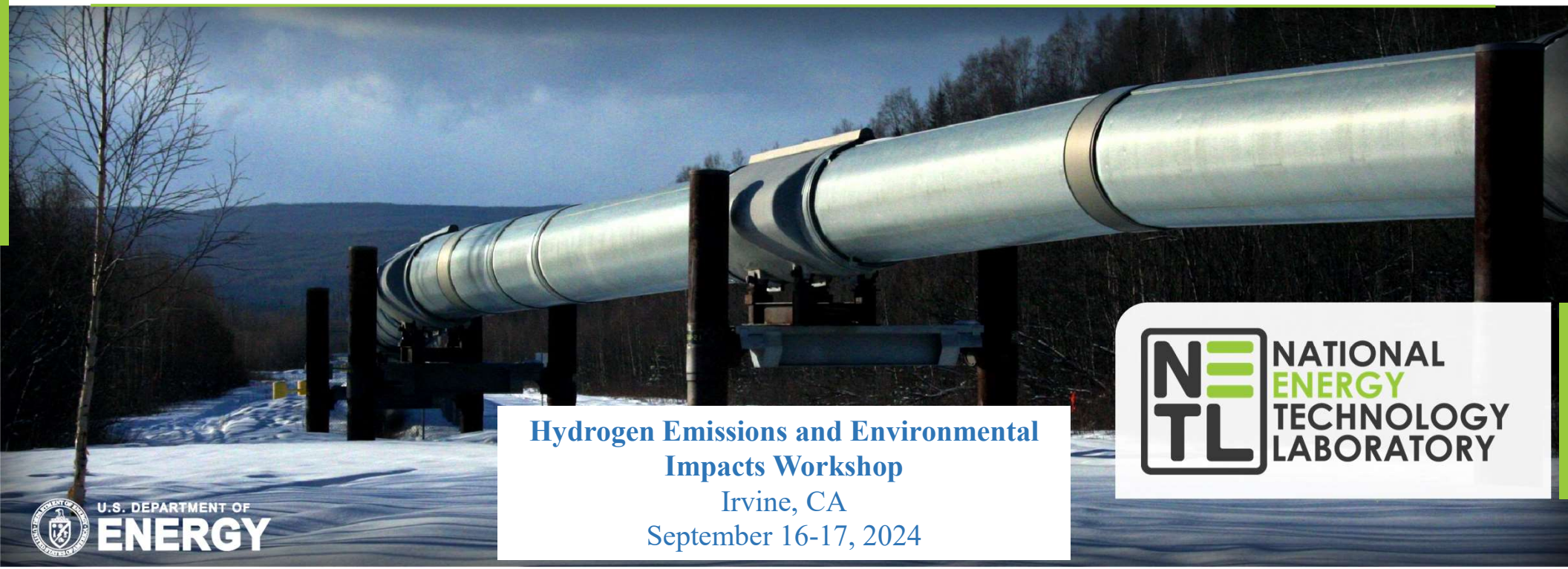
Advanced Sensors for Real-time Pipeline Monitoring

Presenter: **Ruishu F. Wright, PhD**
Technical Portfolio Lead
Research and Innovation Center
National Energy Technology Laboratory



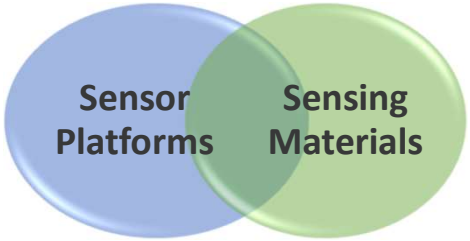
Hydrogen Emissions and Environmental Impacts Workshop
Irvine, CA
September 16-17, 2024

Sensor Materials for Critical Infrastructure and Extreme Environments

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

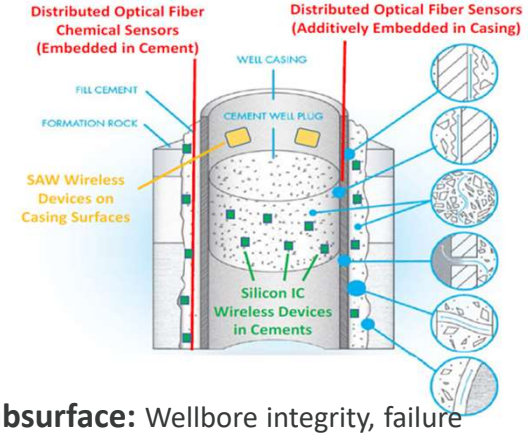
- ✓ Monitor systems and conditions
- ✓ Improve performance & efficiency
- ✓ Enhance reliability & safety
- ➢ Temp, acoustics, chemical, gas, corrosion
- ➢ Composite nano-materials, thin films & fiber optics, sensor devices development



Energy Delivery & Storage

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

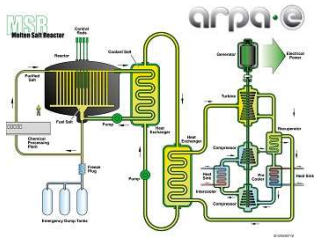
Grid: Transformer, powerline failure prediction, fault detection, state awareness



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

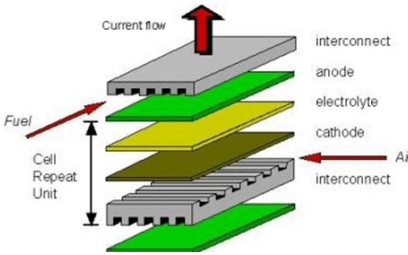
Generation

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



Repurpose of Natural Gas Infrastructure for Hydrogen Use

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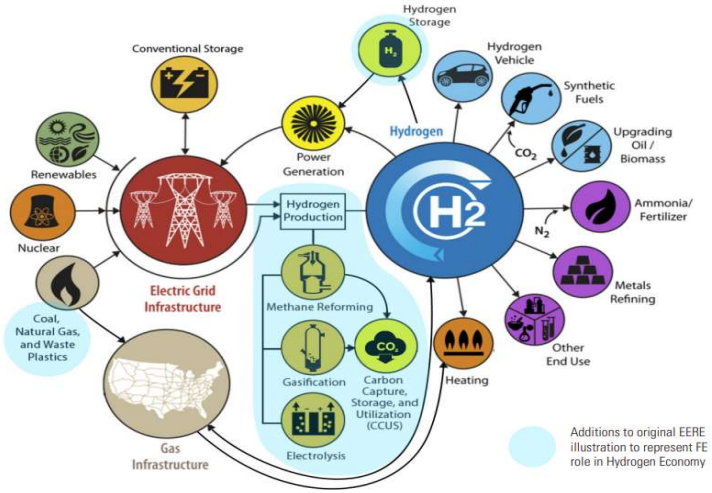
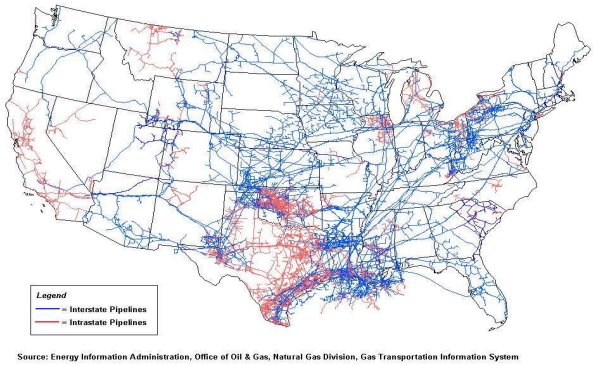
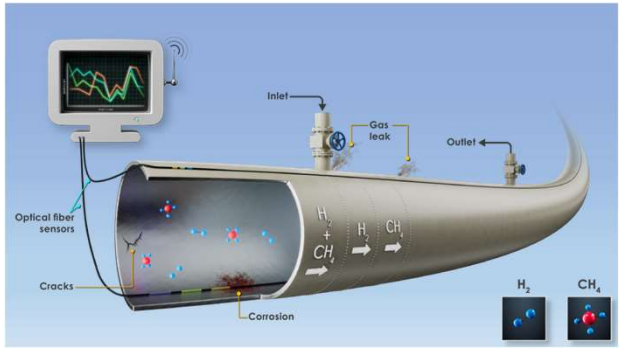
H2@Scale





