Sensors Development for Pipeline and CO_2 Transport Multi-Modal Monitoring and Leak Detection

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DOE's Roadmap for CO_2 Transport Fundamental Research Workshop

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Disclaimer

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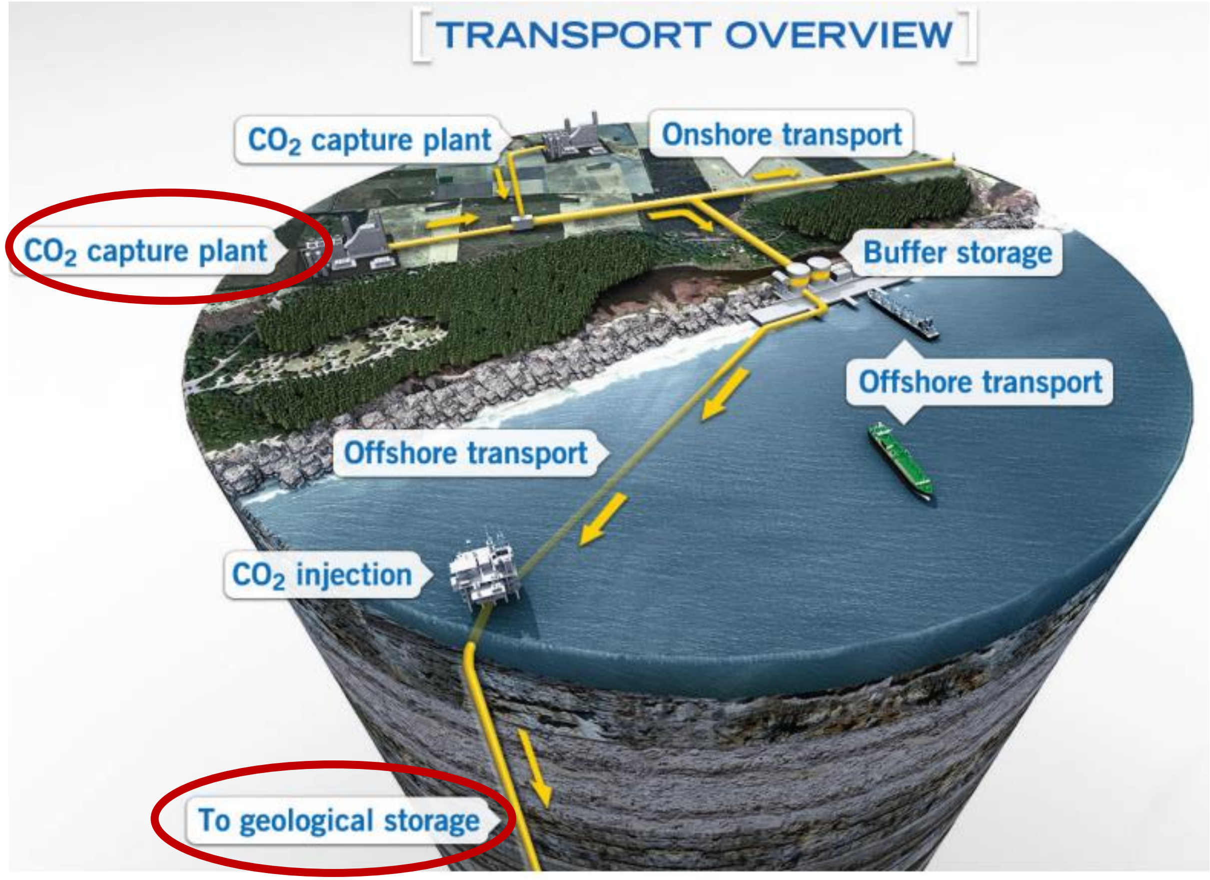
CO_2 Transport from Capture to Storage Sites

- An efficient system is crucial to achieve the mid-century climate goal.
- Pipelines are the most viable means of transport even though small-scale transport is possible by truck, rail, and ship.
- About 5,400 miles of transport pipelines exist in the U.S.
- Significantly more transport infrastructure is to be built over next few decades.
- **Safety and integrity of the system are the key.**



https://www.globalccsinstitute.com/archive/hub/publications/191083/fact-sheet-transporting-co2.pdf

Customer-Based Learning on Natural Gas Pipeline Monitoring Practice

NATIONAL ENERGY TECHNOLOGY LABORATORY

(Energy I-Corps Industry Interviews)

"Regulatory compliances are the major drivers for inspection. The inspection process is a time and labor-consuming process. If any fault happens and goes to leak, it can be a lot of fines. Sometimes, need to pay for local properties as well."

"Over the last 10 years, the whole environmental concerns, including methane emissions, are becoming much more common. So, if you can find that leak the day after the occurrence, so much better."

"Lack of (trained) personnel is the biggest challenge in the industry."

"10 miles long pipe may cost $75k (+$40k city area) on loop closure survey, ~$150k - $250k on pigging, and >$250k for hydro pressure test."

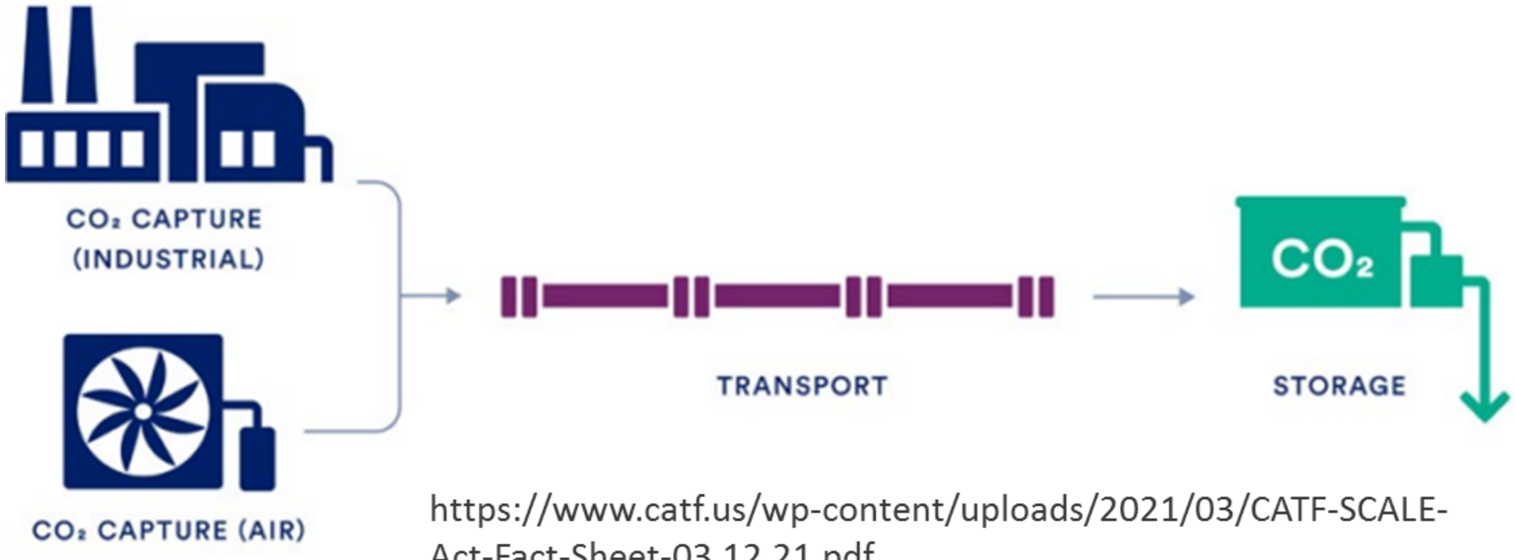
"Localization of leaks is a big problem."

