NETL Sensor Technologies Progress Overview

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National Energy Technology Laboratory (NETL)

UPitt Infrastructure Sensor Collaboration (UPISC)
2024 Workshop
November 13, 2024

UPISC University of Pittsburgh Infrastructure Sensing Collaboration Workshop

NETL National Energy Technology Laboratory

NETL Sensor Expertise and Capabilities for Energy Infrastructure

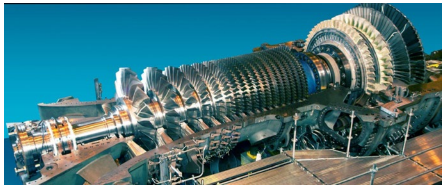
Advanced Sensors for Energy Efficiency, Safety, Resilience, and Sustainability

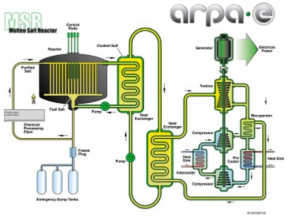
- ✓ **Monitor systems and conditions**
- ✓ **Improve performance & efficiency**
- ✓ **Enhance reliability & safety**
- ➢ Temp, acoustics, chemical, gas, corrosion
- ➢ Composite nano-materials, thin films & fiber optics, sensor devices development

Sensor Platforms | **Sensing Materials**

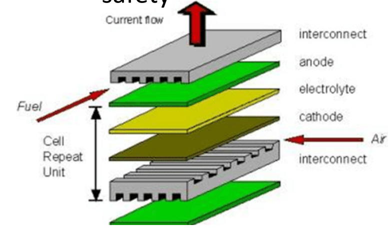
Generation

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

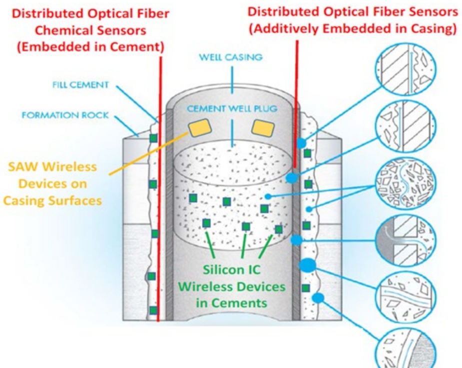


SOFCs: Fuel concentration & temperature gradients for improved lifetime and efficiency

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

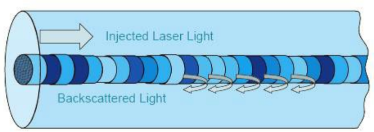


Subsurface: Wellbore integrity, failure prediction, leak detection. Geologic storage of CO_2, H_2/NG, or abandoned wells.

Multiple Sensor Technology Platforms at NETL

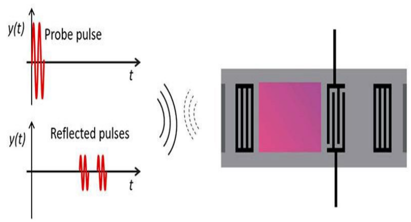
Long-distance Distributed Optical Fiber Sensors

Imperfections in fiber lead to Rayleigh backscatter:



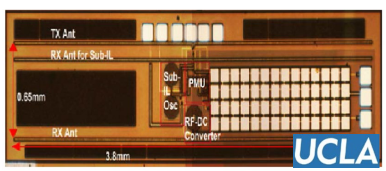
Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

Passive Wireless Sensors



Advanced Electrochemical Sensors

Wireless Miniature Silicon Integrated Circuit (SiIC) Sensors



	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
Wireless Miniature SiIC Sensors	Point Sensor	Low	pH and Chemical Sensing

Multiple Sensor Platforms with Various Cost, Performance, and Geospatial Characteristics have been developed at NETL and via collaborations.

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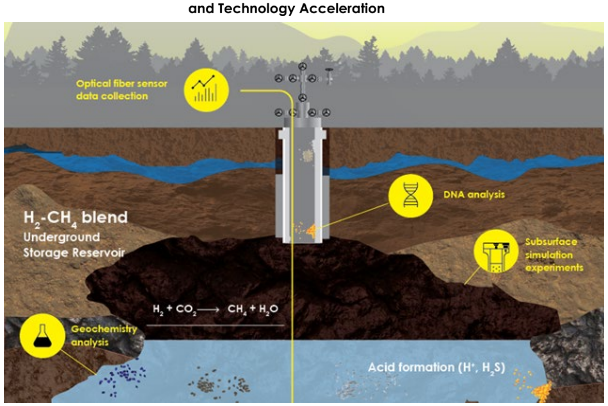
NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL Sensor Technologies Progress and Achievements in 2024

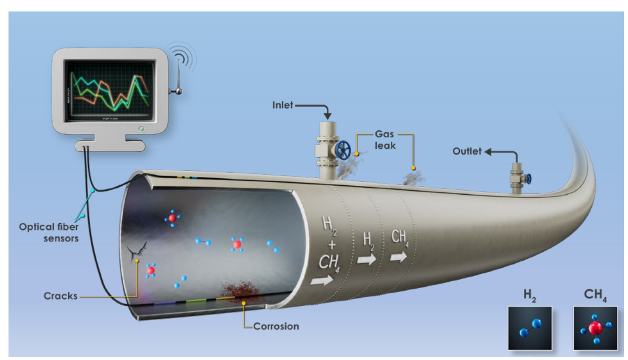
-Hydrogen Pipeline and Subsurface Storage, Hydrogen Emission Monitoring

- The optical fiber H_2 sensor has demonstrated real-time H_2 sensing in simulated subsurface conditions with **microbes** (80 °C, 1000 psi), and detected hydrogen concentration change ***in situ and real time***.
- A low-cost fiber optic hydrogen sensor prototype is assembled and tested in the lab to prepare for field validation at NREL next year.
- Distributed hydrogen sensing technology is under development.

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

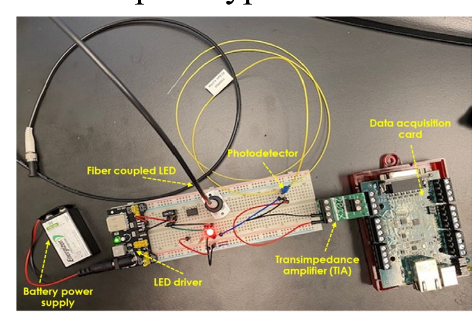


Natural Gas Decarbonization and Hydrogen Technology Project (NGDH2T)



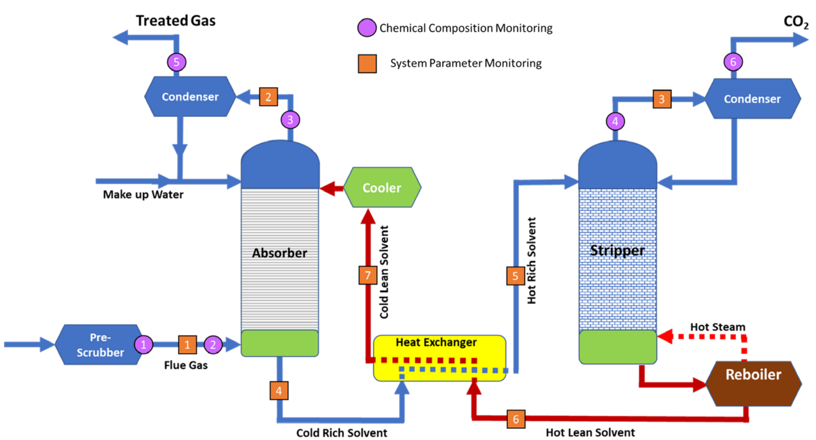
H2@Scale NREL CRADA

H_2 Selective Fiber Optic Sensor low-cost prototype

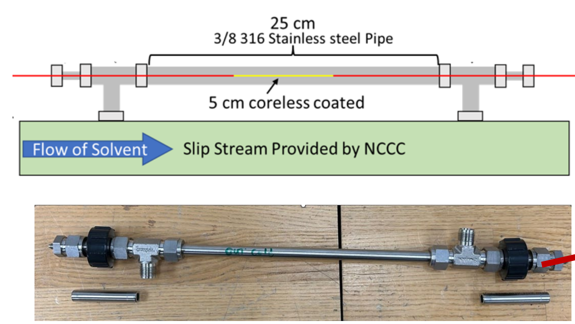


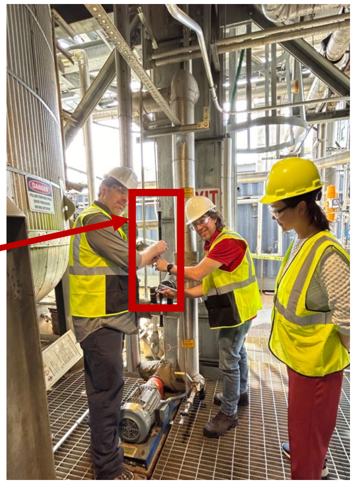
NETL Sensor Technologies Progress and Achievements in 2024
-Carbon Capture Amine Degradation Monitoring

- **Installed in-situ optical fiber sensors in a post-combustion solvent-based carbon capture loop system** at National Carbon Capture Center (NCCC) for pilot-scale demonstration: amine degradation monitoring and CO_2 monitoring.
- Designed and assembled sensor prototypes and integrated automatic data collection.
- Working on quantitative calibration to monitor amine content and degradation percentage in the lab.



Schematic of a carbon capture system with currently available monitoring technologies



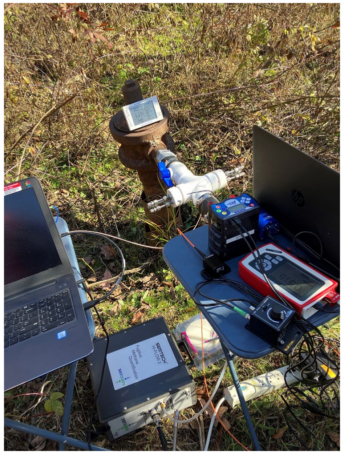


NETL fiber optic amine degradation sensor assembly and installation at NCCC

NETL Sensor Technologies Progress and Achievements in 2024
-Methane Emissions Reduction Program (MERP) Technical Assistance

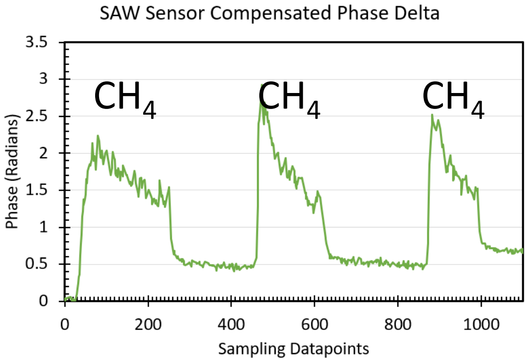
- **"Advanced Methane Sensor Demonstration and Deployment"** under NETL's National Emissions Reduction Initiative (NEMRI) in support of EPA Methane Emissions Reduction Program (MERP), to quantify and mitigate methane emissions from oil and gas industry.
- Field demonstration of optical fiber-based and surface acoustic wave-based methane sensors at an abandoned well.

Marginal Well



NETL sensors installed at an abandoned well

1st gen of NETL sensor assembly



Demonstrated methane sensor responses compared to commercial sensors

NETL Sensor Technologies Progress and Achievements in 2024

-Power Grid Modernization and GRID-Q

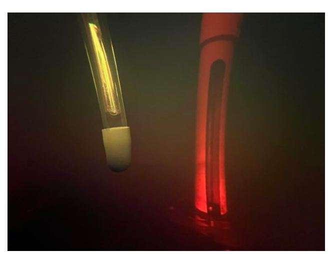
- “Transformer Watchman” developed and matured by NETL, UPitt, and Sensible Photonics won **2023 R&D 100 Award**. “Transformer Watchman” is an integrated and AI-enhanced fiber optics-based sensor system to monitor and warn of any dangers that might be encountered in a power transformer.
- **Grid Research, Integration, and Deployment for Quantum (GRID-Q) is** funded by the U.S. Department of Energy Grid Modernization Laboratory Consortium (GMLC) 2023 lab call under Topic 3. Multi-lab efforts: ORNL (lead), **<u>NETL (quantum sensing thrust lead),</u>** LANL, LLNL, ANL.

Transformer Watchman

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

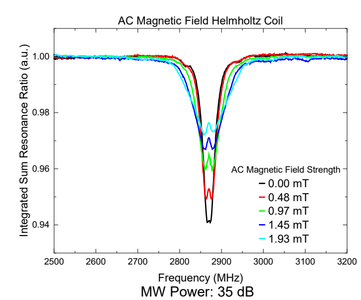
2023 R&D 100 WINNER

Acoustic Sensing at Medium-voltage Transformer



Dissolved Gas Analysis of Transformer Oil

Optically detected magnetic resonance (ODMR) system



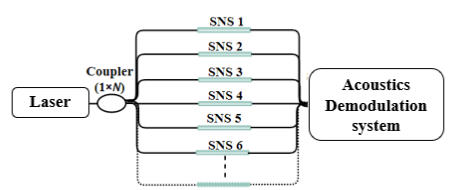
AC magnetic field sensing

NETL Sensor Technologies Progress and Achievements in 2024
-Natural Gas Infrastructure / Methane Mitigation Technologies

- **Distributed fiber optic pipeline sensor technologies developed by NETL** were tested in **a real underground pipeline** via CRADA with Colonial Pipeline Company for gas flow, pressure, and third-party intrusion monitoring.
- **2024 R&D 100 Award for "Ultrasonic Photonics":** Ultrasensitive acoustic sensor based on multiplexed interferometric sensors in combination with machine learning classification of different pipeline events.