HyBlend Pipeline Monitoring



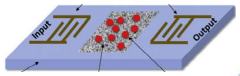
PHMSA Data:
NG Transmission Pipeline: **298,353 miles**
NG Distribution Pipeline: **2,296,214 miles**
Hydrogen Transmission Pipelines: **1,567 miles**
Hydrogen Distribution Main Pipelines: **1 mile**

- **NETL has established Natural Gas Infrastructure Program since 2016 to Quantify and Mitigate Midstream Methane Emission. NG decarbonization and Hydrogen Technology Program since 2022.**
- **Pipeline Sensors address pipeline reliability, public safety, operational efficiency, and flexibility.**

State of the Art of Hydrogen Sensors

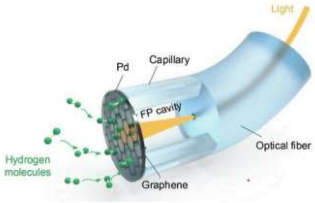
(*Chemistry Select 2020, 5, 7277-7297*)

(**P**: Physical change, **A**: Advantage, **D**: Disadvantage)

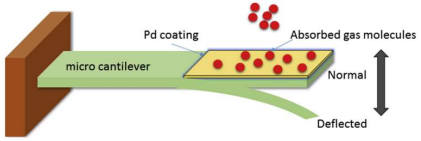


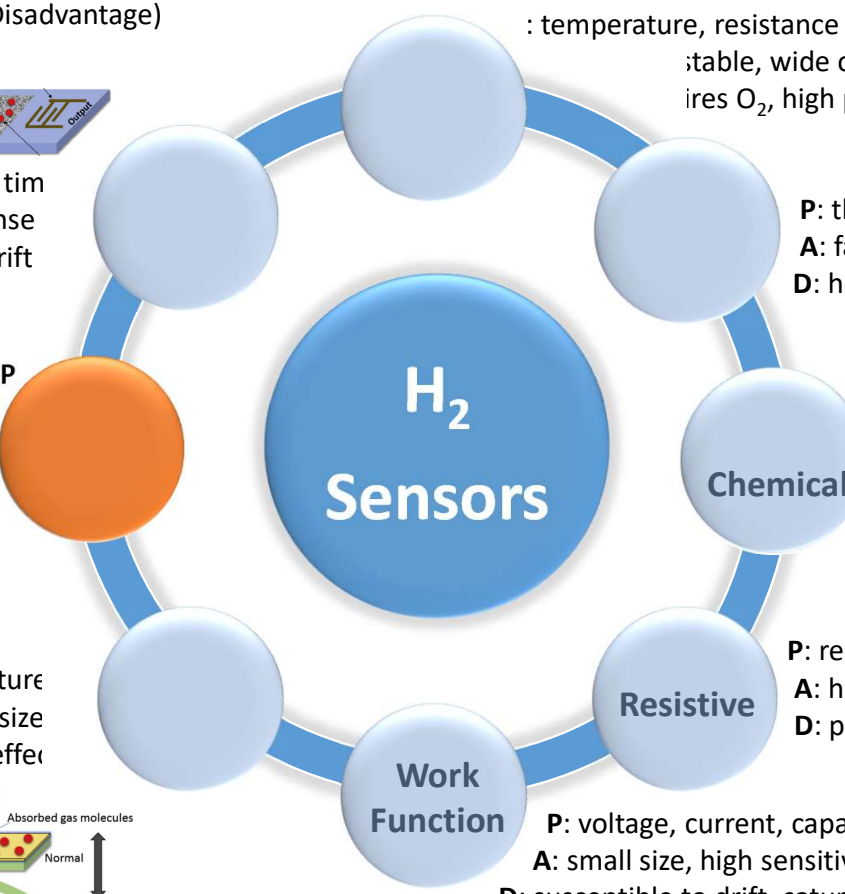
frequency, wave velocity, tim
high sensitivity, fast response
interference from humidity, drift

transmission, reflectance, wavelength: **P**
fast response, no source of ignition :**A**
Interference from ambient light :**D**

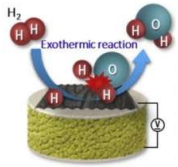


bending, curvature
micromachinable, small size
slow response, aging effe

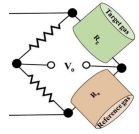




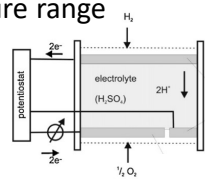
: temperature, resistance
stable, wide operating temperature range
ires O_2, high power consumption



P: thermal conductivity, resistance
A: fast response, low cost, simple construction
D: high lower detection limit, cross-sensitive to He

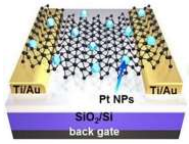


P: electric current, voltage
A: sensitive, working at high temperature
D: low life, narrow temperature range



P: resistance
A: high sensitivity, fast response
D: poor selectivity, interfering with humidity

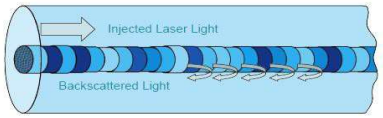
P: voltage, current, capacitance
A: small size, high sensitivity and selectivity
D: susceptible to drift, saturation at modest concentrations



NETL Approach: Advanced Sensor Technologies

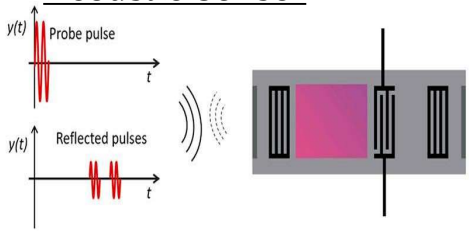
Distributed Optical Fiber Sensor

Imperfections in fiber lead to Rayleigh backscatter:

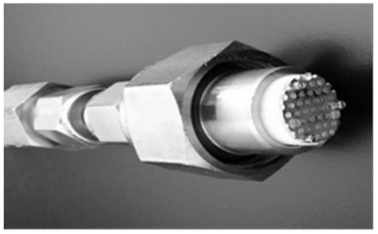


Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

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 Pipeline Integrity and Gas Leak Monitoring.