"Shut down of pipes is needed for some cases."

"Low cost is a key factor for gas companies to adopt the technology. Return on investment is critical."

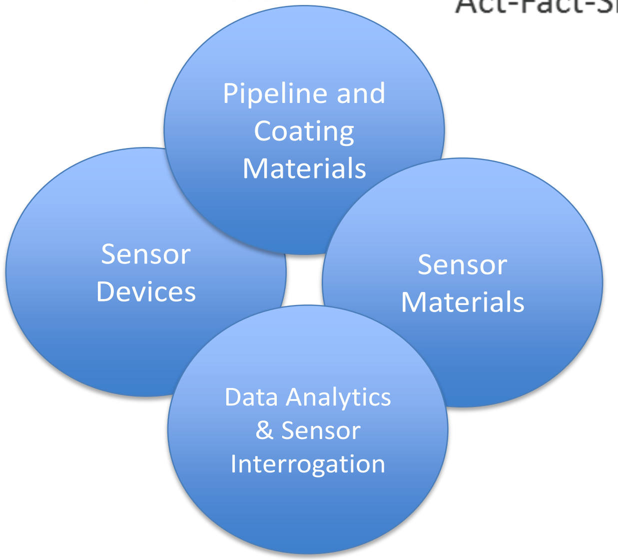
Existing practice for monitoring pipelines is complex – time and labor consuming and costly. The operators intend not to locate the leak or fix unless it is catastrophic.

Integrated Sensors for a Robust Transport System



https://www.catf.us/wp-content/uploads/2021/03/CATF-SCALE-Act-Fact-Sheet-03.12.21.pdf

- A robust transport system incorporated to the capture and storage sites.
- No or minimal disturbance on the mass flow during monitoring/ inspection.
- Alert before failure happens to reduce economic and environmental damages.

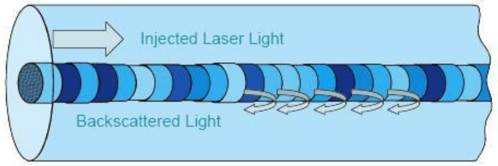


An advanced sensor system having remote, distributed, real-time, and continuous monitoring capability as well as integrated with artificial intelligence methodologies may help improve the reliability, safety, and operation efficiency of infrastructure.

Suite of Pipeline Sensor Technologies at NETL

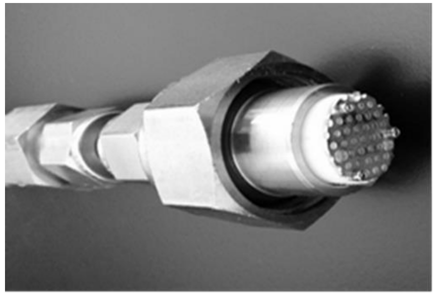
Long-Distance Distributed Optical Fiber Sensors

Imperfections in fiber lead to Rayleigh backscatter:

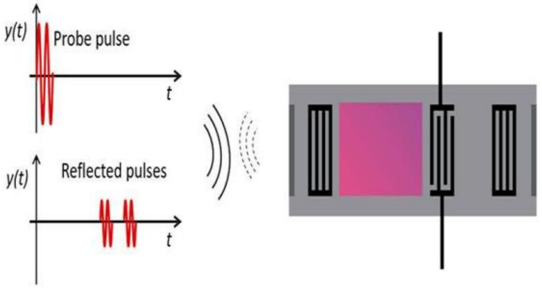


Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

Advanced Electrochemical Sensors



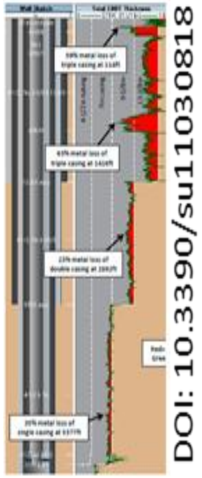
Passive Wireless Sensors



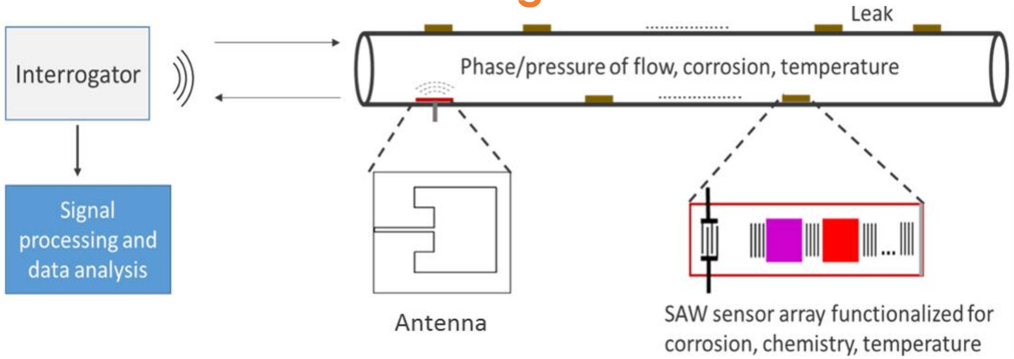
	Geospatial Attributes	Cost	Targeted Function
Distributed Optical Fiber Sensors	Linear Sensor Adjustable Distance and Resolution	Low Cost Per Sensor "Node"	Temperature, Strain, Gas Chemistry (CH_4, CO_2, H_2O, H_2, etc.) Early Corrosion Detection
Passive Wireless Sensors	Point Sensor	Low	Temperature,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

Synergistic sensor platforms with complementary cost, performance, and geospatial characteristics are being developed with emphasis on corrosion, gas, and chemical sensing.

Envision of Sensor Deployment for Long Pipeline Monitoring

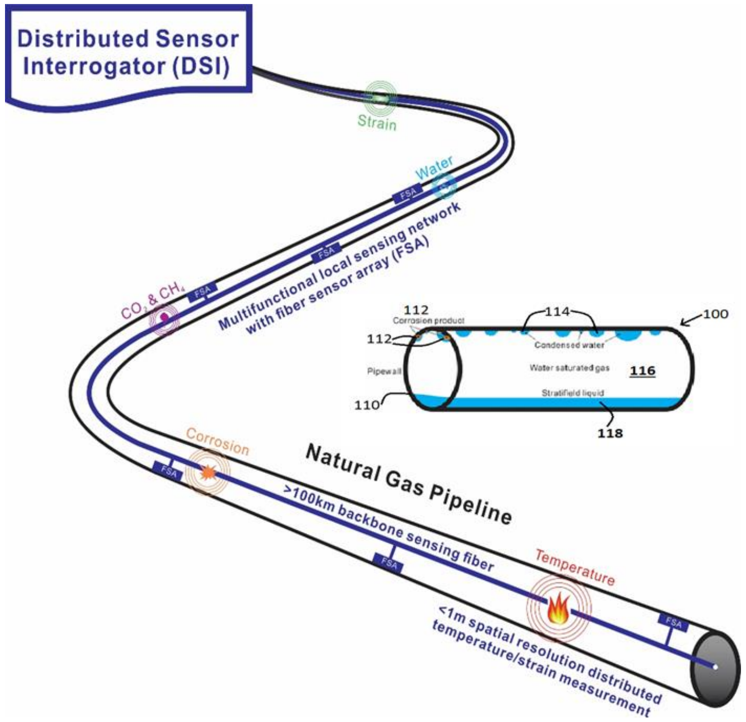


Microwave-based sensors for pipelines, well-bore, and boiler-tube monitoring.