Fiber sensors installation on CPC pipelines

Ultrasensitive optical fiber acoustic sensor system

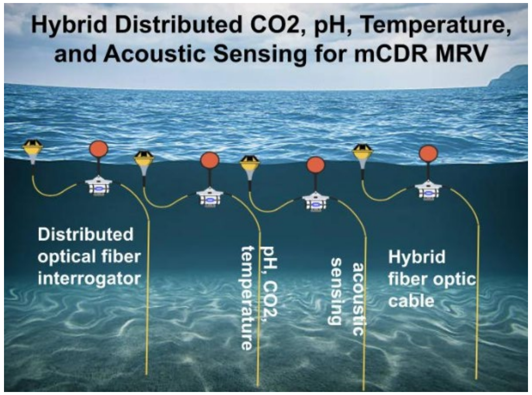


"Ultrasonic Photonics"

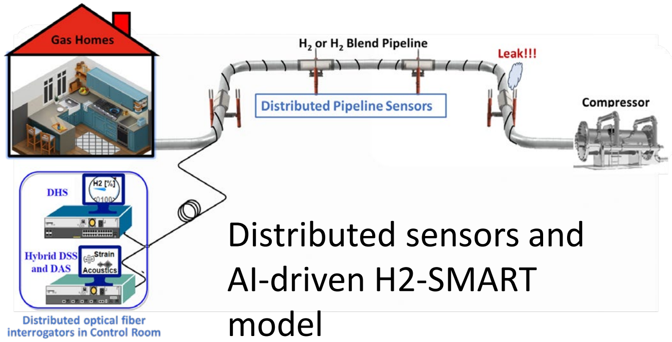
2024 R&D 100 WINNER

NETL and U. Pitt. Sensor Technologies Progress and Achievements -Newly Awarded Project in 2024

- "**Hybrid Distributed pH, CO_2, Temperature, and Acoustic Sensing for Monitoring and Verification of Marine Carbon Dioxide Removal Applications**" in response to ARPA-e 2023 DE-FOA-0002989, Sensing Exports of Anthropogenic Carbon Through Ocean Observation (SEA CO_2). Led by UPitt. NETL is collaborating on chemical and CO_2 sensing and fiber optic interrogation system.



- "**Novel Fiber Optic Sensor Systems and AI-driven Methods for Hydrogen Pipeline Emission Quantification**" in response to ARPA-e 2024 DE-FOA-0002784, H2SENSE. Led by NETL, collaborating with UPitt and Hope Gas Company.



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PITT Sensor Technologies Updates and Overview

Presenter: Paul R. Ohodnicki, Jr.

RK Mellon Faculty Fellow in Energy
Swanson School of Engineering
University of Pittsburgh (PITT)

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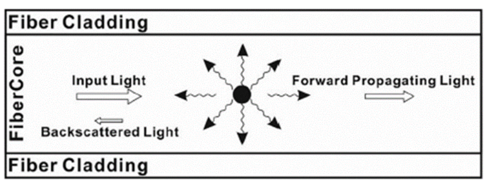
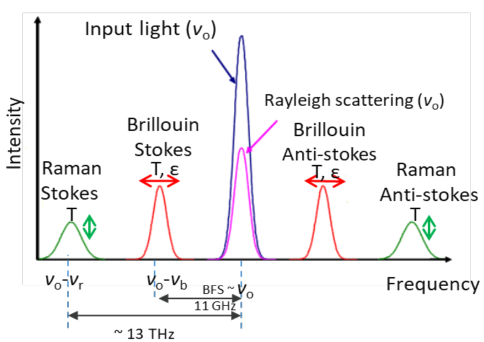
PITT Sensor Technologies Updates and Overview

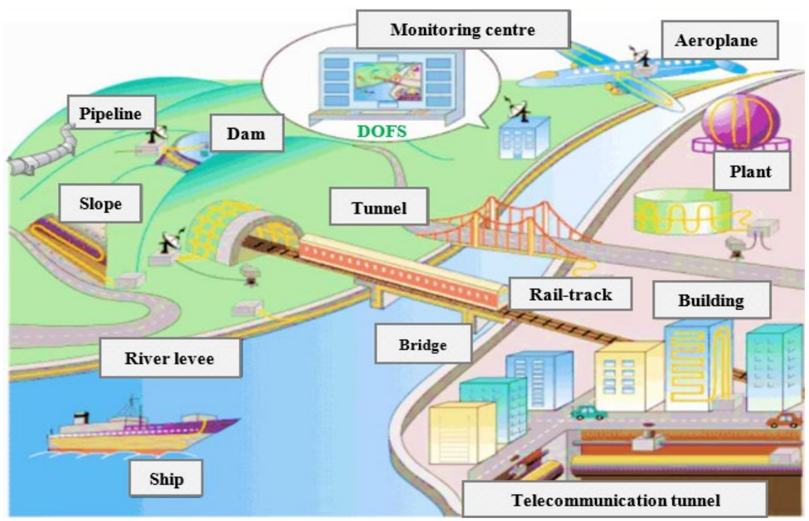
Distributed Sensing and Infrastructure Monitoring

Scattered light spectrum of optical fiber

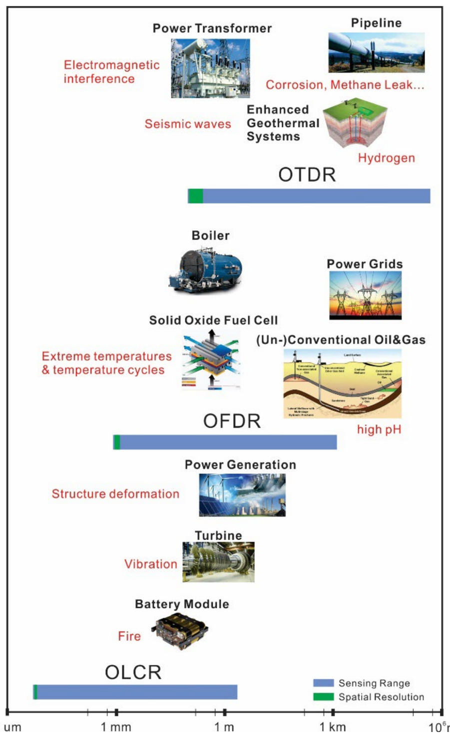




Various Applications



Applied Physics Reviews **6**, 041302 (2019); https://doi.org/10.1063/1.5113955



Distributed Sensing Over Different Length Scales

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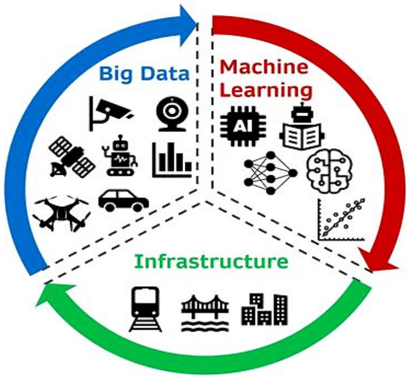
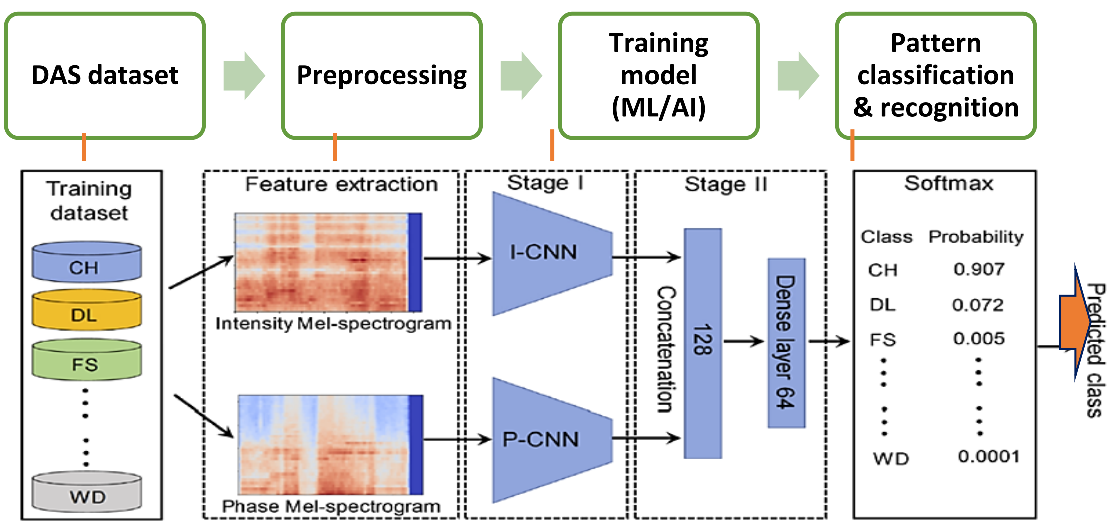
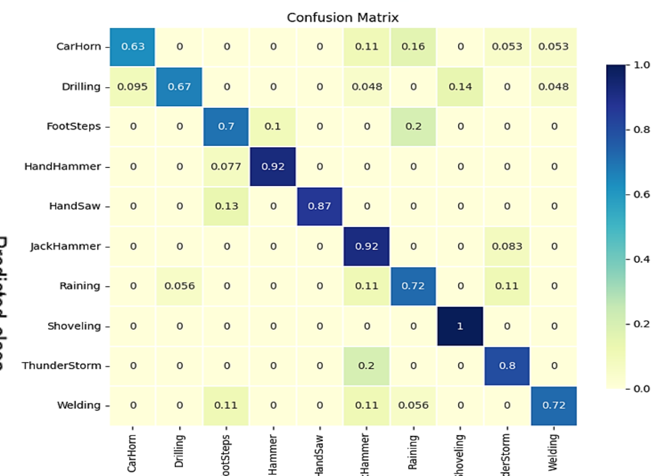
PITT Sensor Technologies Updates and Overview

Intelligent Fiber Sensors: A Fusion of DAS & AI

- Infrastructure type: Threats analysis
- High-quality Datasets: Acoustic signatures of various threats/events
- Data processing: Pre-processing and AI/ML models





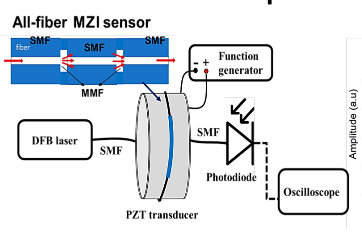


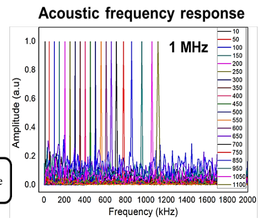
PITT Sensor Technologies Updates and Overview

Distributed Sensing Applications @ PITT Ohodnicki Lab

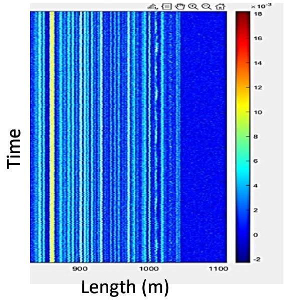
❑ Acoustic sensing

- **Point and Multipoint**



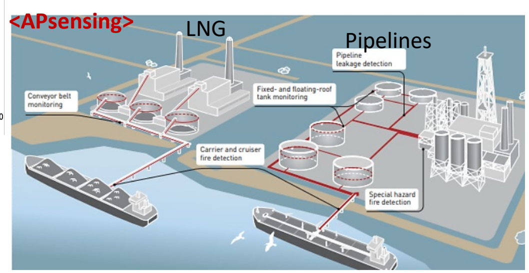


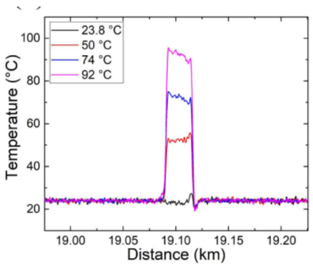
- **Distributed Acoustic Sensor (DAS):**
  - Benchtop Interrogator
  - Commercial Interrogator acquisition



❑ Temperature sensing

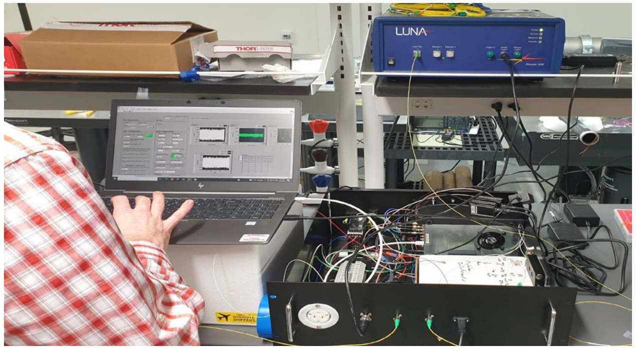
- Distributed Temp Sensor / DTS: Commercial interrogator