Optical Fiber Sensors for Pipeline and Subsurface Infrastructure Monitoring

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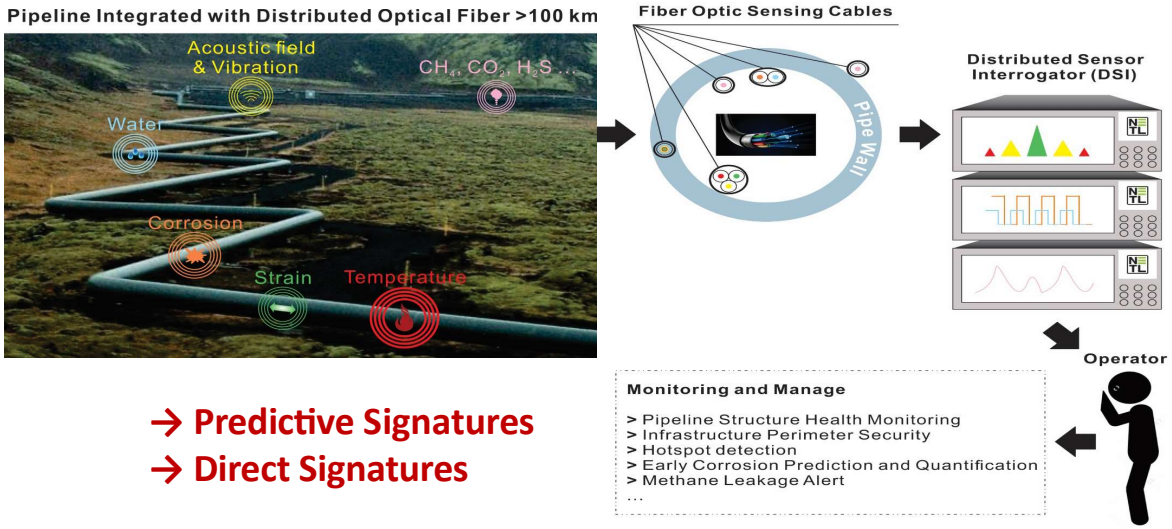
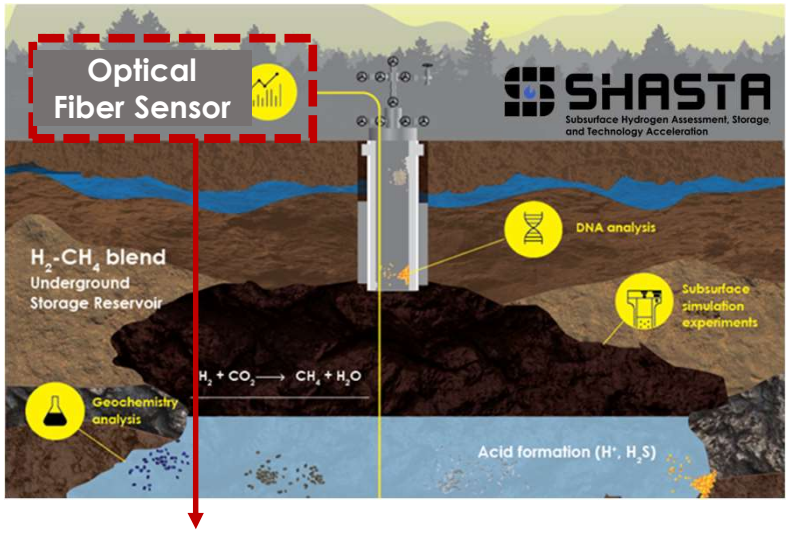
Natural Gas or H_2 Pipelines



→ **Predictive Signatures**
→ **Direct Signatures**

- Optimize Interrogation System (Range, Resolution, Cost)
- Early **Corrosion** On-Set Detection
- **Methane or H_2 Leak** Detection & In-Pipe Gas Composition Monitoring

H_2-NG Subsurface Storage Wells (SHASTA)



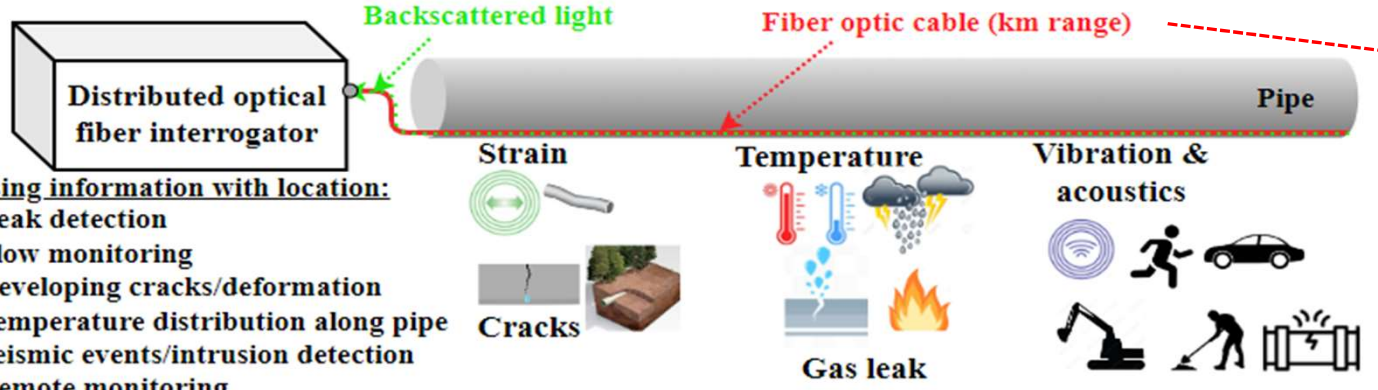
- Subsurface H_2, CH_4, and pH monitoring
- Gas Leak and Wellbore Integrity Monitoring

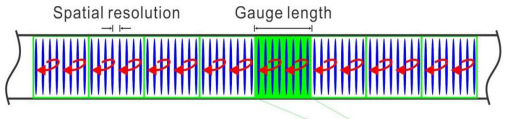
A Multi-Parameter, Distributed Optical Fiber Sensor Platform Enabling Reliability & Flexibility

Target Metrics = >100km Interrogation, <1m Spatial Resolution

Distributed Optical Fiber Interrogator Development

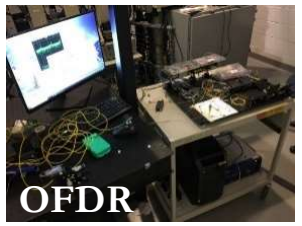
Pipeline integrity monitoring based on various distributed fiber sensor systems





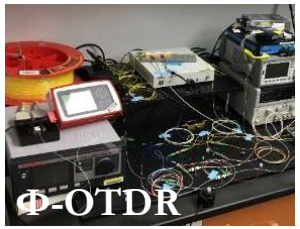
Sensing information with location:

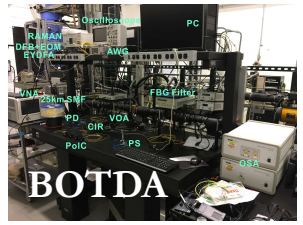
- Leak detection
- Flow monitoring
- Developing cracks/deformation
- Temperature distribution along pipe
- Seismic events/intrusion detection
- Remote monitoring



In-House NETL Distributed Optical Fiber Sensor Interrogators

Technology	Sensing range	Spatial resolution	Measurement time	Target parameter
Rayleigh phase-OTDR	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.

Distributed Temperature and Strain Sensing

Function: Measures ***strain and temperature*** along the pipeline in a ***spatially distributed*** manner using ***one single optical fiber***.

Application: monitor the entire pipeline for pipeline **hoop strain and axial strain**, pipeline **pressure**, **geohazards**, **subsidence**, and **gas or fuel leak** induced temperature change.