(Patented to NETL: No. US 11,113,594 B2)

Distributed fiber-optic sensor network for sensing the corrosion onset and quantification.



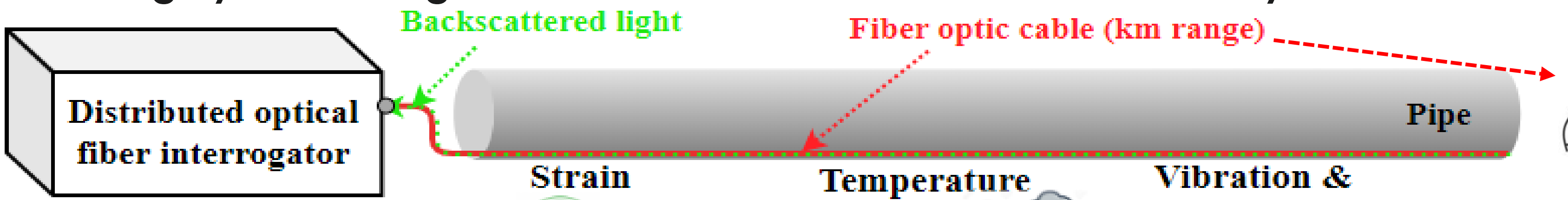
(US Patent App. 16/149,774)

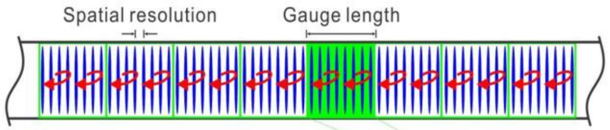
- Hundreds of sensors are possible in one cable for multi-parameters.
- A wide range of distributed interrogation techniques are possible.
- Interrogation technique to be selected based on application.
- Incorporation of machine learning/artificial intelligence helps to enhance performance.

Distributed fiber optic and wireless passive microwave sensors are attractive for infrastructure monitoring (stability, reliability, harsh environment, remote).

Distributed Optical Fiber Interrogator Development

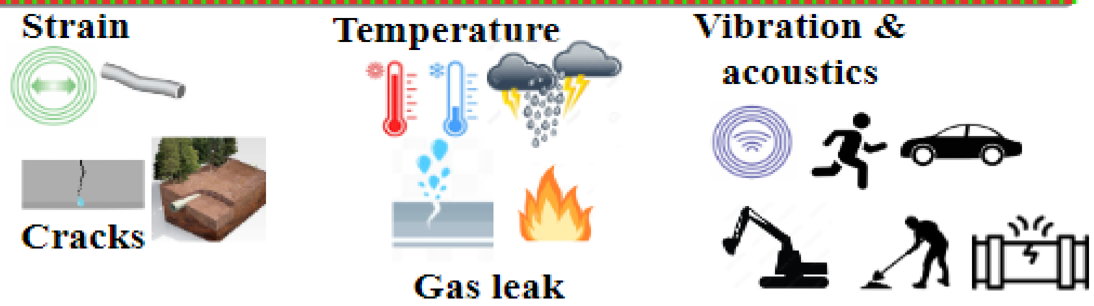
Pipeline integrity monitoring based on various distributed fiber sensor systems.

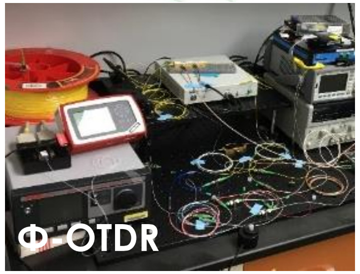


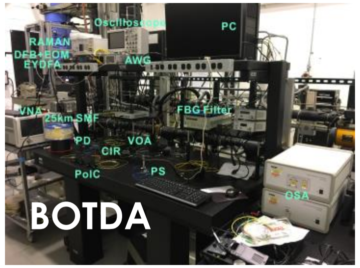


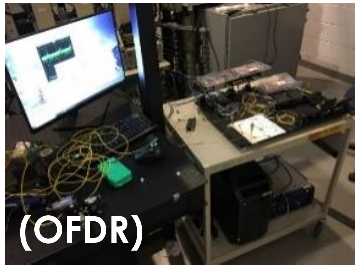
Sensing information with location:

- Leak detection
- Flow monitoring
- Developing cracks/deformation
- Temperature distribution along pipe
- Seismic events/intrusion detection
- Remote monitoring







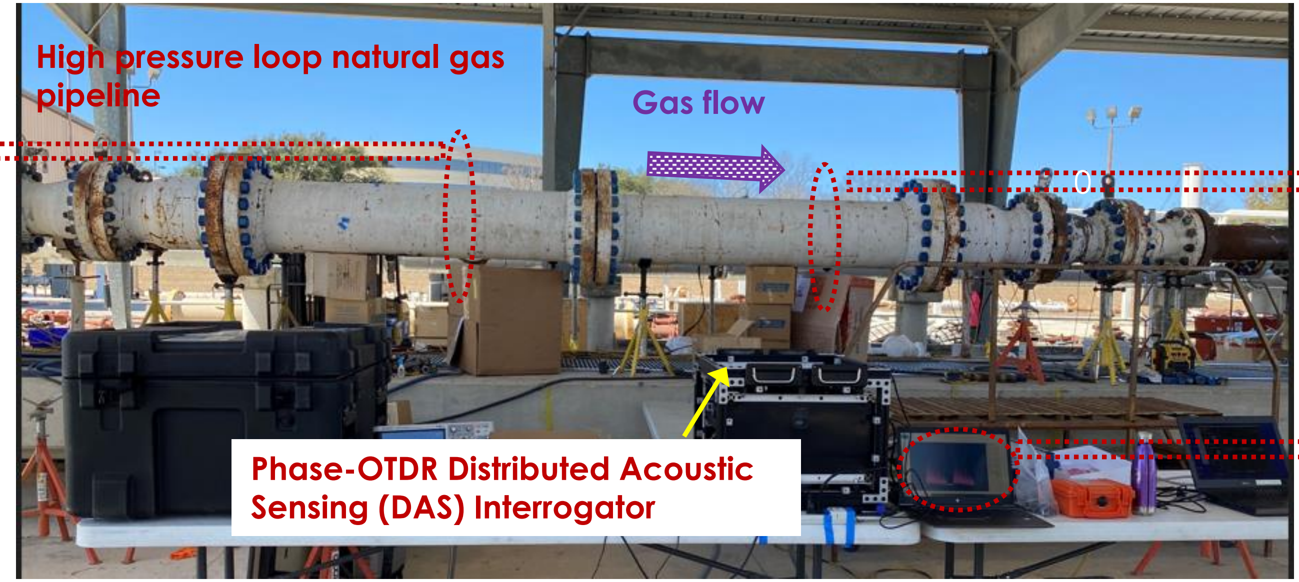


In-House NETL Distributed Optical Fiber Sensor Interrogators

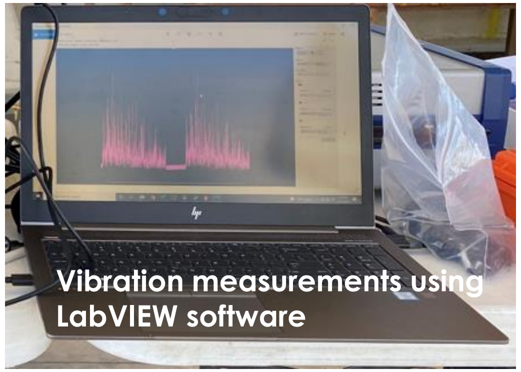
Technology	Sensing range	Spatial resolution	Measurement time	Target parameter
Rayleigh phase-OTDR (optical time domain reflectometry)	Kilometers	Meters	Seconds	Acoustic/vibrations
Brillouin- OTDA (optical time domain analyzer)	Tens of kilometer	Centimeter to meter	Minutes	Temperature and strain
Rayleigh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