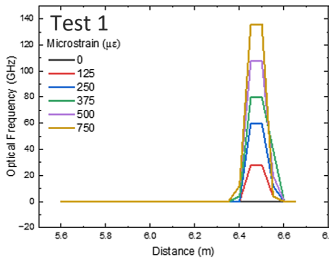


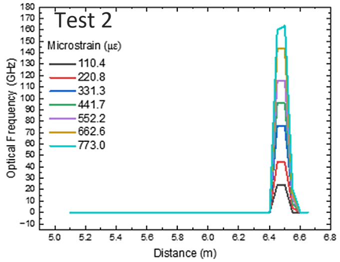


❑ HD Strain/Temperature

- Benchtop OFDR…..PITT/NETL







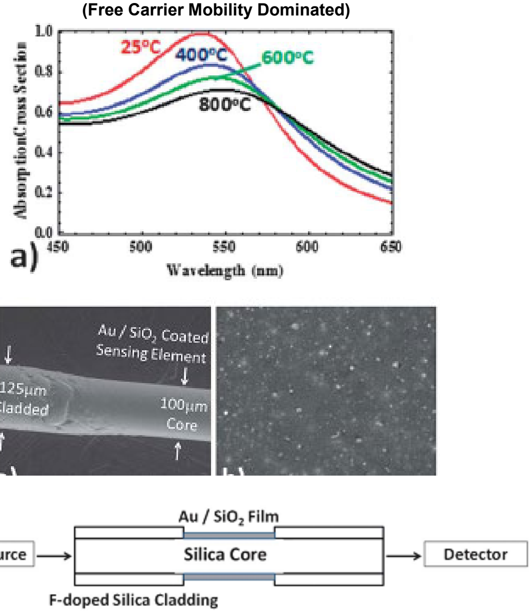
PITT Sensor Technologies Updates and Overview

Functionalized Optical Fiber Sensing @ PITT Ohodnicki Lab

❑ Temperature Sensing

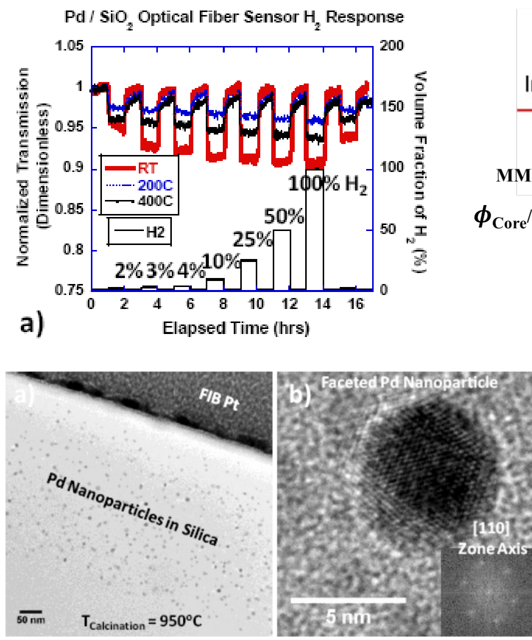
Temperature Response

(Free Carrier Mobility Dominated)



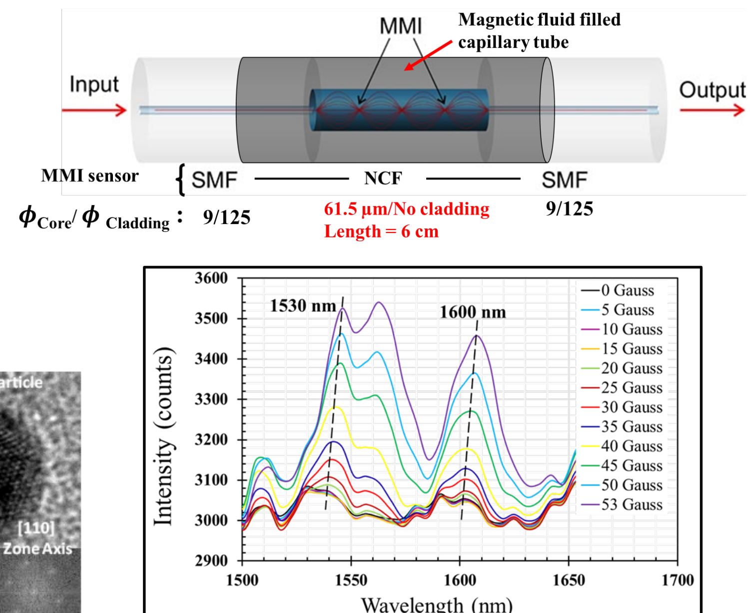
P.R.Ohodnicki et al, Nanoscale 5 (19), 9030-9039 (2013).

❑ Chemical Sensing



P.R. Ohodnicki et al. / Sensors and Actuators B 214 (2015) 159–168

❑ Magnetic Field Sensing

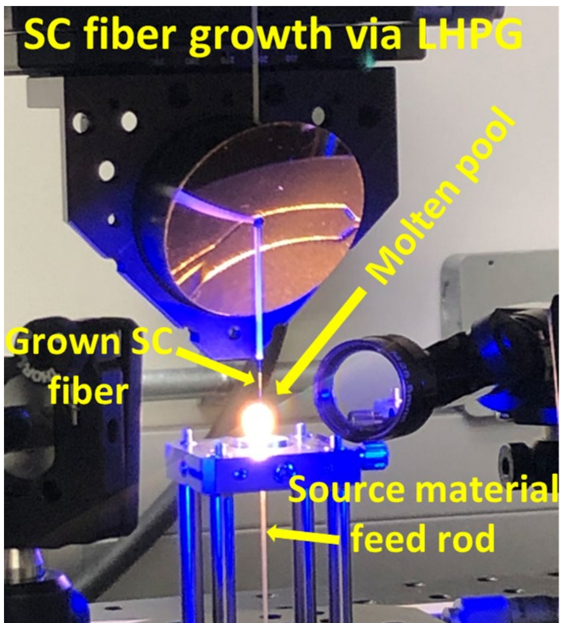


D. Karki et al, Presented at SPIE DCS 2023.

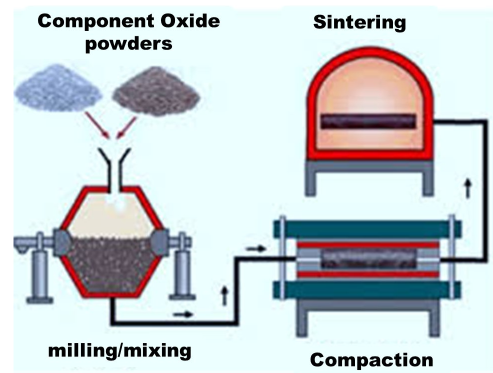
PITT Sensor Technologies Updates and Overview

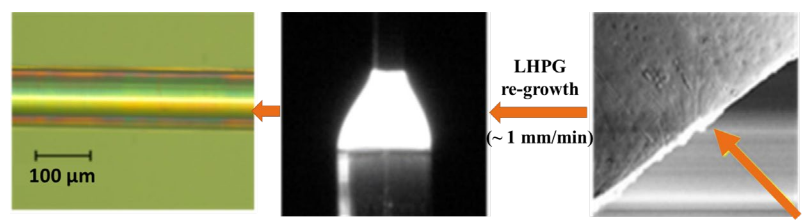
Single Crystal Oxide Fiber Sensing @ PITT Ohodnicki Lab

- ❑ Laser Heated Pedestal Growth



- ❑ Functional Crystal Oxides





Nd:YAG fiber with HoAG cladding | 120µm Ho, Nd:YAG fiber | HoAG coated 330 µm Nd:YAG fiber

Liu, B., Ohodnicki, P. R., Fabrication and Application of Single Crystal Fiber: Review and Prospective. *Adv. Mater. Technol.* 2021, 6, 2100125. https://doi.org/10.1002/admt.202100125

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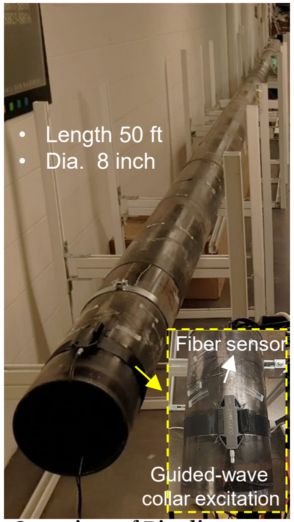
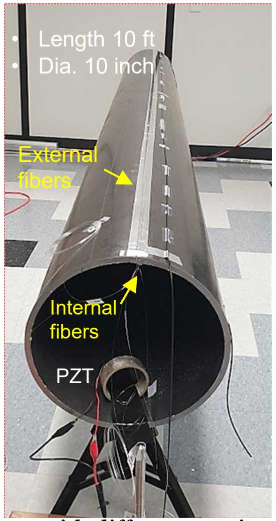
PITT Sensor Technologies Updates and Overview

Example On-Going Work: Fusion of Acoustic NDE + Fiber Optics

Pipeline monitoring

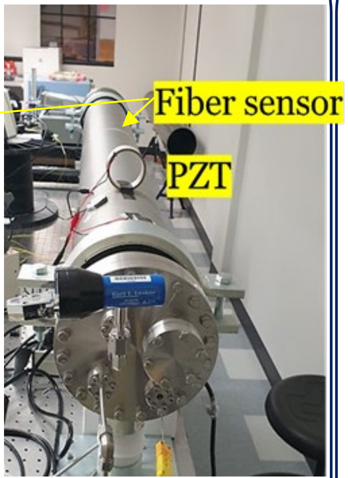




Overview of Pipeline test setup with different sensing optical fibers deployed internally using robotic FODT

Point & Distributed Acoustic Sensing:
-Structural integrity and degradation
-Natural gas and oil leakages
-SHM: Internal state and corrosion

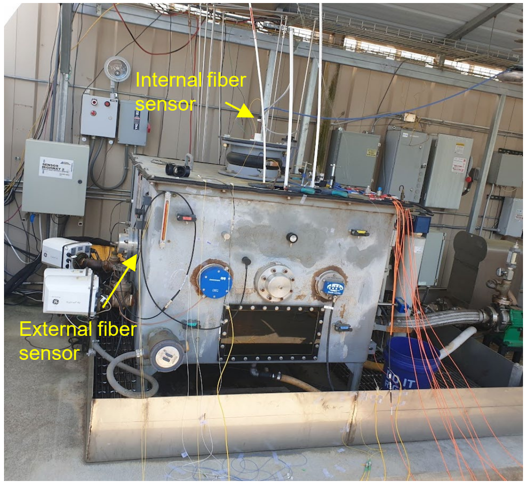
Nuclear Canister monitoring



Dry Cask Storage System for Nuc. Canister monitoring

Q-distributed Acoustic Sensing:
-Internal radio-active leak detection
- Corrosion, gas phase, and temperature monitoring

Elect. Assets monitoring



Test setup for Partial discharge detection @ EPRI

Q-distributed Acoustic Sensing:
-Partial Discharge detection
-Gas and temperature monitoring

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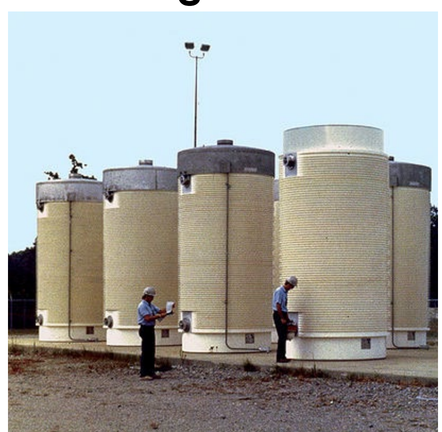
PITT Sensor Technologies Updates and Overview

Example Major R&D Programs Sponsored at University of Pittsburgh

- ❑ Low-Cost Electrical Grid Asset Sensing + Grid Analytics
- ❑ Spent Nuclear Fuel Waste Facility Monitoring
- ❑ Molten Salt Reactor Monitoring
- ❑ Distribution Pipeline Sensing
- ❑ Marine Carbon Capture



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U.S. Department Of Energy

NEUP Nuclear Energy University Program
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CHANGING WHAT'S POSSIBLE

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PITT Sensor Technologies Updates and Overview

Commercialization and Technology Transfer Activities : Electrical Asset Sensing

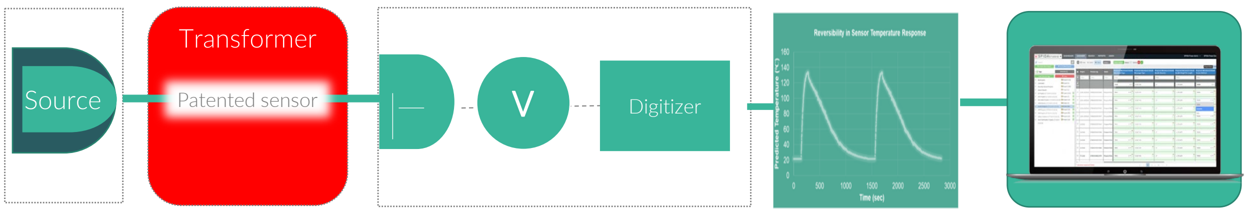
Low-Cost Fiber Optic Sensing Technology

Low-cost light source

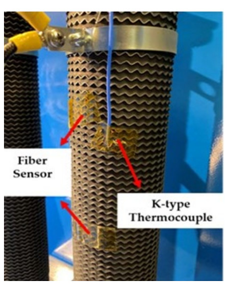
Low-cost detector

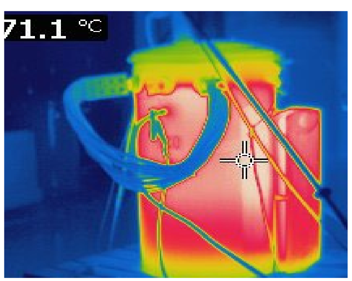
Asset Real-time monitoring (Temperature, acoustics)