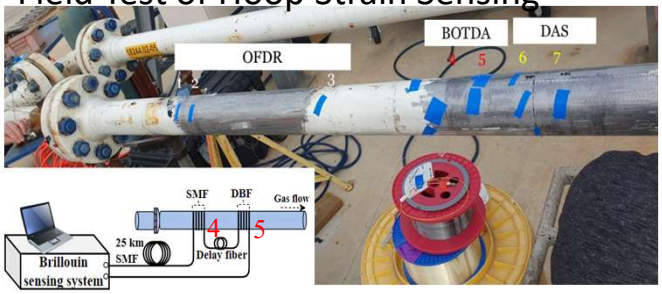
Performance Metrics

	BOTDA	OFDR
Sensing range	150 km	100 m to 2 km
Spatial resolution	1 to 5 meter	0.4 mm to 1 cm
Temp accuracy and range	± 1°C, -100 °C to +500 °C	± 0.5°C, -100 °C to +500 °C
Strain accuracy and range	± 20 με, -2% to +3%	± 5 με, -2% to +3%

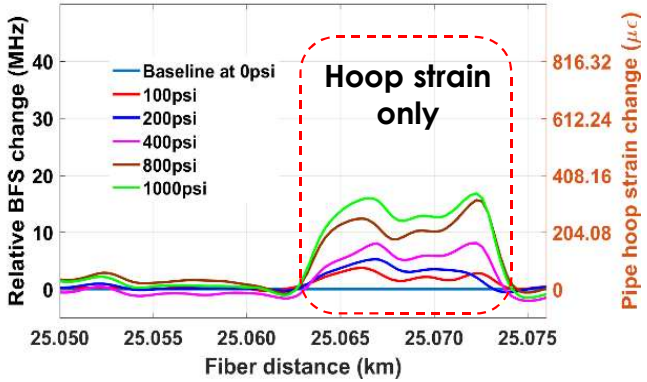
Brillouin Optical Time-domain Analysis (BOTDA)

Optical Frequency Domain Reflectometry (OFDR)

Field Test of Hoop Strain Sensing



Pressure induced hoop strain from 0 psig to 1000 psig



Distributed Acoustic Sensing (DAS) and Ultra-sensitive Acoustic Sensor

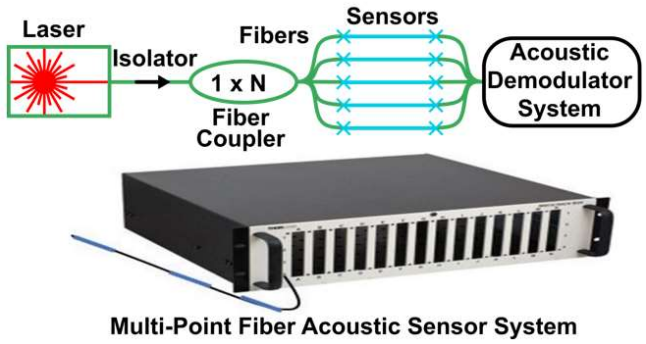
Function: Measures spatially ***distributed acoustic vibrations*** along the pipeline in kilometer-range.

Application: Monitor **gas leaks, flow rates, and third-party intrusion detection, pigging tracking**, etc.

Performance Metrics

	DAS	Multi point
Sensing range	~50 km	flexible
Spatial resolution	1 to 2 meters	flexible
Frequency resolution	< 2 Hz	1 Hz
Vibration detection range	Up to 40 kHz	1 Hz to 1.2MHz

Ultrasonic Photonics: Quasi-distributed highly sensitive fiber optic-based acoustic sensor system



2024 R&D 100 WINNER

Field Test on a Natural Gas Pipe Loop

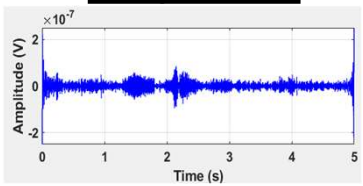
Field Demonstration on a real buried pipeline

Fiber Optic Acoustic Sensing Results

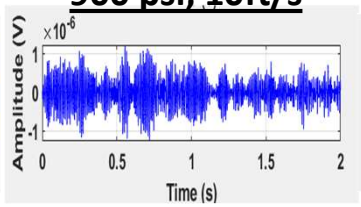
NATIONAL ENERGY TECHNOLOGY LABORATORY

Flow rate:

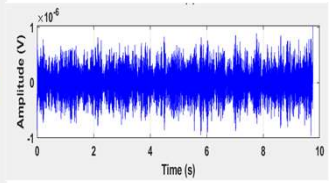
800 psi, 5ft/s



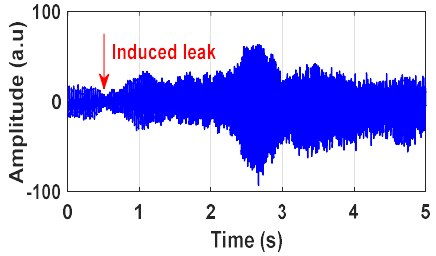
900 psi, 10ft/s



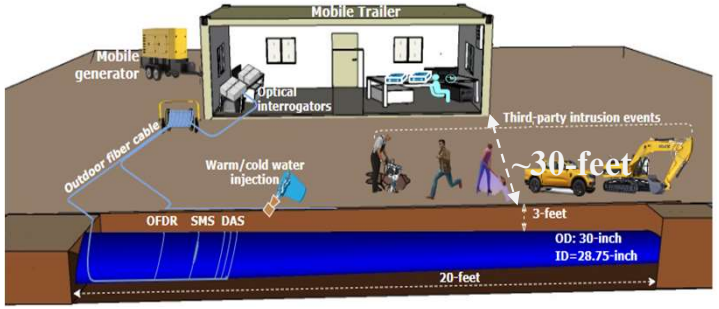
1000 psi, 15ft/s

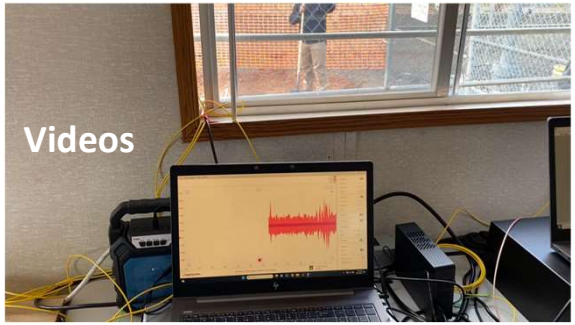


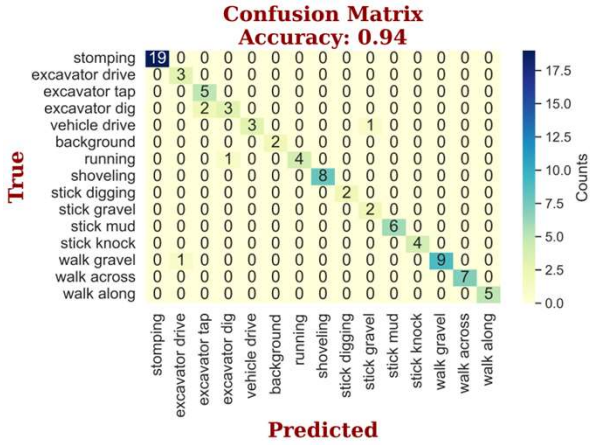
Leak detection:



Third-party intrusion:





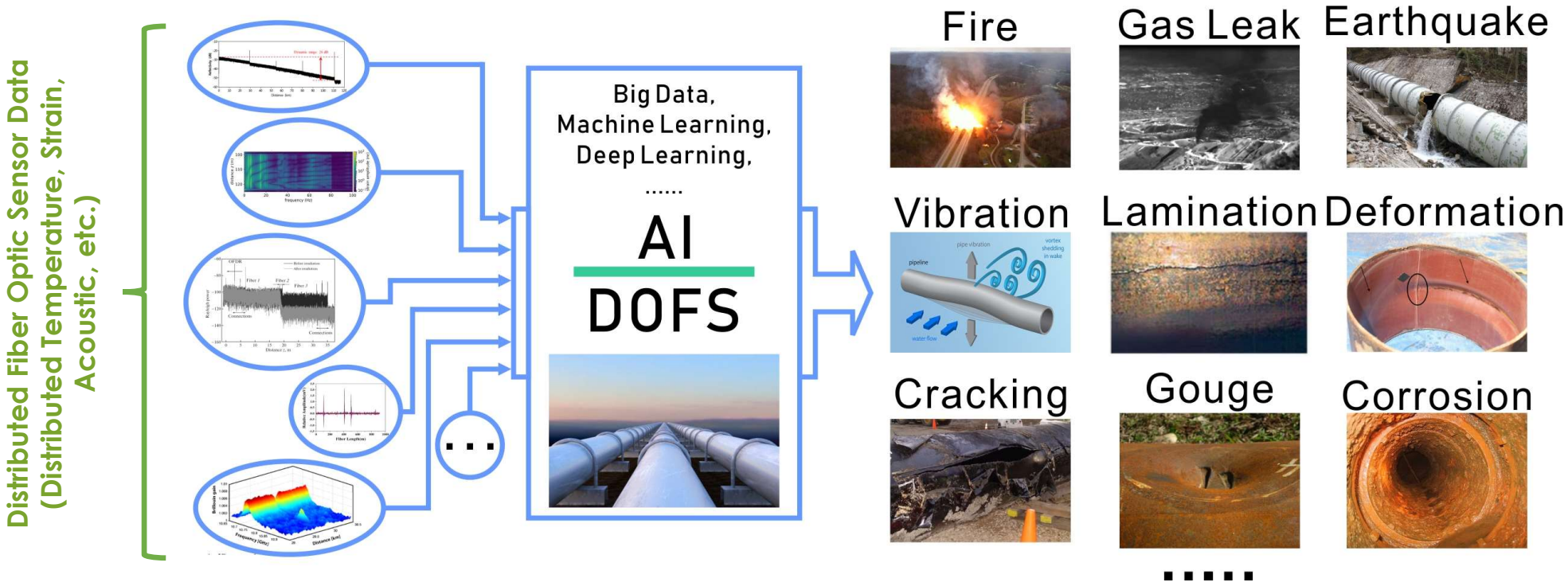


CNN for event classification with 0.94 accuracy

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

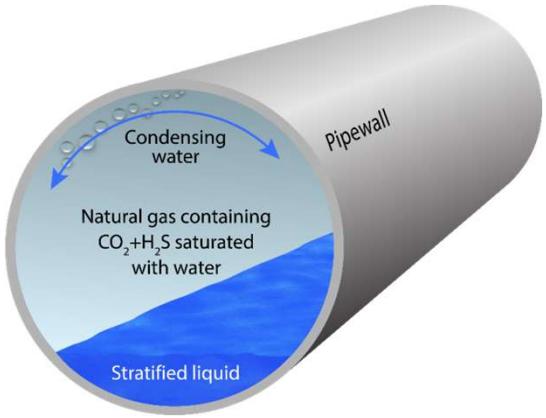
AI-Enhanced Distributed OFS Network

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

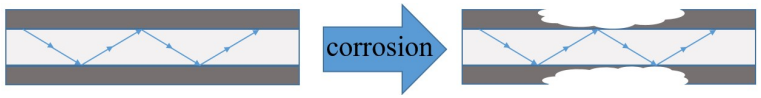


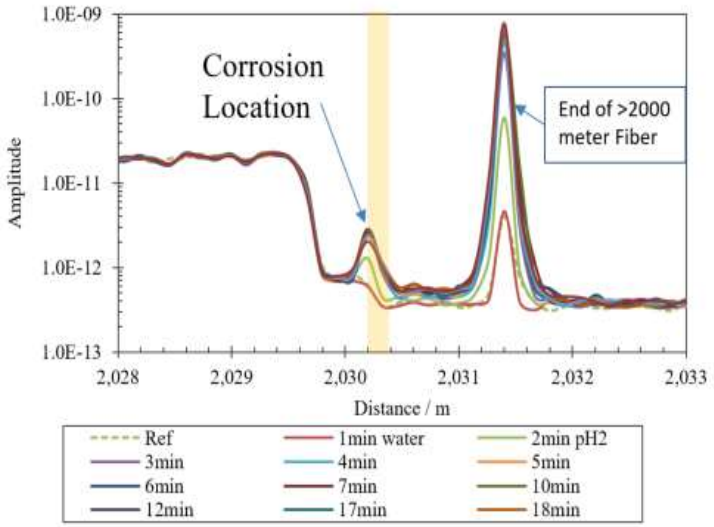
Corrosion Sensing and Early On-Set Detection

Metallic film coated optical fibers

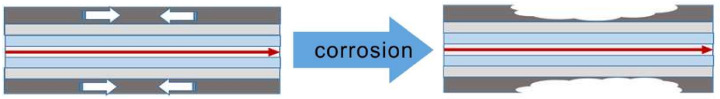


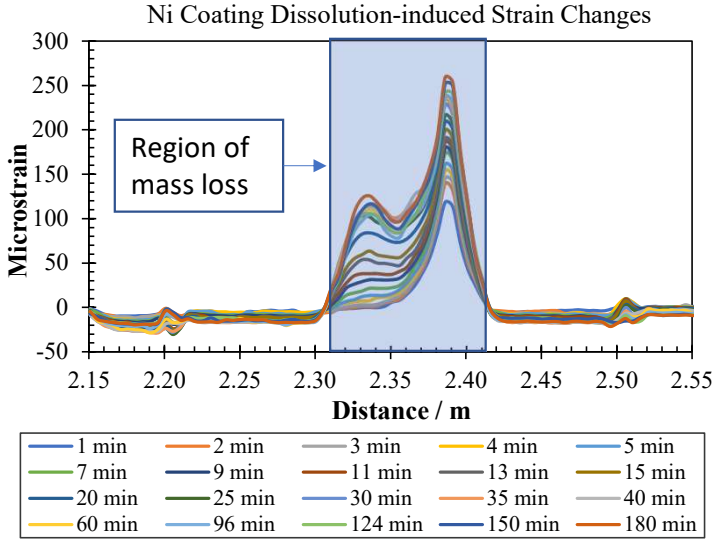
Optical Power Based





Strain Based

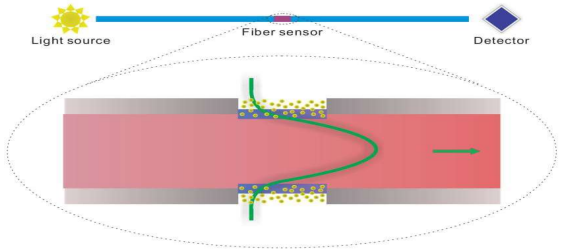




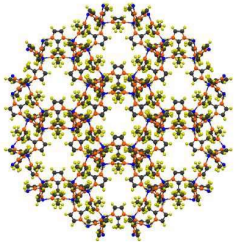
Corrosion can be detected and located along the optical fiber, which enables distributive corrosion monitoring for long-distance infrastructure.