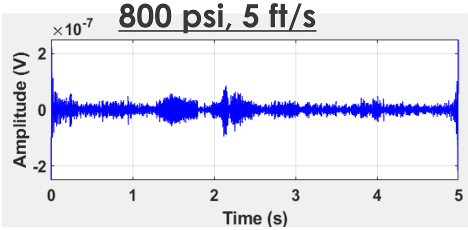
Multiple distributed optical fiber sensing platforms have been developed to enable structural health monitoring of pipeline and other infrastructure.

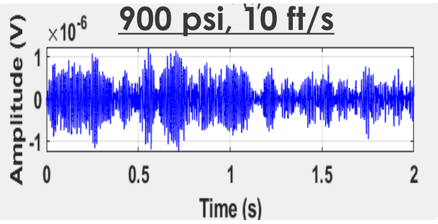
Pilot-Scale Test of Phase-OTDR Distributed Acoustic Sensing in a High-Pressure Natural Gas Pipeline

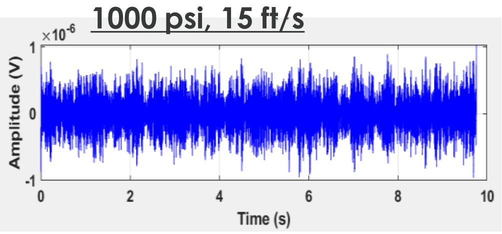


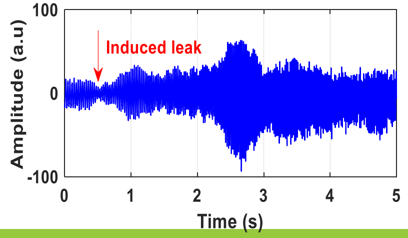
Installed fiber acoustic sensor on pipeline



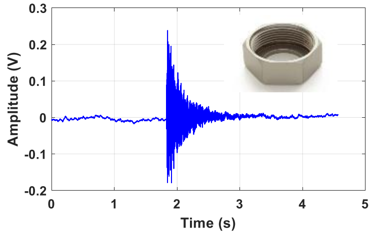








Drop a stainless-steel hex nut on pipe



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

AI-Enhanced Distributed Optical Fiber Sensor Network

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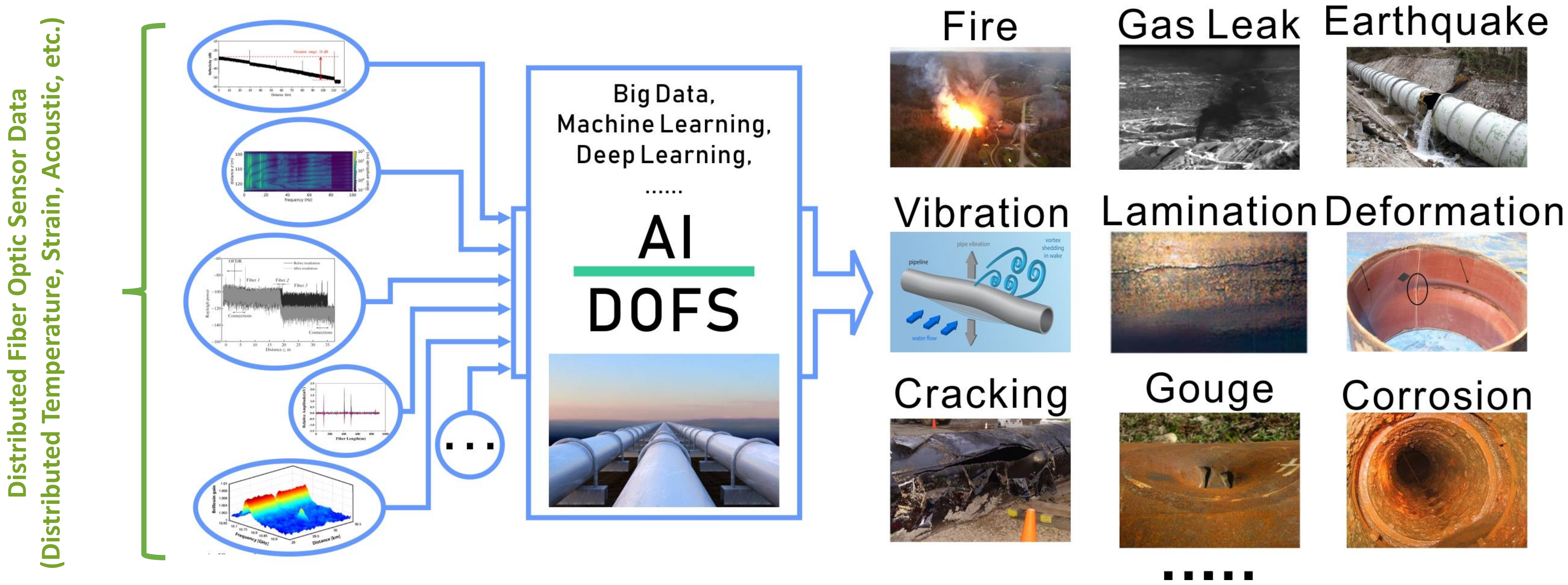
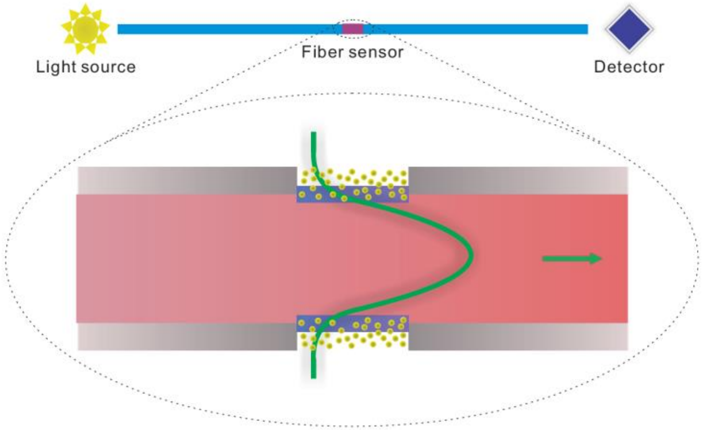
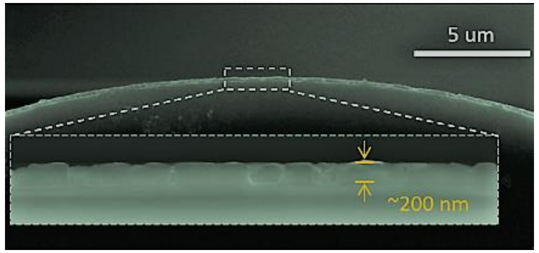
Fiber optic-based distributed sensing technology integrated with advanced analytics including pattern and feature recognition can convert large datasets to actionable information.