Incorporated into existing dashboards to enhance utility capability

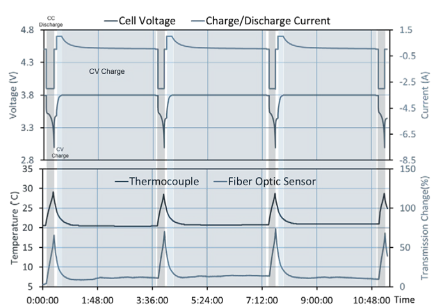


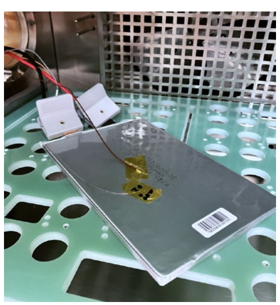
Electrical & Magnetic Components Sensing (e.g. Transformers)





Internal and External Battery Monitoring





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SENSIBLE PHOTONICS

www.sensiblephotonics.com

Currently in Seed Stage Fundraise

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COLLABORATION WORKSHOP

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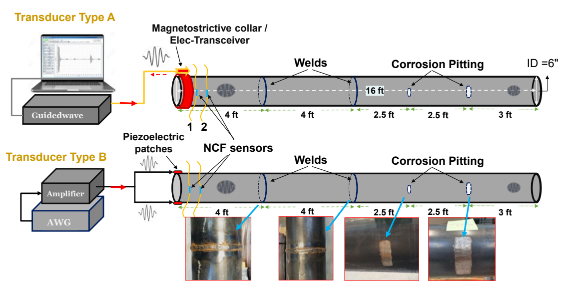
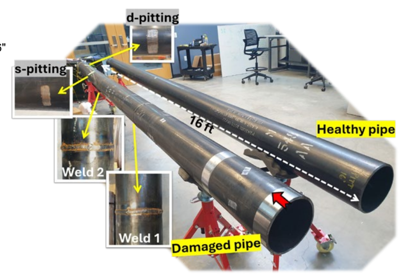
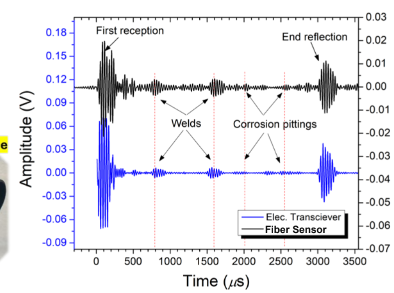
PITT Sensor Technologies Updates and Overview

Commercialization and Technology Transfer Activities : Ultrasonic Photonics

Pipeline Structural Health Monitoring







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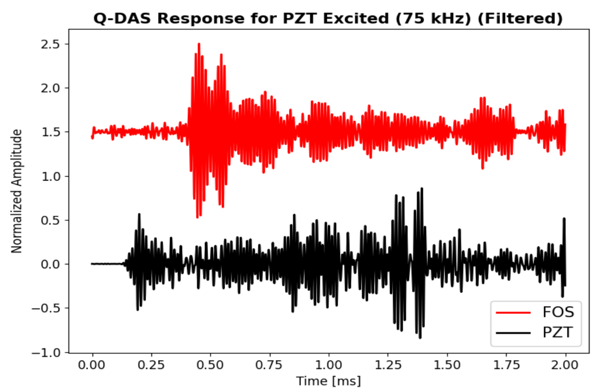
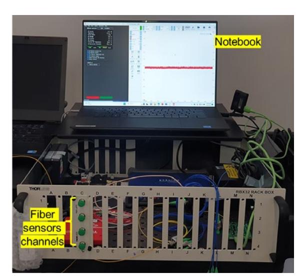
Spent Nuclear Fuel Canister Monitoring

Ultrasonic Acoustic NDE of Canisters





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Summary

- Distributed fiber optical sensors and passive wireless sensors enhanced with AI-enhanced data analysis to build an in-situ, multi-parameter, distributed, and cost-effective sensor network, as well as quantum sensor technologies.
- Functionalization using a wide range of sensing materials to achieve high sensitivity, selectivity, and fast response, including MOF, polymers, metallic films, and nanocomposites.
- Multi-parameter sensing:

  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, vibration, acoustic, magnetic field
- Artificial intelligence-enhanced sensor network with ubiquitously embedded sensors will ultimately achieve desired visibility across the critical infrastructure.
- Broad applications include natural gas infrastructure, power grid, power generation, carbon capture and storage, hydrogen infrastructure, nuclear spent fuel, environmental monitoring, etc.

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PITT Poster Presentation Slide Summaries

UPitt Infrastructure Sensor Collaboration (UPISC)
2024 Workshop
November 13, 2024

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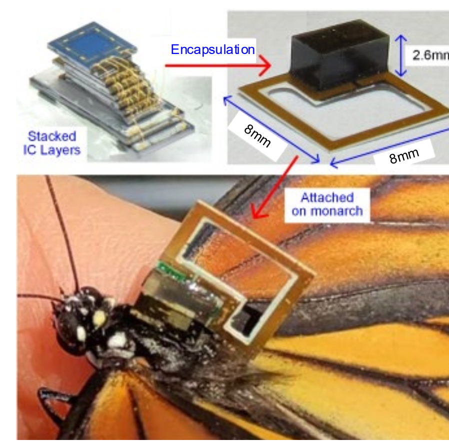
Contact: **Inhee Lee**
Email: **inhee.lee@pitt.edu**

Millimeter-Scale Smart Sensing System

- Miniaturize the computing/sensing system by stacking bare chip modules without individual packaging → Recognized as the world's smallest computer
- The sensor is powered by integrated miniature thin-film batteries, it operates without long wires and external wireless equipment.
- We used this sensor for ecological snail research. Now, we are working to track the migration path of Monarch butterfly using a recorded light profile.
- We are looking for other space-limited applications.
- Inhee Lee, Assistant Professor, Electrical & Computer Engineering since 2019

Computer History Museum

The New York Times



MobiCom'21 Best Paper

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Contact: Dr. Khurram Naeem
Email: khn16@pitt.edu

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Overview of Fiber Optic Sensors R&D: Interrogation Systems and their Applications

Khurram Naeem[1], Tulika Khanikar[1], Yang Duan Su[1], Dolendra Karki[1], Pengdi Zhang[1], Enrico Sarcinelli[1] and Paul Ohodnicki[1,2]

[1]*Mechanical Engineering & Materials Science, University of Pittsburgh, USA ;* [2]*Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh, USA*

NEUP Nuclear Energy University Program
U.S. Department of Energy

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1 Infrastructure Monitoring

- **long-haul size** (in Kms range)
- **Safe infrastructure usage**
- **Economic development**
- **Optimal management**
- an **early-warning** solutions,
- helps key **decision-making**

Natural Gas, Oil, & H_2 Transport, Storage & Plants

Civil (Road, Bridges, Water)

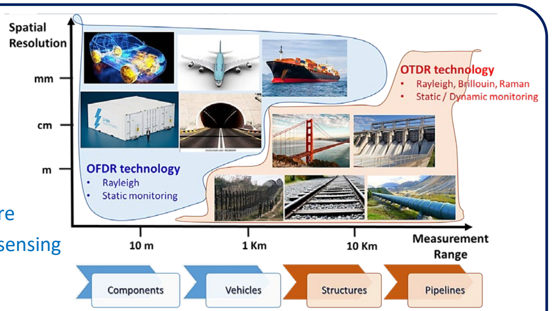
Electricity Grid Transport & Transformer

Conventional & Renewable Generation

2 Fiber-optic Sensor (FOS) Technology

Optical fiber is:

- Lightweight / embeddable
- Explosion- and electrical-proof
- Can work up to 1000 ºC temperature
- **Quasi-distributed** and **distributed** sensing



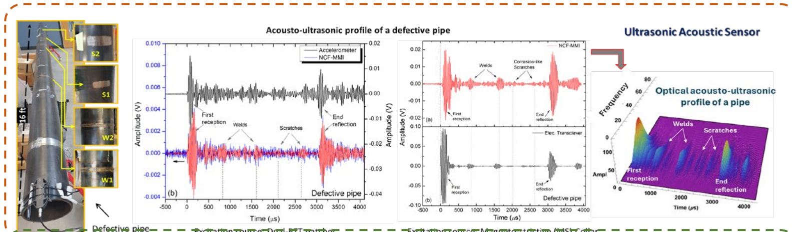
Distributed FOS:

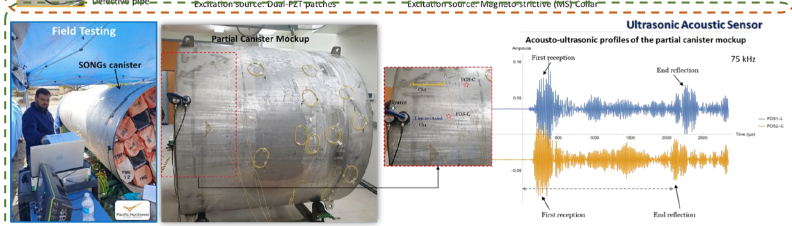
- **Fiber optic** cable act as a transducer
- **Real-time detection** of diverse events and objects
- **Identify and Classify** the events and objects; ML/AI
- **Ability to simultaneously monitor**: Acoustics/ Vibration, Temperature & Strain

4 Sensing applications

Pipeline Monitoring

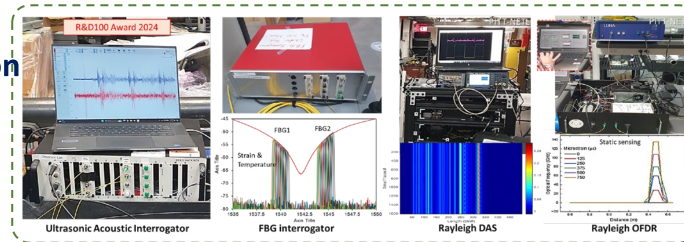
Spent-fuel Nuclear canister Monitoring



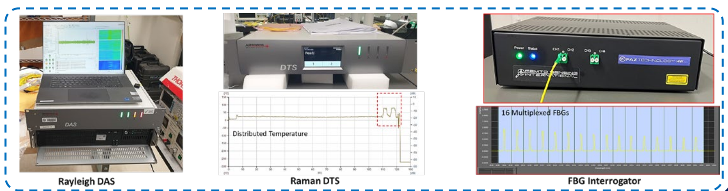


3 Optical Interrogation Methods

Custom designed systems



Commercial systems



Contact: Enrico Sarcinelli
Email: ens65@pitt.edu

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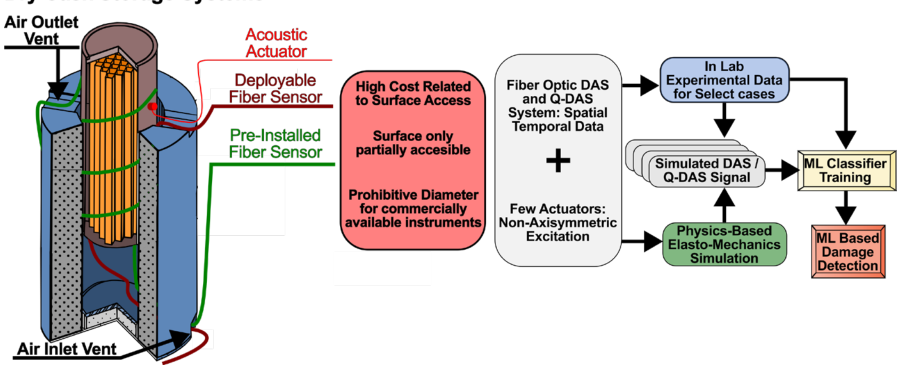
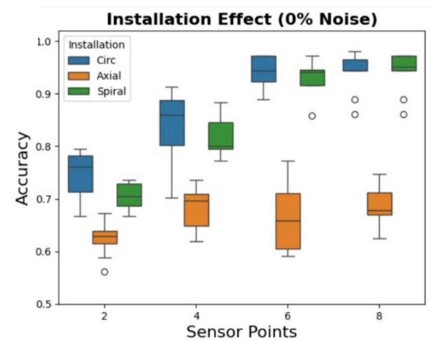
Fusion of Distributed Fiber Optics, Acoustic NDE and Physics-Based AI for Spent Fuel Monitoring