Optical Fiber Methane Sensing

Functional Sensing Layer Integrated Fiber Optic



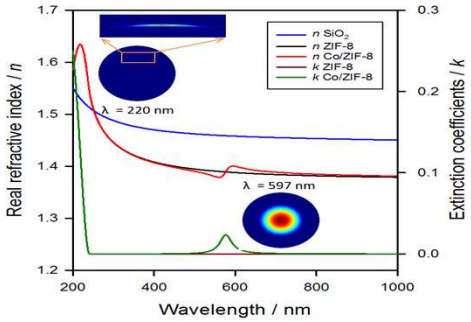
Porous Metal Organic Framework (MOF)



Micro-porous Gas Permeable Polymers

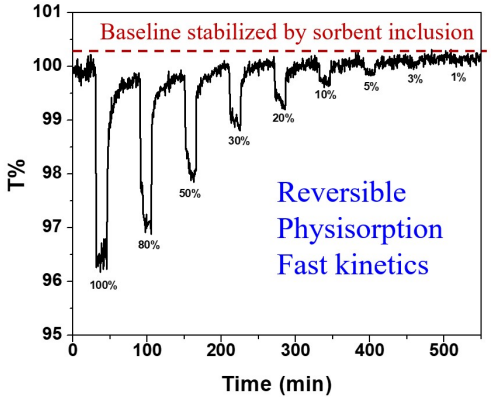
Evanescent Wave Absorption Based Sensors

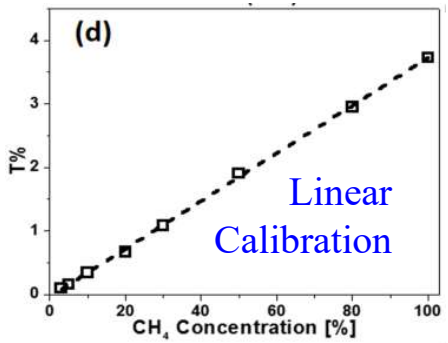
$$I_T(\lambda) = I_0 \exp[-\gamma\alpha(\lambda)CL]$$



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

CH_4 Detection Limit: < 5% in N_2



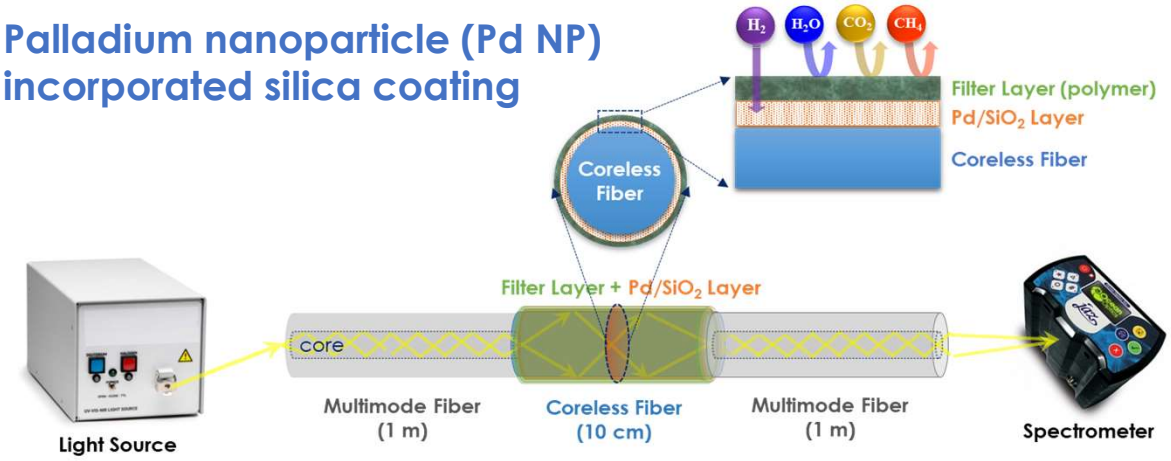


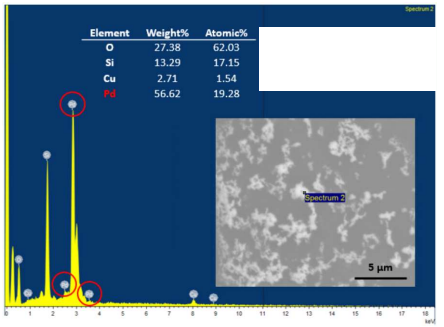
- Light Intensity Based Methane Sensing Technology.
- Integration of Fiber Optic Sensors with Engineered Porous Sensing Layers by Design.

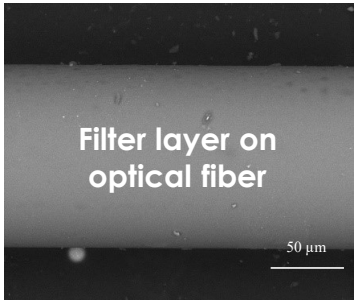
Optical Fiber Hydrogen Selective Sensor

NATIONAL ENERGY TECHNOLOGY LABORATORY

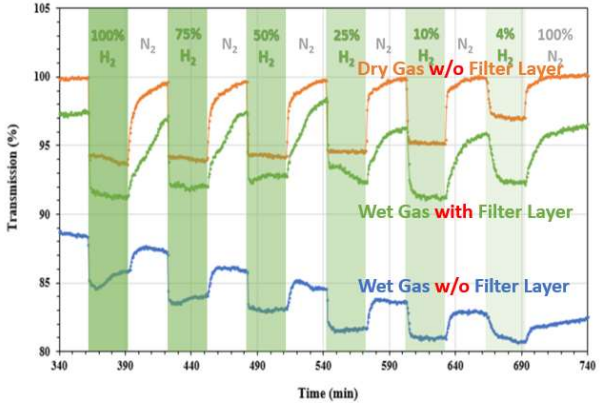
Palladium nanoparticle (Pd NP) incorporated silica coating



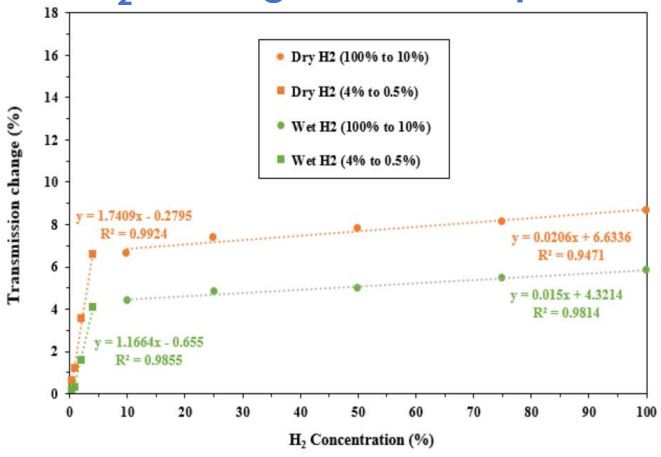




H_2 sensing in 99% relative humidity with a newly developed filter layer.



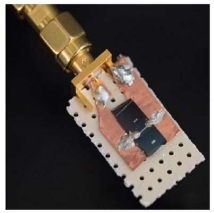
H_2 sensing calibration plot

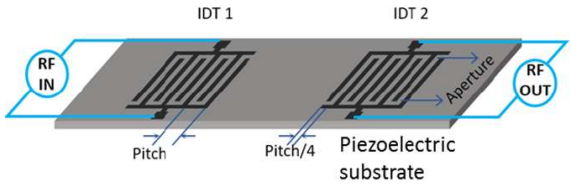


- Optical fiber H_2 sensor was developed for selective hydrogen monitoring.
- H_2 sensing calibration plots under humidity conditions for a wide range of 500 ppm to 100%.