Gas Sensing Materials Enabled CH_4 and CO_2 Gas Sensors

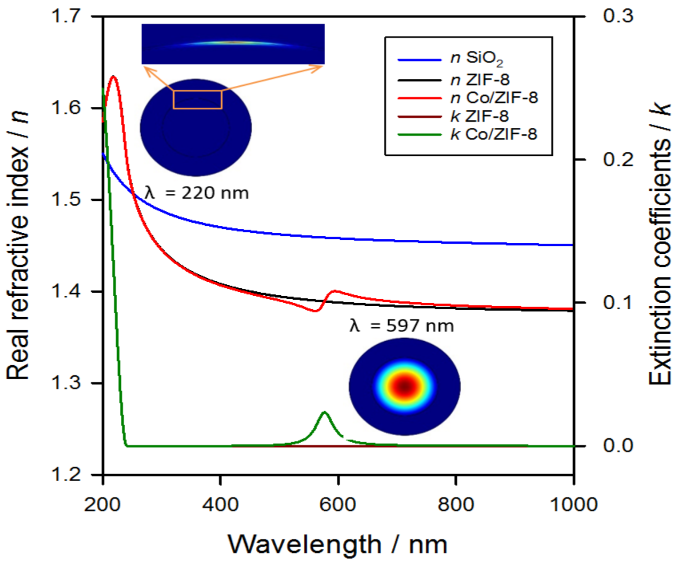
Thin Film Coated Sensing Elements

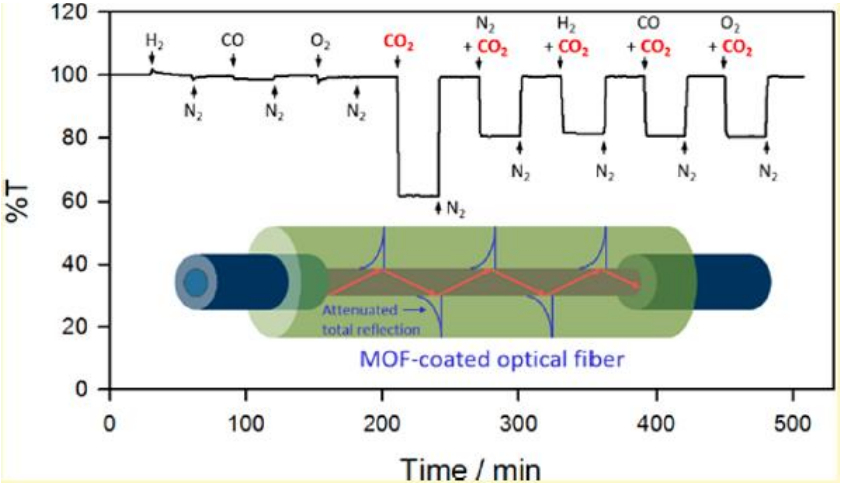


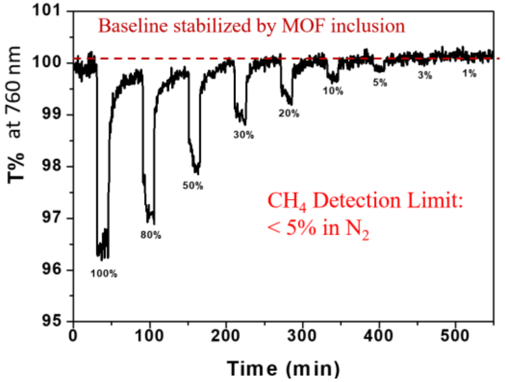


Evanescent Wave Absorption-Based Sensors

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





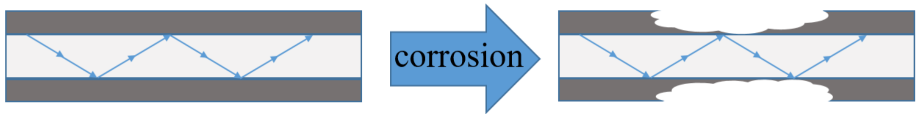


Integration of fiber optic sensors with engineered functional materials enables gas sensing.

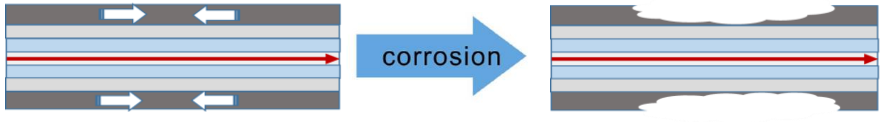
Pipeline Corrosion Sensing and Early On-Set Detection