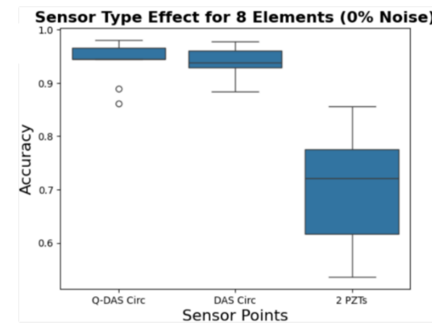
Enrico Sarcinelli[1], Pengdi Zhang[1], Khurram Naeem[1], Kayte Denslow[2], Ruishu F. Wright[3], Nageswara Lalam[3], Paul Ohodnicki[1]
[1]Department of Mechanical Engineering and Materials Science, University of Pittsburgh
[2]Pacific Northwest National Laboratory, Richland, WA, USA 99345
[3]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA, USA 15236

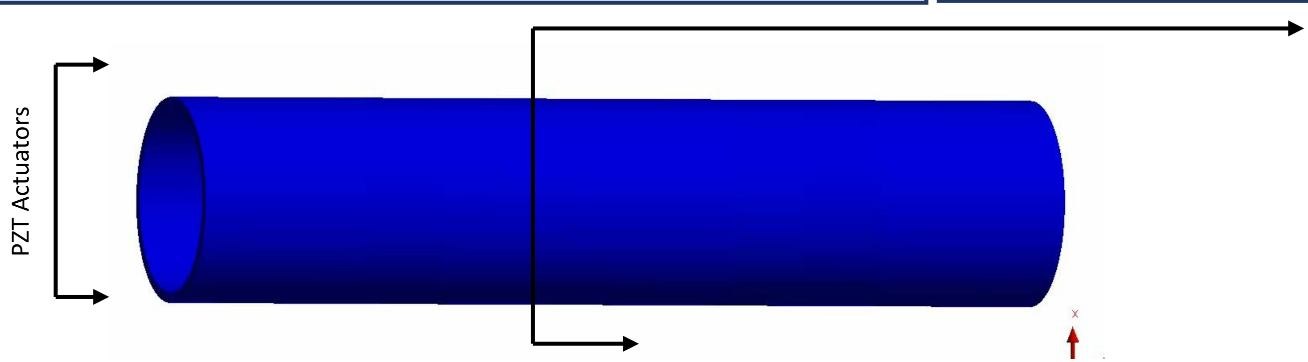
Stainless-Steel Canister Monitoring System Overview



Investigation of Different Fiber Optic Sensor Installation Schemes on AI damage Identification Performance







Simulation x Experiment Angular Profile

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Contact: Pengdi Zhang
Email: pez37@pitt.edu

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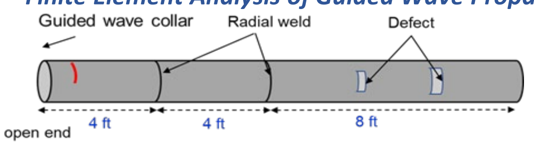
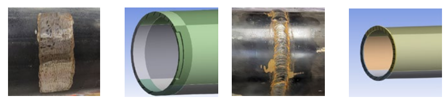
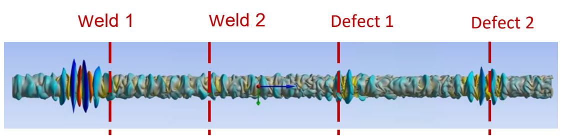
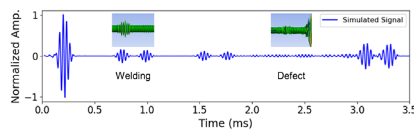
Innovative Fusion for Pipeline Corrosion Detection: Fiber Optic Sensing, Physics-Based Modeling, and Deep Learning

Finite Element Analysis of Guided Wave Propagation:



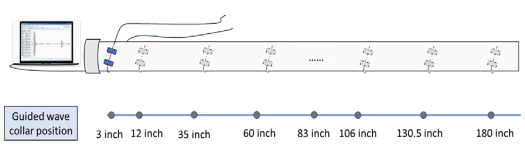


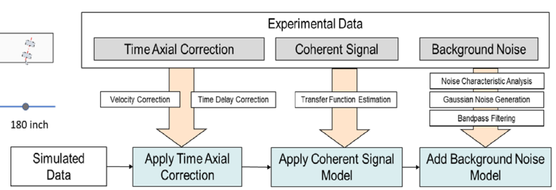




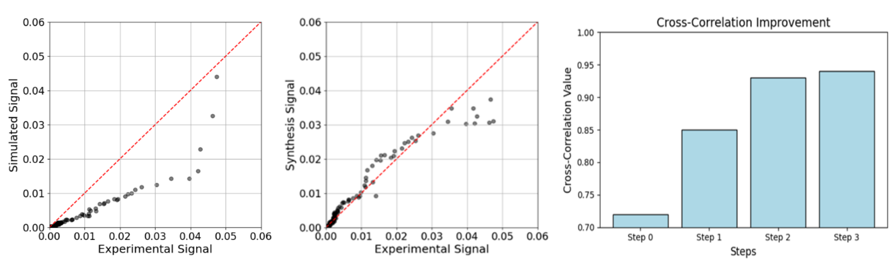
Noise Model for Synthetic Simulated Data:

Signal (12 inch away from excitation):



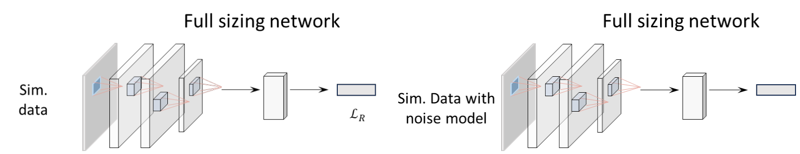


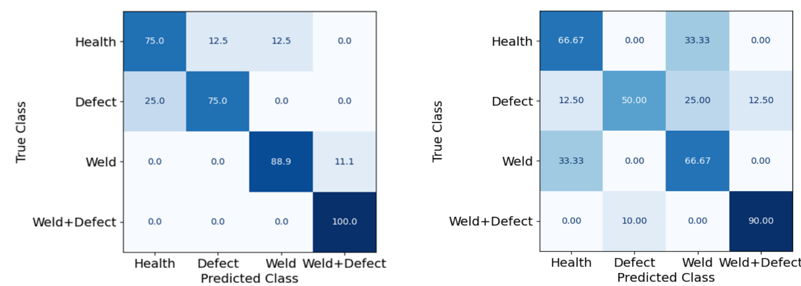
Comparative Analysis of Simulated and Synthetic Signal



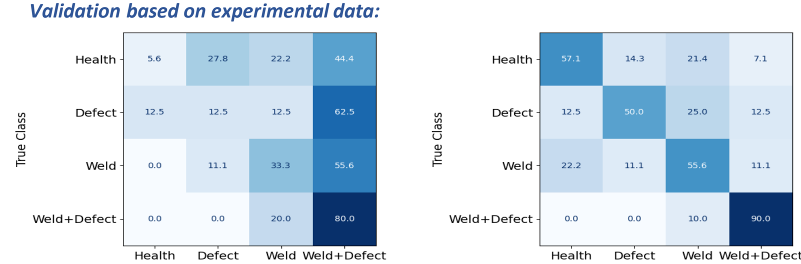
Improvement from Step 0 to Step 3; Steps Explained: Step 0: Pure simulated signal; Step 1: Simulated signal with time-axis correction; Step 2: Simulated signal with transfer function applied; Step 3: Synthetic signal with added background noise.

Defect defection based on different data source:





Validation based on experimental data:



Training Testing	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
Sim → Sim	90.00	90.63	90.00	90.31
Sim → Exp	52.94	50.00	52.94	51.43
Syn → Syn	77.50	79.17	77.50	78.32
Syn → Exp	73.68	75.00	73.68	74.34

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

Contact: Dr. Paul Ohodnicki
Email: **pro8@pitt.edu**

NATIONAL ENERGY TECHNOLOGY LABORATORY

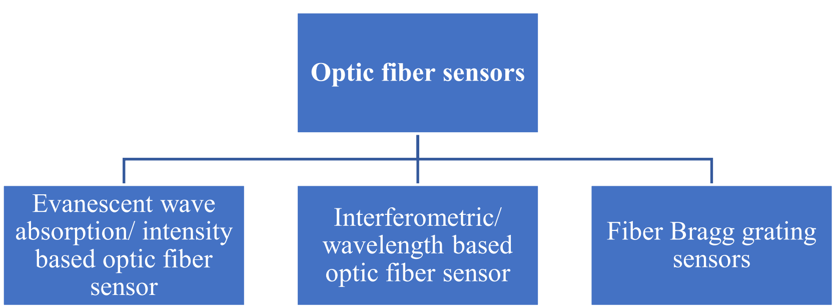
Distributed Fiber Optic Chemical Sensing for marine CO_2 Detection and Removal applications

Introduction

- Focus on developing a distributed fiber optic sensor system for **real-time monitoring** of CO_2 and pH levels.
- Importance: High sensitivity and selectivity are essential for environmental monitoring, biomedical applications, and industrial processes.

Objective

- Design and implement an **optical fiber-based sensor** capable of detecting low concentrations of CO_2 and varying pH levels.
- Enhance sensor accuracy through tailored **material coatings** and optimized fiber optics.



Sensing Mechanisms

- **CO_2 Sensing**: Leverages fiber-optic materials with high sensitivity to CO_2, employing materials such as PDMS and ZIF-8 for enhanced detection at concentrations <1000 ppm.
- **pH Sensing**: With the aid of polymer matrices and sensing additives coated on the optic fiber the pH of the sensing medium can be detected through absorbance-based or strain-based sensing mechanisms.

Initial sensing materials under testing

pH sensing		CO_2 sensing
Absorbance-based	**TOES-** sol-gel Indicator: meta-Cresol Purple	PDMS
Strain-based	Polyaniline (PANI)	ZIF-8

Acknowledgments

University of Pittsburgh, ARPA-E, NETL, SOFAR, OFS

Contact: Jun Young Hong
Email: juh112@pitt.edu

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

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NATIONAL ENERGY TECHNOLOGY LABORATORY

Integration of Magnetic Field Sensing Materials with Fiber Optic Sensors for Optical Based Field and Current Sensing Applications

Research Highlights

1. Advanced Magnetic Field Sensing Materials Integrated with Optical Platforms

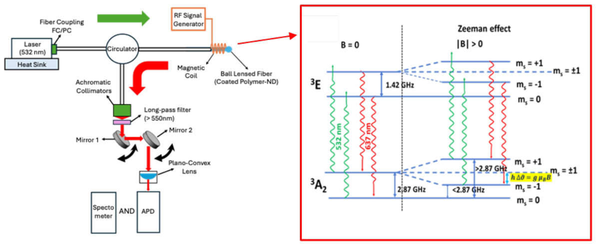
- ❑ YIG single-crystal fibers for Faraday rotation-based sensing.
- ❑ NV center nanodiamonds for fluorescence-based sensing using Optically Detected Magnetic Resonance (ODMR) and Zeeman effect.
- ❑ Polymer-magnetic nanoparticle composites for intensity-based MMI sensing.

2. Power-Grid Applications Potential

- ❑ Real-time fault detection to prevent outages and equipment damage.
- ❑ High EMI immunity, ideal for operation in challenging industrial environments.
- ❑ Improved efficiency and load balancing for stable and reliable grid performance.

1. Yttrium Iron Garnet (YIG, $Y_3Fe_5O_{12}$) Single Crystal Fiber

2. Polymer-Nitrogen-Vacancy (NV) Center Nanodiamond Composite



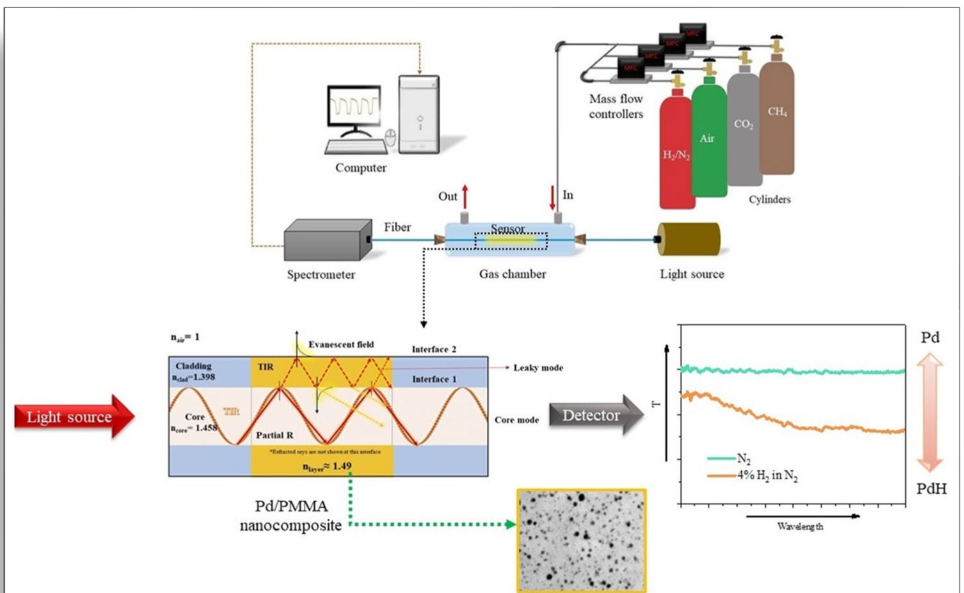
3. Polymer-Magnetic Nanoparticles (NP) Composite

Contact: Dr. Tulika Khanikar
Email: tuk11@pitt.edu

Pd/PMMA nanocomposite coated fiber optic hydrogen sensor

Tulika Khanikar, Dolendra Karki, Yang-Duan Su, Jun Young Hong, Yuankang Wang, Khurram Naeem and Paul R. Ohodnicki

Department of Mechanical Engineering and Materials Science, University of Pittsburgh, PA, USA.