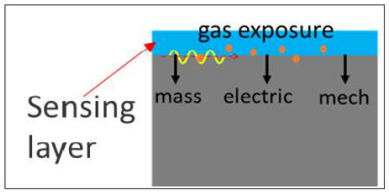
Passive Wireless Surface Acoustic Wave (SAW) Sensors

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

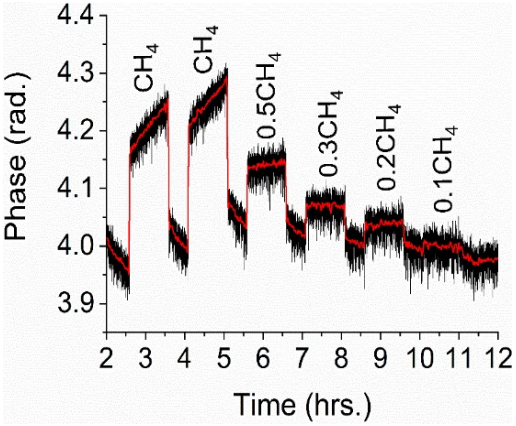




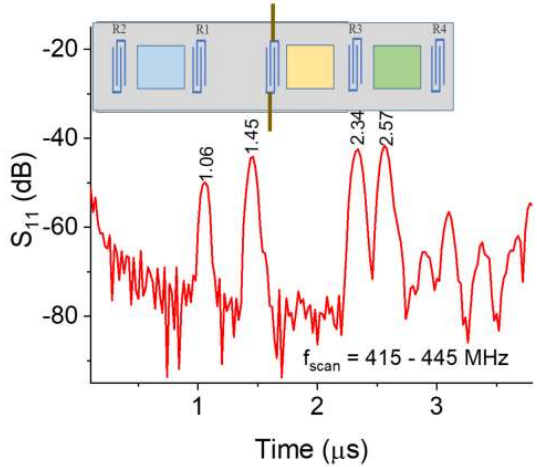
$$\frac{\Delta v}{v_0} = \frac{\Delta f}{f_0} = \frac{\Delta \phi}{\phi_0}$$



Wireless CH_4 Sensing

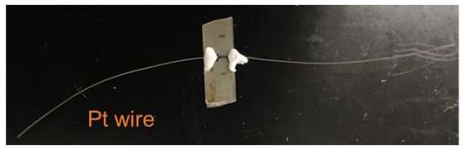


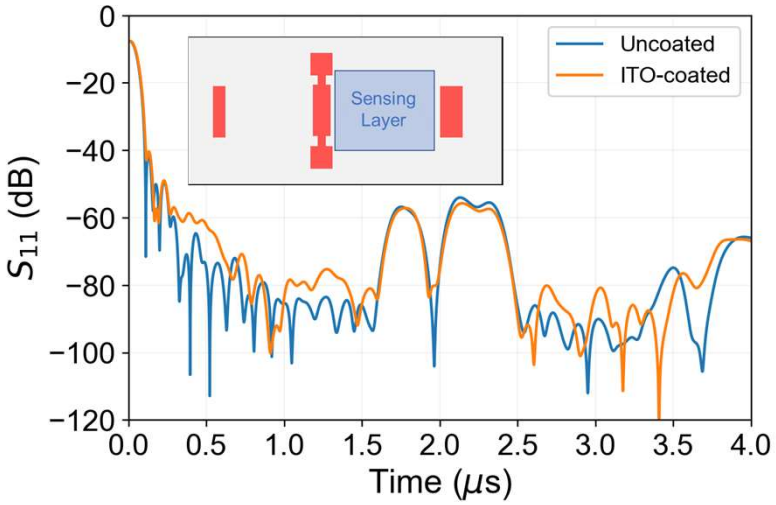
SAW Sensor Array for Multiple Gases



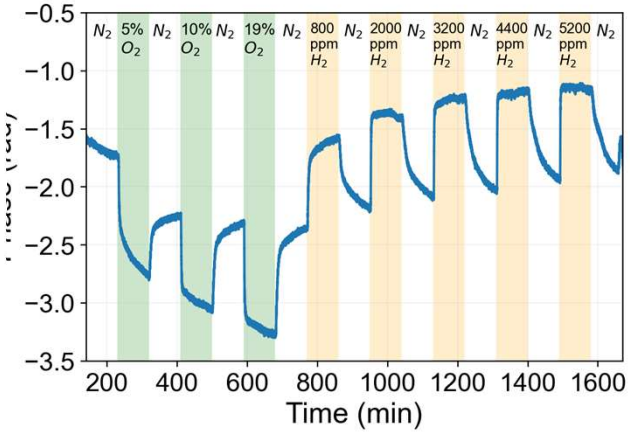
- **Improved safety in flammable gases using passive and wireless sensors**
- **SAW sensor array devices can be functionalized for simultaneous monitoring of multiple elements.**

Surface Acoustic Wave Hydrogen Sensor at High Temperature

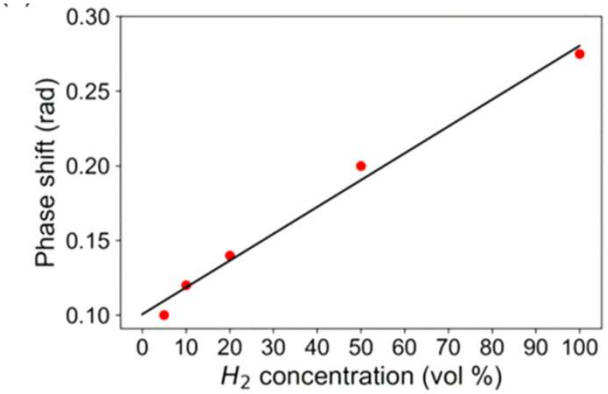




Reversible Hydrogen & Oxygen Sensing at 350°C



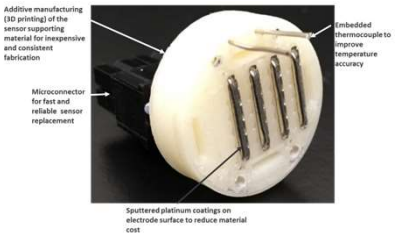
Linear Correlation



Conducting oxide coated SAW sensors have demonstrated hydrogen sensing at high temperatures.

Advanced Electrochemical Sensor (AES) for Water Content & Corrosion Rate Monitoring

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

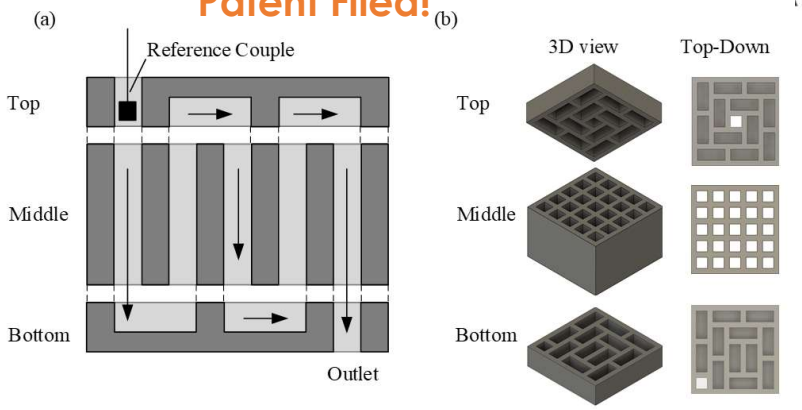


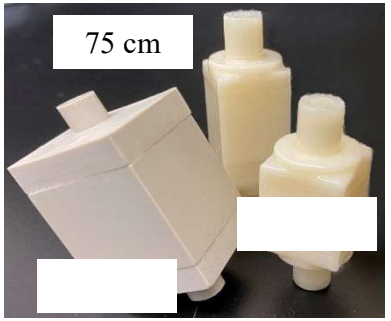
2nd generation AES during testing in water-saturated natural gas at CEESI multi-phase flow facility in 2020.