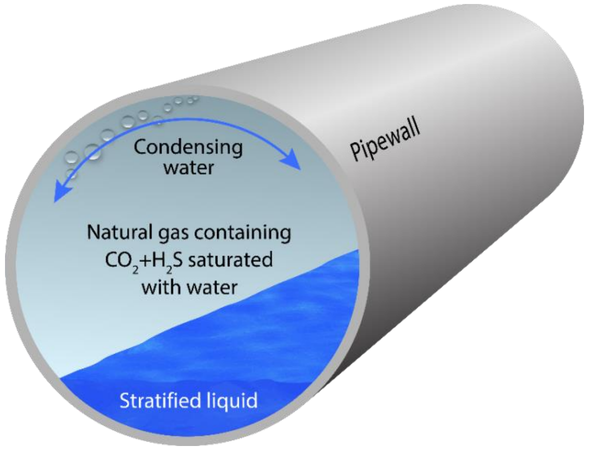
Metallic Film Coated Optical Fibers

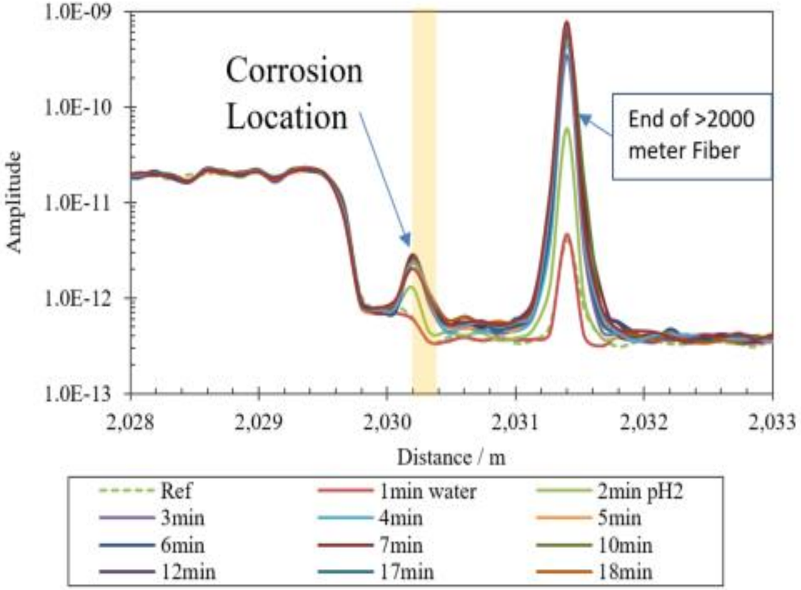
Optical Power-Based

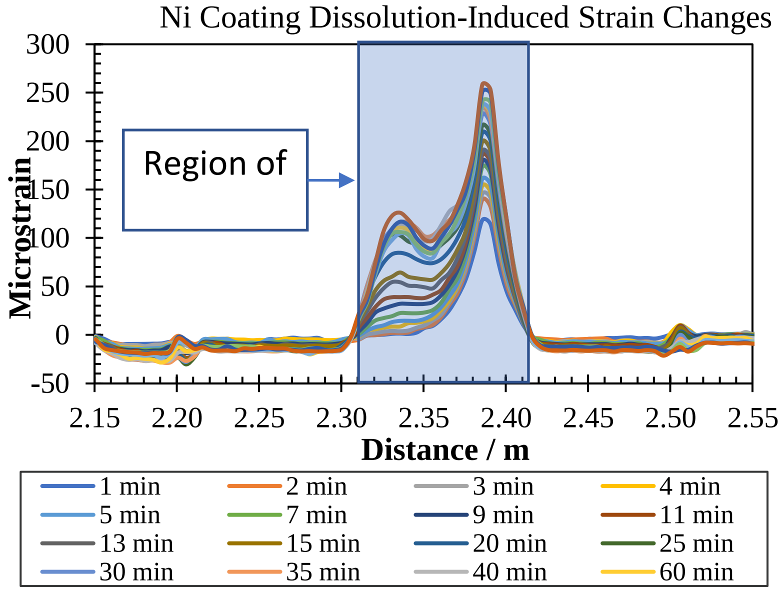


Strain-Based



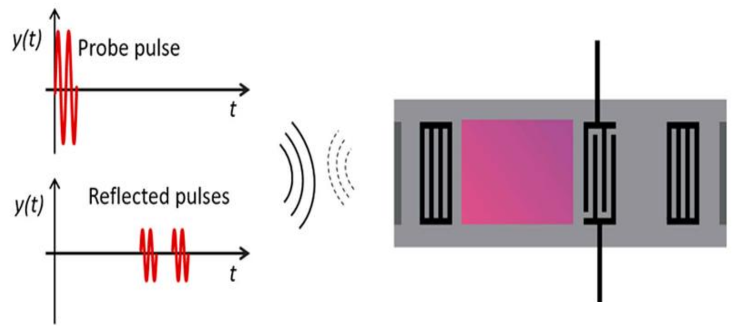




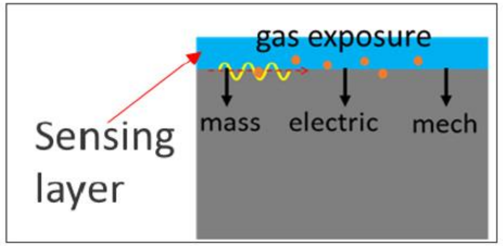


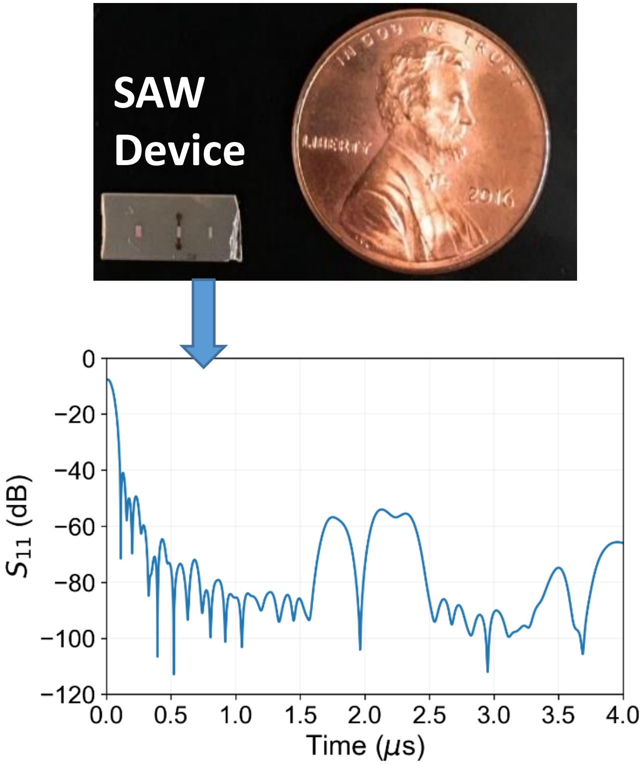
Corrosion can be detected and located along the optical fiber, which enables distributive corrosion monitoring for long-distance pipelines.