- A fiber optic hydrogen sensor coated with a palladium/polymethyl methacrylate (Pd/PMMA) nanocomposite layer is fabricated and benchmarked here.
- The sensor with Pd/PMMA substituted cladding, operates by intensity modulation technique through partial reflection in the sensing region.
- In-situ thermal reduction method has been adopted for nanocomposite synthesis due to reduced processing steps required and to avoid material waste.
- The sensor exhibits excellent resistance to humidity and good environmental stability in presence of interfering gases. Furthermore, it can detect low hydrogen concentration of down-to 0.1%, shows suppressed hysteresis and has response time of 25 sec to 4% hydrogen
- The feasible and cost-effective sensor preparation protocol make the sensor a competitive candidate for hydrogen gas monitoring applications that operate at near room temperatures.

Contact: Yang-Duan Su
Email: yas57@pitt.edu

NATIONAL ENERGY TECHNOLOGY LABORATORY

Next-Generation Multiparameter Fiber Optic Photonic Nose for Energy Infrastructure Sensing

Yang-Duan Su,[1] Paul R. Ohodnicki,[1,2,3] Jeffrey K. Wuenschell,[4] Nageswara Lalam,[4] Enrico Sarcinelli,[1] Michael P. Buric,[5] and Ruishu Wright[4]

[1] Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, PA, USA
[2] Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh, PA, USA
[3] Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, USA
[4] National Energy Technology Laboratory, Pittsburgh, PA, USA
[5] National Energy Technology Laboratory, Morgantown, WV, USA

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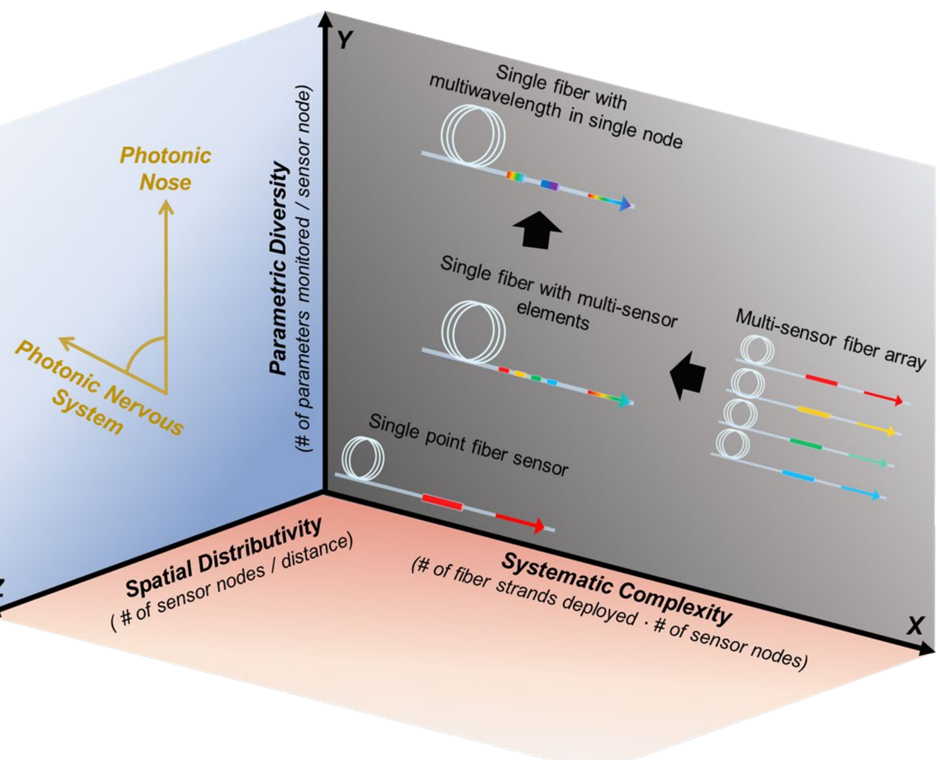

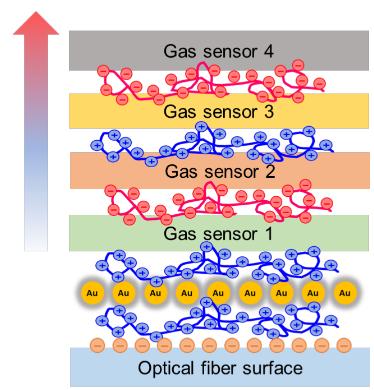

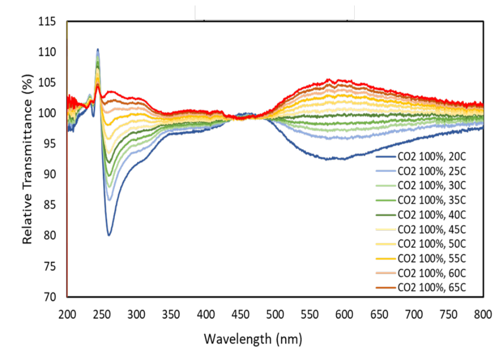

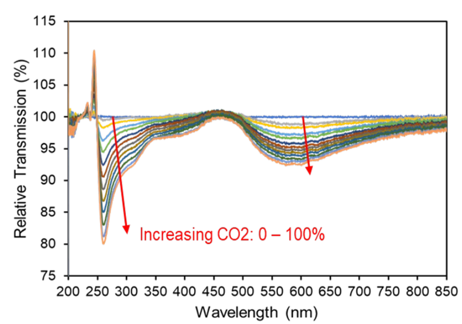

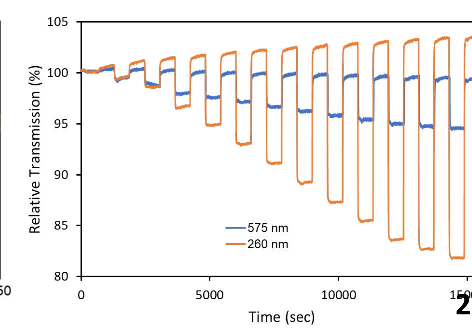

Contact: Dr. Paul Ohodnicki
Email: pro8@pitt.edu

NATIONAL ENERGY TECHNOLOGY LABORATORY

Low-Cost Multi-Channel Fiber Optic Interrogator with Energy Harvesting and LoRa Wireless Communication for Power Grid Applications

Heather Phillips[1], Jacob Jones[2], Peter Kutschke[2], Jillian Zitcovich[2], Yang-Duan Su[3], Brandon Grainger[2] and Paul Ohodnicki[1,2,3]
[1]Engineering Science, University of Pittsburgh
[2]Department of Electrical and Computer Engineering, University of Pittsburgh
[3]Department of Mechanical Engineering and Materials Science, University of Pittsburgh

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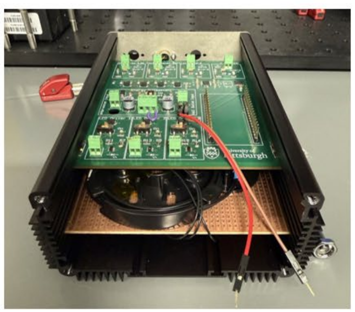

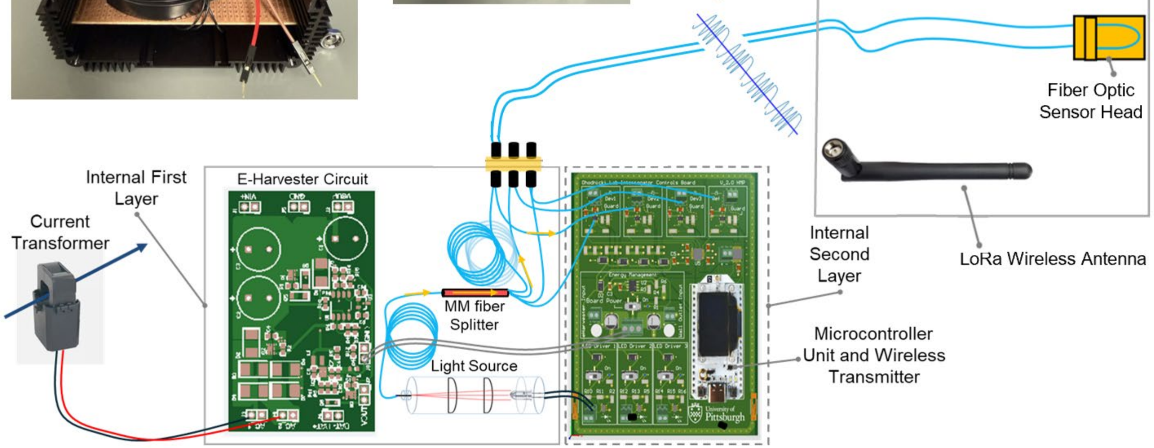

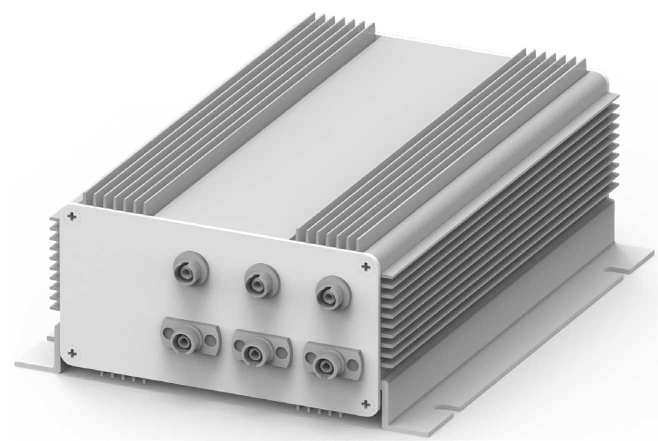

Contact: Dr. Paul Ohodnicki
Email: pro8@pitt.edu

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PITT Poster Presentation Slide Summaries

Sensor Platform Technologies

- Millimeter Scale Smart Sensing System (Dr. Inhee Lee)
- Overview of Fiber Optic Sensors R&D: Interrogation Systems and Their Applications (Dr. Khurram Naeem)
- Next-Generation Multiparameter Fiber Optic Photonic Nose for Energy Infrastructure Sensing (Yang-Duan Su)

Hydrogen Sensors for Leak Detection in Emission and Safety Applications

- Innovative Fusion for Pipeline Corrosion Detection: Fiber Optic Sensing, Physics-Based Modeling, and Deep Learning (Pengdi Zhang)

Natural Gas Pipeline and Methane Leak Sensors

- Pd/PMMA nanocomposite coated fiber optic hydrogen sensor (Dr. Tulika Khanikar)

Carbon Capture System Monitoring

- Distributed Fiber Optic Chemical Sensing for marine CO_2 Detection and Removal applications (Jahid Chowdhury and Devika Mohan)

Nuclear Sensor Systems

- Fusion of Distributed Fiber Optics, Acoustic NDE and Physics-Based AI for Spent Fuel Monitoring (Enrico Sarcinelli)
- Fiber Optic Sensors for Molten Salt Reactor Monitoring Applications (Ian Hendricks)

Electric Power Grid Sensing (Including Quantum)

- Low-Cost Multi-Channel Fiber Optic Interrogator with Energy Harvesting and LoRa Wireless Communication for Power Grid Applications (Paul Ohodnicki, Heather Phillips, Yang-Duan Su)
- Integration of Magnetic Field Sensing Materials with Fiber Optic Sensors for Optical Based Field and Current Sensing Applications (Jun Young Hong)

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Contact: Dr. Nageswara Lalam
Email: Nageswara.Lalam@netl.doe.gov

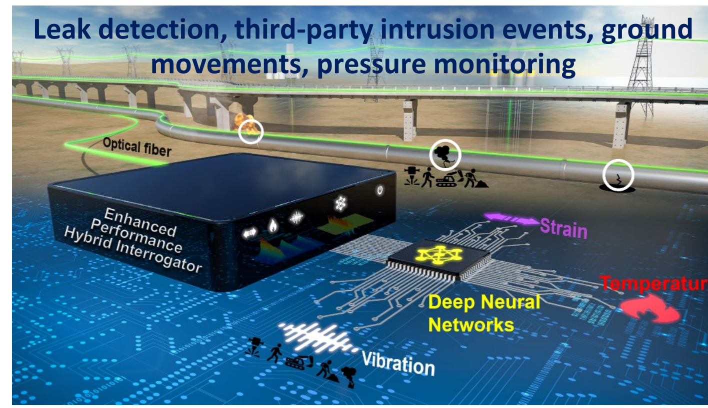
NATIONAL ENERGY TECHNOLOGY LABORATORY

Advanced Distributed Optical Fiber Sensor Systems for Pipeline Integrity Monitoring

Nageswara Lalam[1,2], Matthew Brister[1,2], Hari Bhatta[1,2], Sandeep Bukka[1,2], Abu Mitul[1], Michael Buric[1], and Ruishu Wright[1]

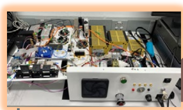
Distributed fiber optic sensor interrogators integrated with deep neural network:

- ❖ Brillouin optical time domain analysis (BOTDA).
- ❖ Phase-sensitive optical time domain reflectometry (phase-OTDR).
- ❖ Optical frequency domain reflectometry (OFDR).
- ❖ Single-mode–multi mode–single-mode (SMS) fiber acoustic sensor.



