2 and T was achieved through Au-Pd nanoparticles incorporated SiO_2 thin films via Principal Component Analysis (PCA).



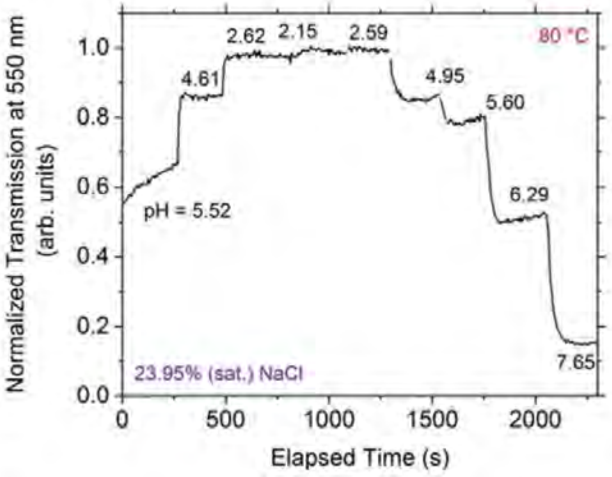
PCA



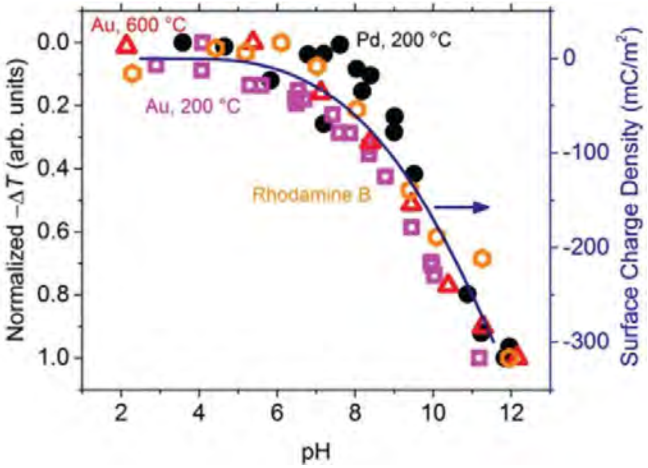
Ref: Sun et al, Proc. SPIE 10654, Fiber Optic Sensors and Applications XV, 1065405 (14May 2018);

Distributed pH Sensing

Au nanoparticles incorporated SiO_2 thin film

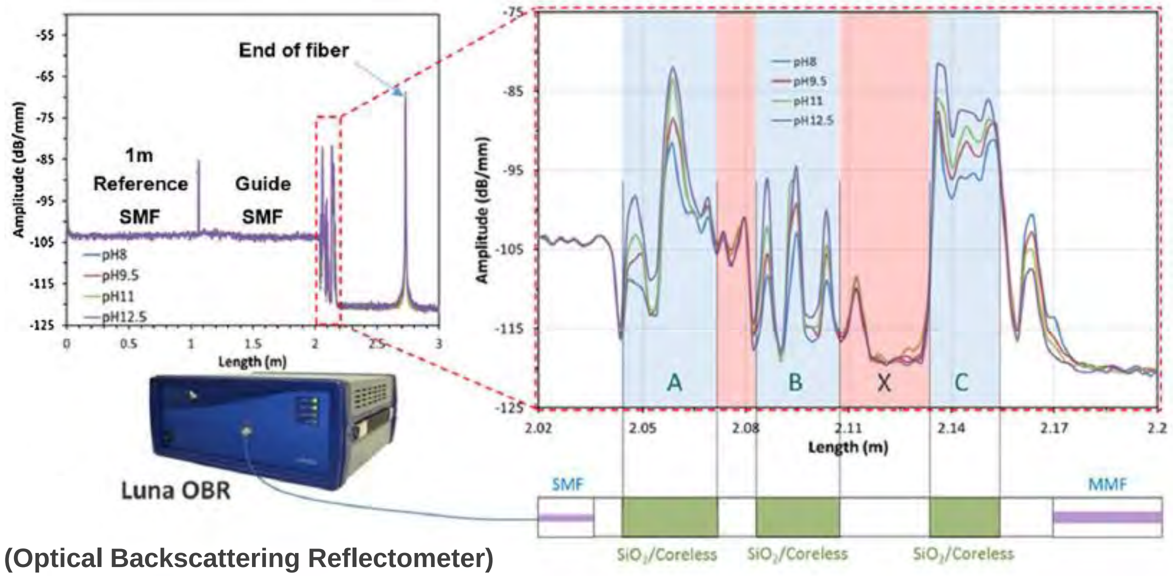


Optically active materials incorporated SiO_2 thin film



Ref: Wang et al, Nanoscale,2015,7,2527–2535

Distributed pH Sensing



(Optical Backscattering Reflectometer)

Ref: Lu et al, Sensors and Actuators B: Chemical, Volume 340, 1 August 2021, 129853

pH sensitivity was demonstrated with optically active materials-incorporated SiO_2 thin film using the optical fiber sensors.