Passive Wireless Surface Acoustic Wave Sensors

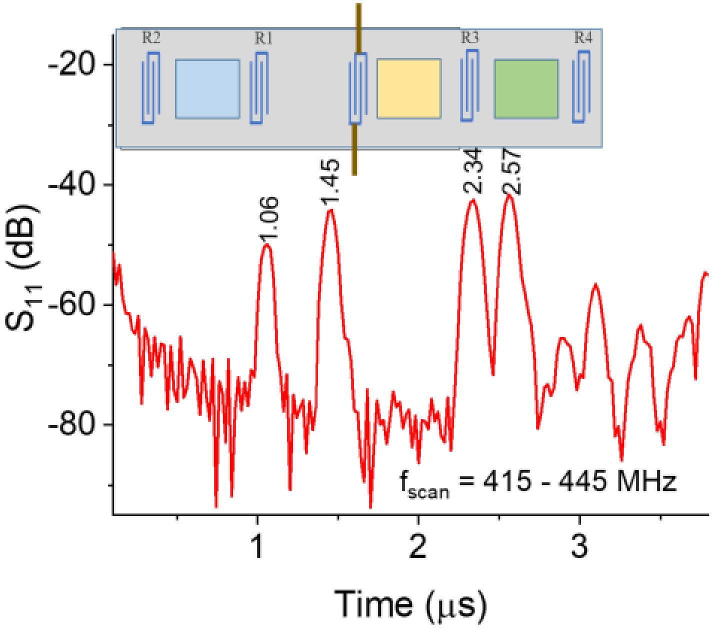


$$\frac{\Delta v}{v_0} = \frac{\Delta f}{f_0} = \frac{\Delta \phi}{\phi_0}$$





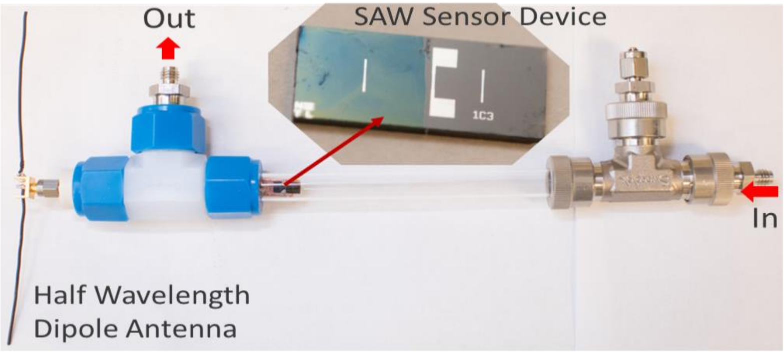
SAW Sensor Array for Multiple Gases

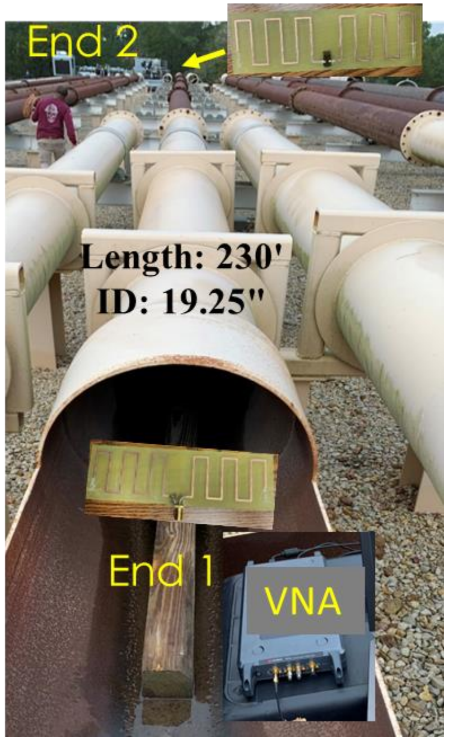


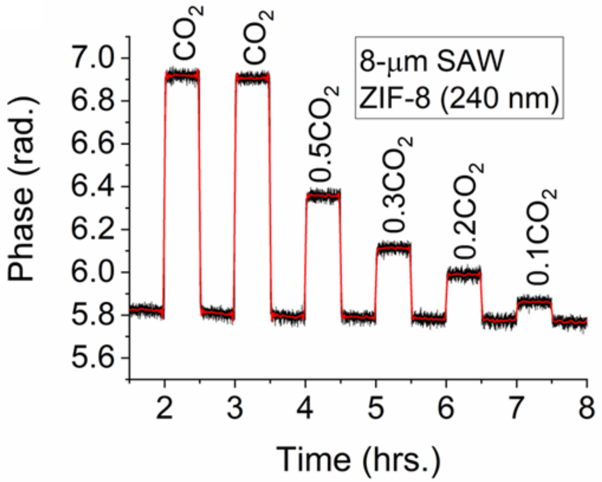
Small (~5x5 cm²), Low Cost (~ $1.00 /device + antenna installed) ubiquitous wireless sensors deployed externally and internally to the pipeline.

Target Metrics ~ 1 km interrogation distance in-pipe, cost <$2/m total (telemetry + devices).

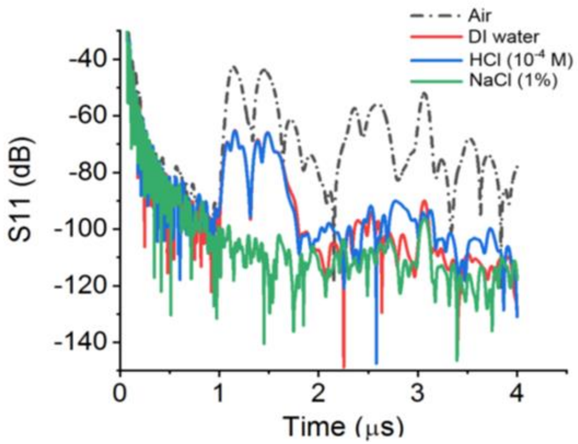
Passive Wireless Point Sensors for Pipelines







Wireless CO_2 Sensing



pH Sensing

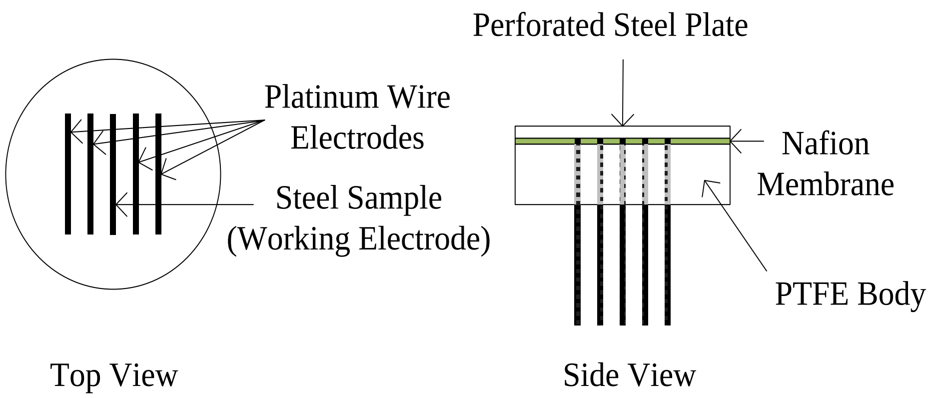
Long Distance Interrogation Inside Metal Pipes

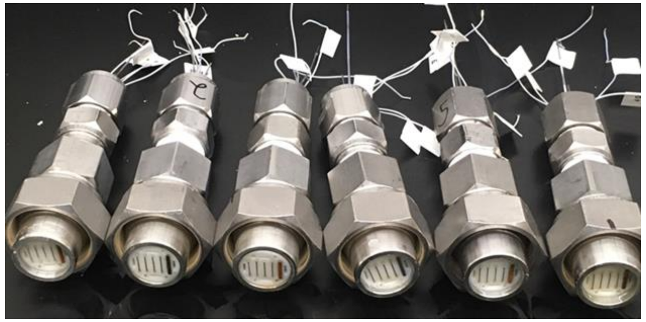
Low-cost SAW devices are attractive sensors for monitoring CO_2 transport pipes at long distances.

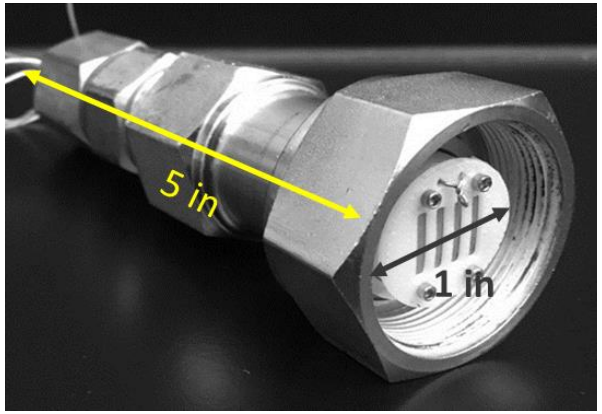
Multifunctional Advanced Electrochemical Sensors

In collaboration with Pennsylvania State University

Conductivity & Corrosion Monitoring







- Capable of remote in-situ monitoring
- Capable of measurements in non-aqueous phases
- Easy to install
- Successful field test

Electrochemical sensors for quantification of corrosion rates and environmental monitoring (humidity, water content, etc.).