BOTDA

Sensing range = >100 km
Spatial resolution = <5 m
Measurable parameters:
static strain, temperature



ϕ-OTDR/DAS Patented

Sensing range = >10 km
Spatial resolution = <2 m
Measurable parameters:
acoustics, dynamic strain

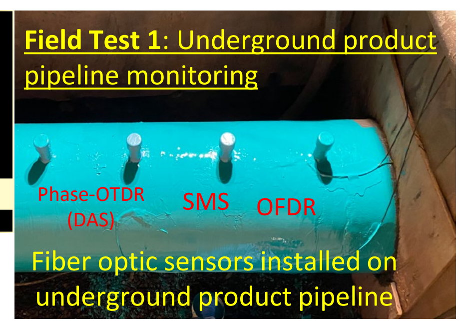
OFDR

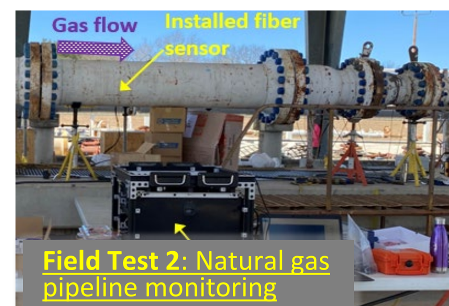
Sensing range = >100 m
Spatial resolution = <1mm
Measurable parameters:
static strain, temperature

SMS Patented

Frequency range= 1 Hz to 1.2 MHz
Resolution= <1 to 2 Hz

2024 R&D 100 WINNER





Field validated at natural gas pipeline and underground product pipeline

Accomplishments:

[1]. N. Lalam, S. Bukka, H. Bhatta, M. Buric, P. Ohodnicki, and R. Wright, “Achieving Precise Multiparameter Measurements with Distributed Optical Fiber and Deep Neural Networks”, *Communications Engineering*, vol. 3, p. 121, 2024.
[2]. N. Lalam, H. Bhatta, N. Diemler, S. Bukka,….P. Ohodnicki, and R. Wright, “DNN-Assisted Distributed Strain and Temperature Fiber Sensor System for Natural Gas Pipeline Monitoring”, *IEEE Transactions on Instrumentation & Measurement*, 2024.
[3]. N. Lalam, P. Westbrook, K. Naeem, P. Lu, P. Ohodnicki, N. Diemler, et al., "Pilot-scale testing of natural gas pipeline monitoring based on phase-OTDR and enhanced scatter optical fiber cable," *Scientific Reports*, vol. 13, p. 14037, 2023.
[4]. N. Lalam, H. Bhatta, X. Sun, P. Lu, P. Ohodnicki, M. P. Buric, and R. Wright, "Multi-parameter distributed fiber optic sensing using double-Brillouin peak fiber in Brillouin optical time domain analysis," Optics Express, vol. 31, pp. 36590-36602, 2023.
[5]. A. Venketeswaran, N. Lalam, P. Lu, S. R. Bukka, M. P. Buric, and R. Wright, "Robust Vector BOTDA Signal Processing with Probabilistic Machine Learning," Sensors, vol. 23, p. 6064, 2023.

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Email: sandeep.bukka@netl.doe.gov

Reduced order model for Guided Wave propagation on gas pipelines to enable real time simulation

Sandeep Reddy Bukka[1,2], Nageswara Lalam[1,2] , Pengdi Zhang[3] , Ruishu F. Wright[1], Paul R Ohodnicki[3]
[1]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA, USA 15236
[2]NETL Research Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA USA
[3]University of Pittsburgh, 3700 O'Hara Street Benedum Hall of Engineering, Pittsburgh, PA 15261

Motivation

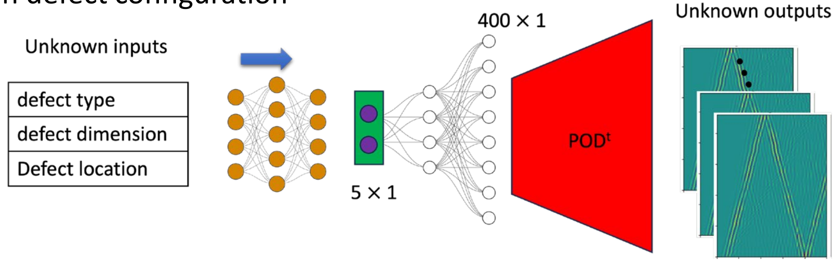
- There is a need to build a model to simulate guided wave propagation for physical defects such as welding, corrosion since experiments are difficult to perform
- Finite element Simulations are often expensive to perform and time consuming
- Reduced order models based on autoencoder networks can be built on simulation data for a specific use case and domain of operation.

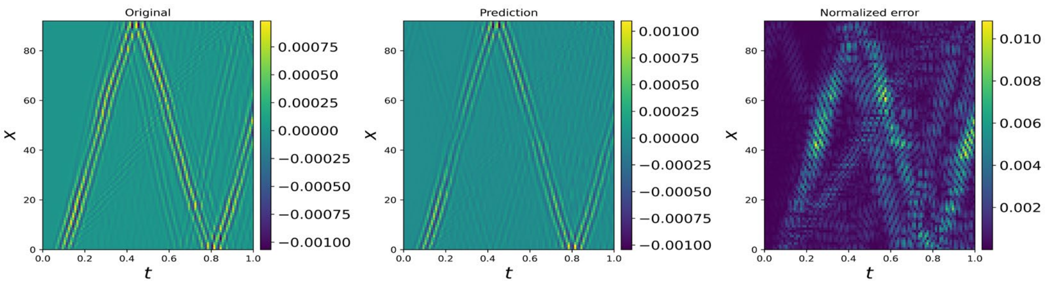
Advantages

- Reduced order models (ROM's) will have low memory footprint and computationally cheap.
- ROM's can be easily integrated to other computational workflows like Digital Twin where access to simulation data in real time is needed.
- ROM's will avoid the redundant computational simulations for a similar parameter in a given domain of operation.

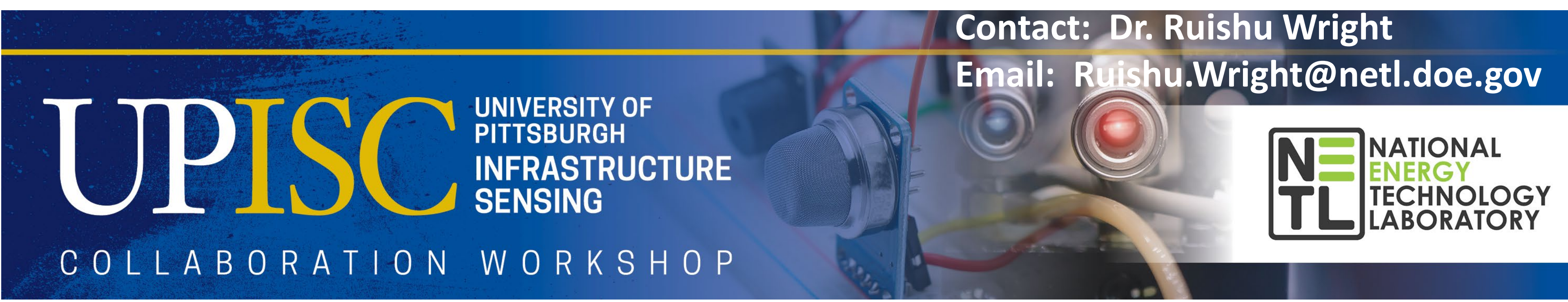
Approach

Proper Orthogonal Decomposition (POD) and autoencoder networks are utilized for dimensionality reduction and the sensor response is predicted by ROM for a given defect configuration





ROM time: 0.00387(s) , Full Order Model (FOM) time: ~30 mins(s) ~1800(s), Speed up: 465116x ~ 47000 times faster



Multi-Parameter Optical Fiber for Distributed Sensing of Humidity, CH_4, CO_2, and Corrosion

Badri P Mainali[1,2]; Alexander Shumski[1,2]; Ruishu Wright[1]

[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA

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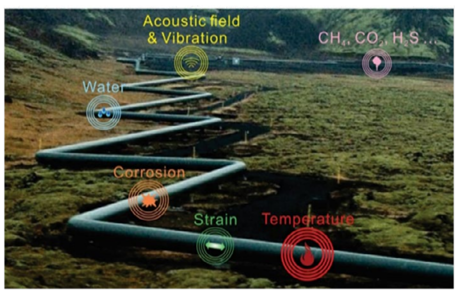
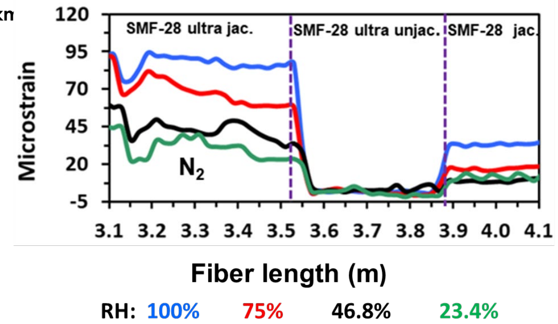
Pipeline Monitoring Concerns

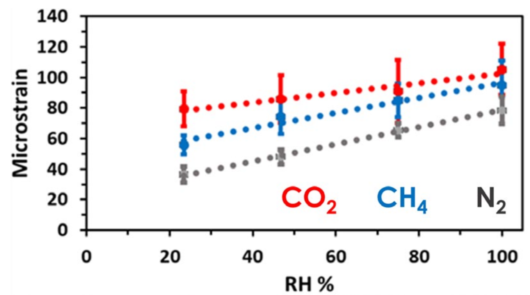
Pipeline Integrated with Distributed Optical Fiber > 100 km

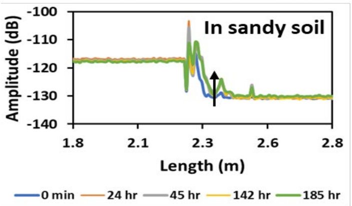


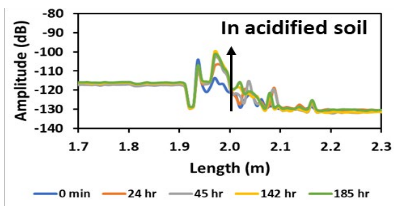
- Pipeline corrosion costs billions of dollars annually.
- Increased humidity and CO_2 can predict corrosion favoring conditions.
- Real-time monitoring of humidity, CO_2, and corrosion is important for safe pipeline operation.

Humidity, CH_4, CO_2, and Corrosion Monitoring









- Single-mode fiber (SMF) jacket detects humidity, CH_4, and CO_2 using swelling-induced strain.
- Increase in backscattered light intensity indicates corrosion of a thin Fe film coated onto the fiber.
- Fe-coated fiber sensors are reinforced by Draka cable which enables corrosion monitoring in soil.

Optical fiber sensors provide long distance distributed sensing of humidity, CH_4, CO_2, and corrosion in natural gas pipeline conditions.

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UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

Passive Wireless Surface Acoustic Wave Sensors for Methane Leakage and Corrosion Monitoring in Pipelines

Richard Pingree[1,2]; David W. Greve[1,3]; Jeff Culp[1,2]; Daejin Kim[1,2]; Swetha Menon[1,2]; Matthew Brister[1,2]; Badri Mainali[1,2]; Ruishu Wright[1]

[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [3]Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

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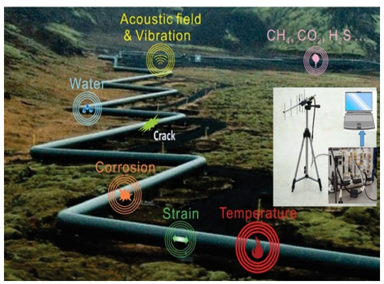
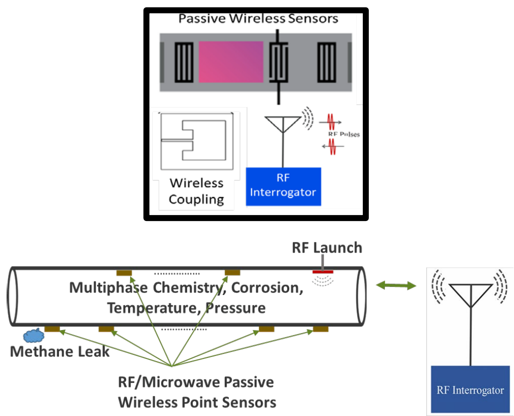
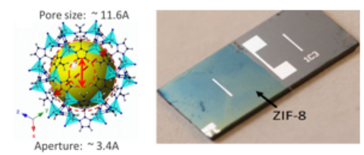
Motivation



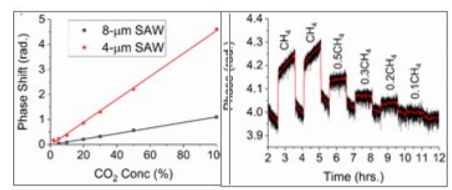
- Conventional monitoring techniques are infrequently performed making prediction of potential events difficult.
- Continuous and real-time monitoring technologies are helpful to better identify, locate, and quantify methane leaks and corrosion events.
- Passive wireless sensors and their network are emerging platforms for remote and real-time monitoring of long pipelines.
- We help operators to reduce monitoring costs and simplify the inspection process by developing a low-maintenance, remote, and real-time capable multiparameter monitoring tool.