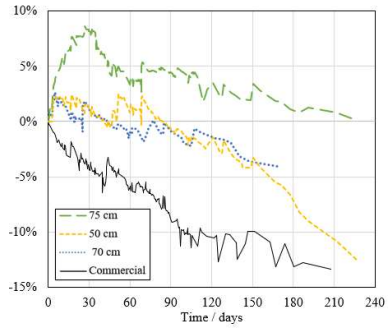
Electrochemical testing equipment is in weather-proof container.

- ✓ ***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!





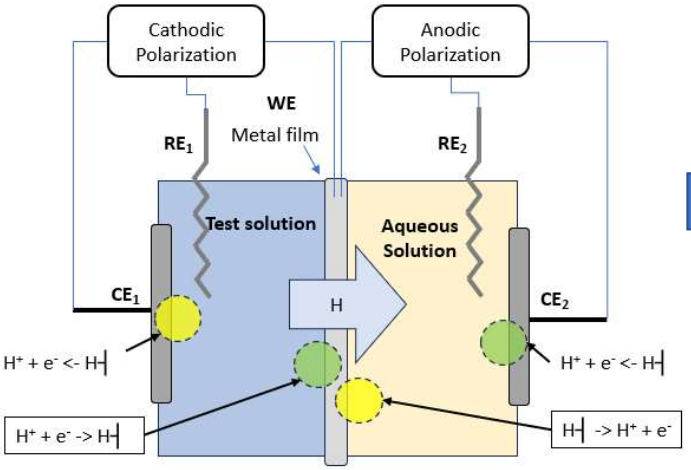


New solid-state reference electrodes (SSRE) outperformed commercial probes in multi-month testing

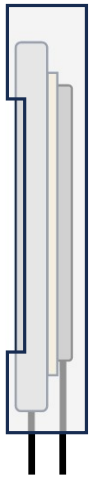
Electrochemical H_2 Permeation Sensor

First prototype design demonstrated promise in detecting hydrogen permeation through metal without the need for electrochemical pumping.

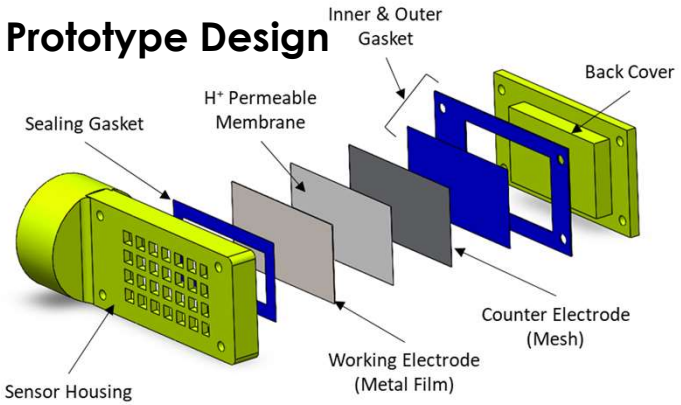
Conventional Devanathan Cell



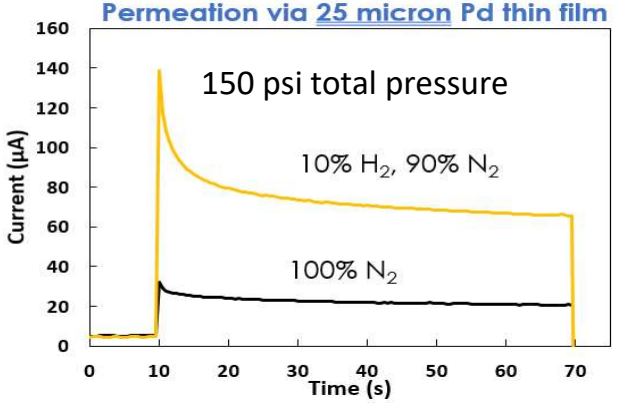
H_2 permeation without electrochemical pump



Prototype Design



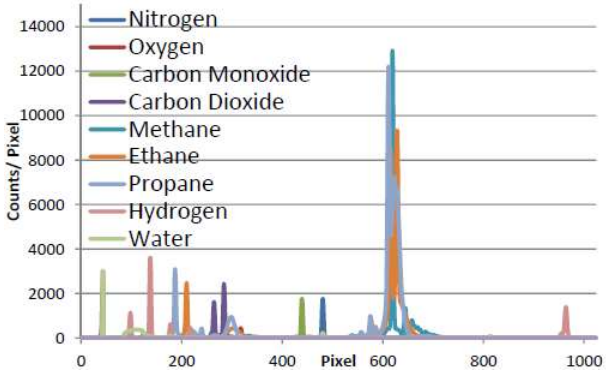
Prototype Data Demonstrating H_2 Permeation via 25 micron Pd thin film



Fast Raman Gas Analyzer (RGA) for Real-time Gas Analysis

- Applications to **in-pipe gas composition monitoring.**
- Field prototype constructed for testing, up to 1000 psi
- Fast - **1 second** measurement time
- Measures difficult gases: **H_2**, N_2, O_2 (they have no IR transitions)
- Easily distinguishes CO from N_2 (difficult for mass spectrometer)
- Species concentrations measured to 0.1%
- Optical waveguide technology boosts Raman signal more than 1000X

No commercial technology has this combination of speed, accuracy, and multi-gas capability.



US Patent 8,674,306, NETL and U. of Pittsburgh

Summary

- For safety and global warming impact evaluation, it is critical to monitor low-concentration CH_4 and H_2 leaks in real time to mitigate greenhouse gas emissions and ensure safe operations using the flammable gases.
- Quantification of gas emissions from pipelines and oil and gas infrastructure is needed for evaluation of global warming impact.
- Multiple complementary sensor technologies developed at NETL can monitor pipeline gas leaks, leveraging the advantages of ***optical, electrochemical, and microwave / wireless sensor platforms***, to build an in-situ, multi-parameter, distributed, and cost-effective sensor network.
- ***A wide range of sensing materials*** are developed to achieve high sensitivity, selectivity, and fast response, including MOF, polymers, and nanocomposites.
- Predictive and early detection of pipeline structural and equipment failures can inform timely maintenance and mitigate risks and gas emissions.
- Artificial intelligence-enhanced sensor network with ubiquitously embedded sensors will ultimately achieve desired visibility across the energy infrastructure.

Acknowledgements and Disclaimer

Research Team: Ruishu Wright (PI)**,** Nageswara Lalam, Daejin Kim, Michael Buric, Matthew Brister, Hari Bhatta, Richard Pingree, Dave Greve (CMU), Ömer Doğan, Derek Hall (PennState), Jeffrey Culp, Jeff Wuenschell, Alexander Shumski, Badri Manali, Nathan Diemler, Paul Ohodnicki (UPitt), Kevin Chen (Pitt), Ben Chorpening, Scott Crawford, etc.

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