NETL R&IC Capability: Sensor Platforms and Materials for Critical Infrastructure and Extreme Environments

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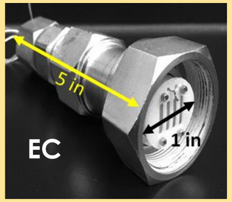
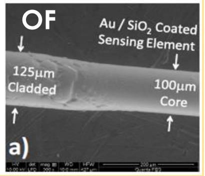
Advanced sensors for energy efficiency, safety, resilience, and sustainability:

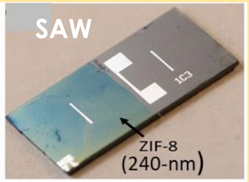
- ✓ Monitor systems and conditions
- ✓ Improve performance & efficiency
- ✓ Enhance reliability and safety
- ➢ Temp, acoustics, chemical, gas, corrosion
- ➢ Composite nano-materials, thin films and fiber optics, sensor devices development

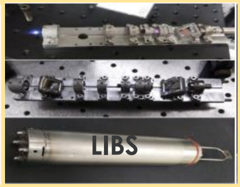
Multiple Sensor Platforms

- Distributed Optical Fiber (OF)
- Surface Acoustic Wave (SAW)
- Electrochemical (EC)
- Laser-induced breakdown spectroscopy (LIBS)
- Raman









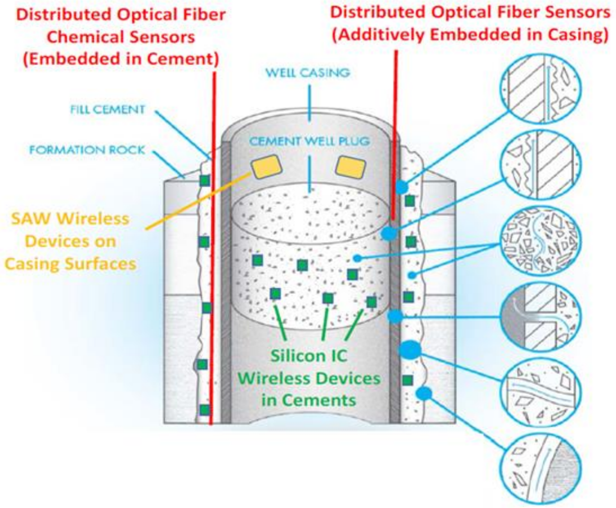
GENERATION

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

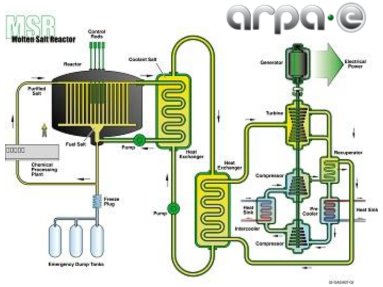
ENERGY DELIVERY & STORAGE

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.

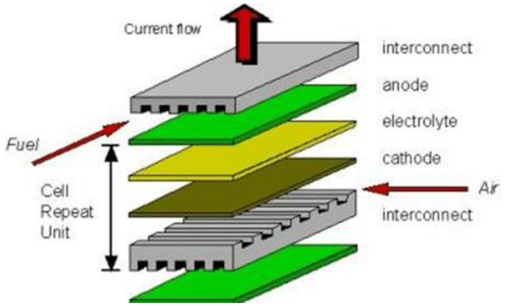


Subsurface: Wellbore integrity, failure prediction, leak detection. Geologic storage of CO_2, H_2/NG, or abandoned wells.



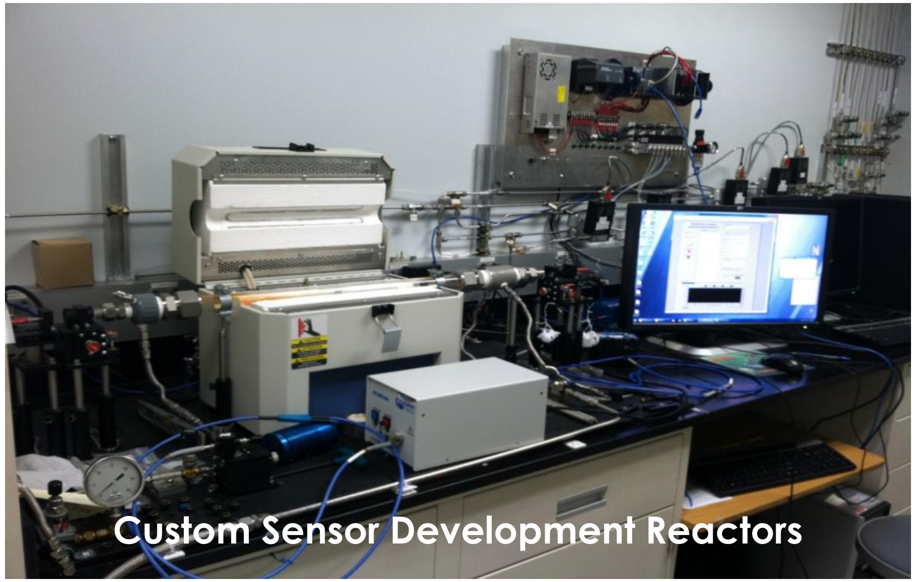
Nuclear: Core monitoring and molten salt temperatures for reactor fuel efficiency and reactor safety.

Solid Oxide Fuel Cells (SOFC): Fuel concentration and temperature gradients for improved lifetime and efficiency.



NETL R&IC Facility: Sensor Preparation and Test Equipment

Custom sensor development reactors simulate:
- Power generation and combustion systems
- Subsurface/geological environments
- Pressurized gas and oil-based systems



Automated High Pressure High Temperature (HPHT) Reactors

Reel-to-Reel Coating for Optical Fiber Sensors

NETL has established capabilities and a number of well-equipped laboratories to enable new sensor material and device research and development activities.

NETL R&IC Capability: Technical Team

NATIONAL ENERGY TECHNOLOGY LABORATORY

Federal Staffs, Contract Scientists, ORISE Fellows, and External Collaborators

Dr. Ruishu Wright
Dr. Michael Buric
Dr. Benjamin Chorpening
Dr. Dustin McIntyre
Dr. Omer Dogan

Dr. Jagannath Devkota
Mr. Richard Pingree
Dr. Nageswara Lalam
Dr. Matthew Brister
Dr. Hari Bhatta
Dr. Sandeep Bukka

Dr. Jeffrey Wuenschell
Dr. Jeffrey Culp
Dr. Alexander Shumski
Dr. Ki-Joong Kim
Dr. Scott Crawford
Mr. Nathan Diemler
Dr. Daejin Kim
Dr. Krista Bullard

University of Pittsburgh
- Dr. Paul Ohodnicki
- Dr. Kevin Chen

Carnegie Mellon University
- Dr. David W. Greve

Pennsylvania State University
- Derek Hall

Highly interdisciplinary team consisting of sensor device and interrogator experts, materials scientists, and data scientists.

Key Take-Aways and Next Steps

NATIONAL ENERGY TECHNOLOGY LABORATORY

- It is critical to monitor CO_2 pipeline integrity and leaks in real-time to predict failures, reduce emissions, and increase efficiency.
- Conventional pipeline monitoring techniques are complex and are limited in capability to identify failures before they occur.
- Advanced sensor technologies are being developed at NETL to enable low cost, low maintenance, distributed monitoring of pipeline corrosion rates and gas stream chemistry in real-time. The sensor technologies can support in-situ CO_2 pipeline monitoring and leak detection.

- Increase the technology readiness level of the sensor technologies for low-concentration gas sensing and structural health monitoring.
- Leverage sensors platforms, advanced materials, and data analytics methodologies that being developed for Natural Gas pipelines for CO_2 pipeline-relevant parameters including structural health and gas chemistry.
- Artificial intelligence-enhanced sensor network with ubiquitously embedded sensors to achieve desired visibility across the energy infrastructure.
- Engage stakeholders including research institutes, industries, and regulatory boards.

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