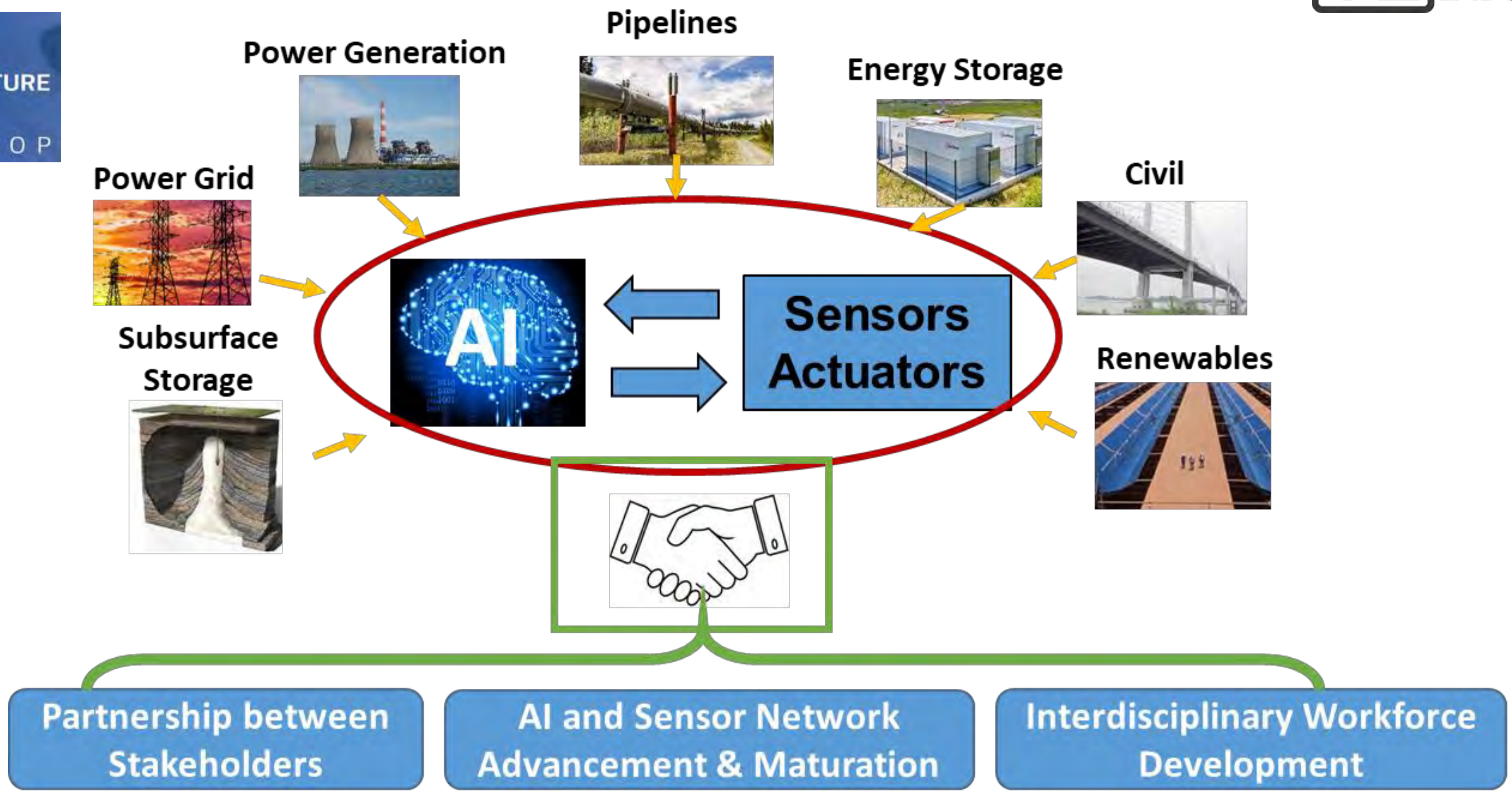
Spatially distributed pH sensing with location information was demonstrated using the optical backscatter reflectometer (OBR) at room temperature. Only the functionalized SiO_2 coated segments have the pH sensitivity.

UPitt-NETL Infrastructure Sensing Collaboration (UPISC)

NATIONAL ENERGY TECHNOLOGY LABORATORY

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING COLLABORATION WORKSHOP

UPittISC Workshop



University, Lab, Industry, and Government Partnerships are Necessary to Maximize Impact

NETL, University of Pittsburgh Sign MOU on Infrastructure Sensor Development | netl.doe.gov

Summary

- Multiple complementary sensor technologies are developed to leverage the advantages of optical, electrochemical, and microwave / wireless sensor platforms, to build an in-situ, multi-parameter, distributed, and cost-effective sensor network for energy infrastructure.
- A wide range of sensing materials are developed to achieve high sensitivity, selectivity, and fast response, including MOF, polymers, metallic films, and nanocomposites.
- Sensing parameters:

  Gas: CO_2, CH_4, H_2, O_2, CO, and other gases;
  Chemical: pH, corrosion, water condensation, ionic strength, salinity, REE;
  Physical: strain, temperature (T), vibration, acoustic

- Artificial intelligence-enhanced sensor network with ubiquitously embedded sensors will ultimately achieve desired visibility across the energy infrastructure.
- Advanced sensors and materials for critical infrastructure and extreme high-T environments.

Acknowledgements and Disclaimer

NATIONAL ENERGY TECHNOLOGY LABORATORY

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