Pipeline Monitoring with Passive Wireless Sensors

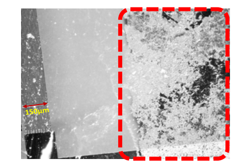




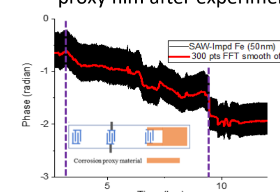
A MOF (ZIF-8) nanoporous material (left) and coated SAW sensor (right)



Mass-based sensing of CO_2 and CH_4 at room temperature.



Optical Image of corrosion proxy film after experiment.



Phase response of a Fe (50nm) coated IL-RDL sensor.

Advantages

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

Other Applicable Industries

- Subsurface Wellbores
- Harsh Environments in Energy Generation
- Automotive
- Aerospace

Small (~5x10 cm^2), Low-Cost, Passive Wireless SAW Sensors to enable Ubiquitous Wireless Sensor Network for Energy Infrastructure Monitoring

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UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

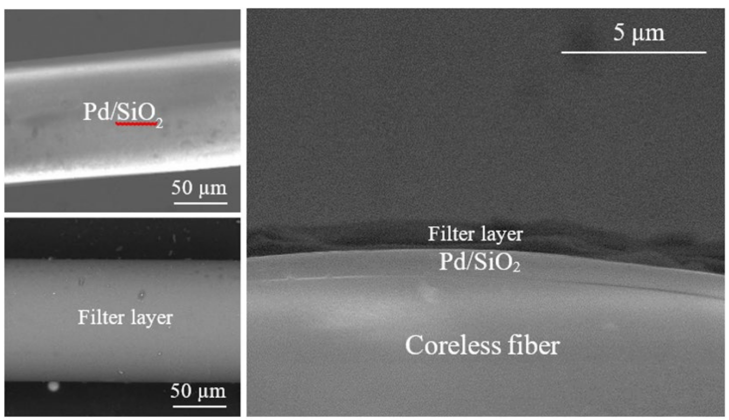
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

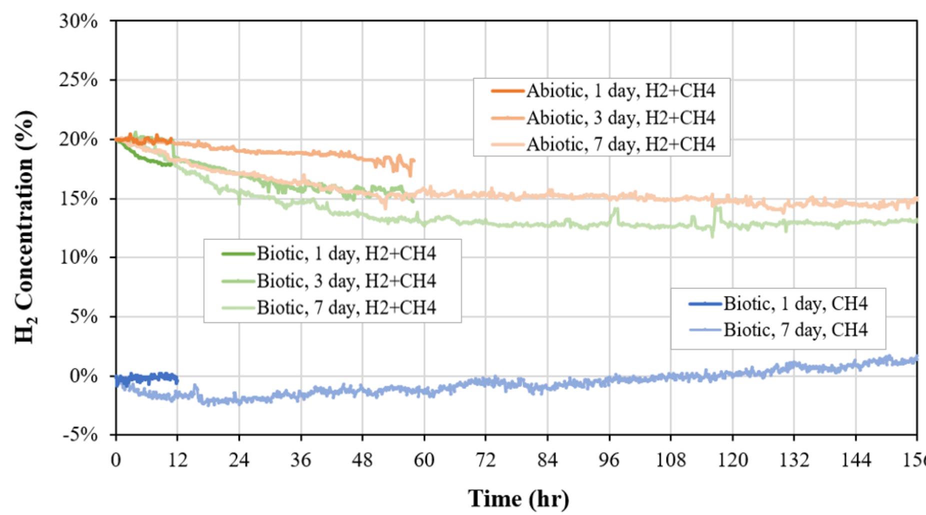
H_2 Sensing with an Optical Fiber Sensor in the Subsurface H_2 Storage Conditions

Daejin Kim[1,2], Alexander Shumski[1,2], Kara Tinker[1,2], Djuna Gulliver[1], Ruishu Wright[1]
([1]National Energy Technology Laboratory; [2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA)

- Demonstrated capability of real-time H_2 concentration monitoring with the optical fiber H_2 sensor at **80 °C**, **1000 psi**, and **99% RH** in the presence of **subsurface biological samples**.



(SEM images of the optical fiber H_2 sensor coated with the Pd/SiO_2 and filter layers)



- The **biotic** sample has shown a **higher impact** on hydrogen sensing than the **abiotic** sample.
- The **H_2 concentration has decreased** for 7 days by about 5% and 7% with the abiotic and biotic samples, respectively.

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COLLABORATION WORKSHOP

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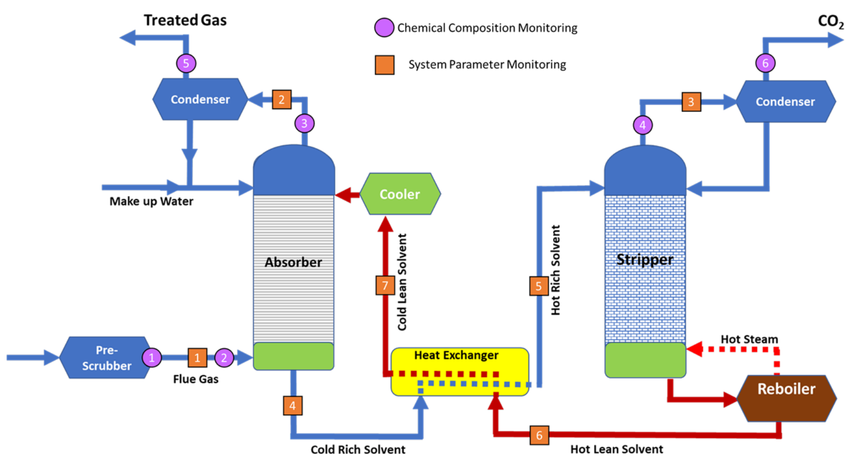
NATIONAL ENERGY TECHNOLOGY LABORATORY

Advanced Sensors for In-Situ Amine Degradation Monitoring in Post-Combustion Carbon Capture

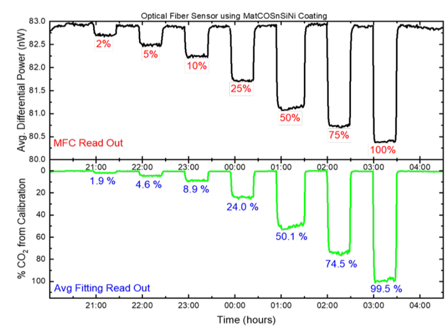
Matthew M. Brister[1,2]; Alexander Shumski[1,2]; Jeffrey Culp[1,2]; Chet R. Bhatt[3,4]; Ruishu F. Wright[1]

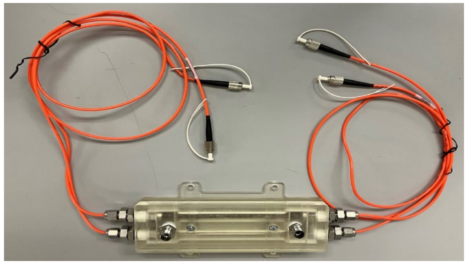
[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [3]National Energy Technology Laboratory, 3610 Collins Ferry Road, Morgantown, WV 26505, USA; [4]NETL Support Contractor, 3610 Collins Ferry Road, Morgantown, WV 26505, USA



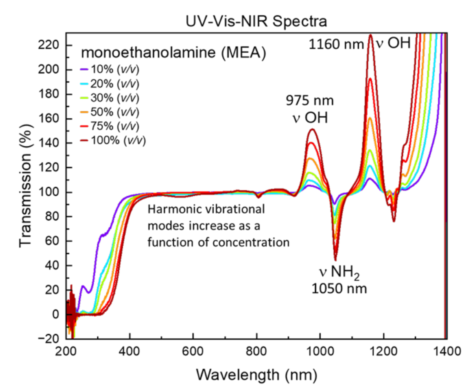
- Solvent based post combustion CO_2 capture systems undergo solvent degradation and loss of CO_2 capture efficiency.
- Current detection methods use periodic non-continuous sampling of the solvent paired with monitoring CO_2 output to identify solvent degradation.
- Two optical fiber-based sensors were developed to continuously monitor CO_2 capture efficiency and solvent characteristics using a low-cost system.

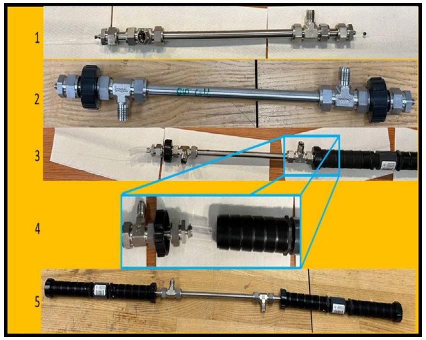
Prototype CO_2 Sensor





Prototype Amine Degradation Sensor





Contact: Dr. Scott Crawford
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UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

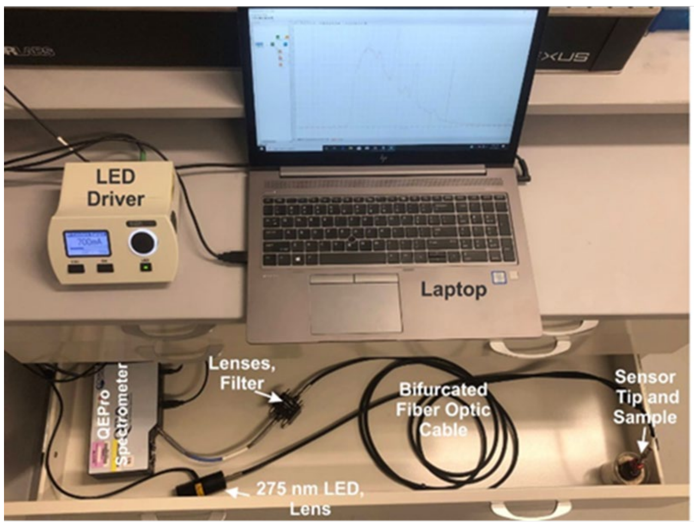
COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

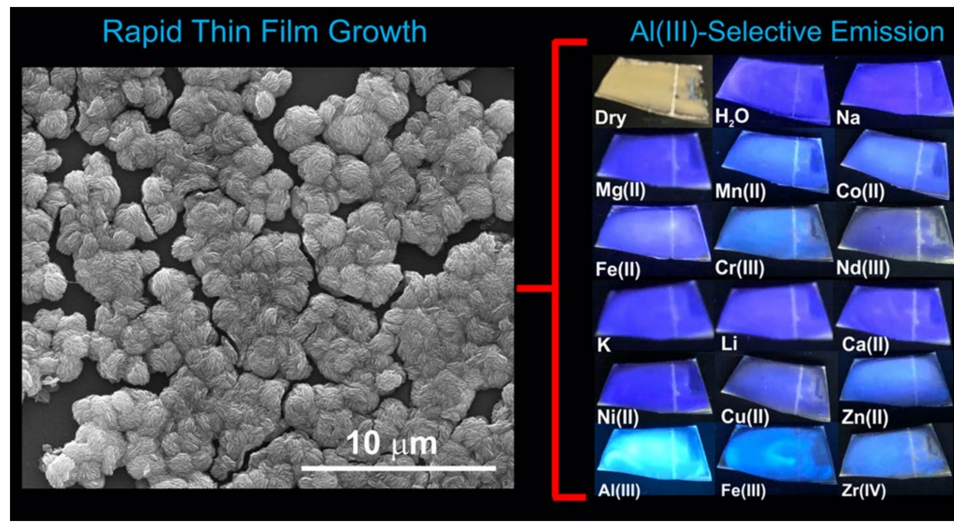
Materials and Platforms for Luminescence-Based Sensing of Economically Critical Metals

Scott E Crawford,[1] Ariana J. Adkisson,[1] Ki-Joong Kim,[1] Tessnim A. Mohammed,[1] James E Ellis,[1,2] Nathan A. Diemler,[1,2] and John P. Baltrus[1]
[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA

Low-cost, portable sensing platforms



Sensitive, selective luminescent materials



- Alleviates pain point of expensive, slow characterization during processing and prospecting
- Sensor costs range from ~$1k to $20K with comparable performance to commercial systems
- Limits of detection for rare earths, cobalt, and aluminum within part-per-billion range

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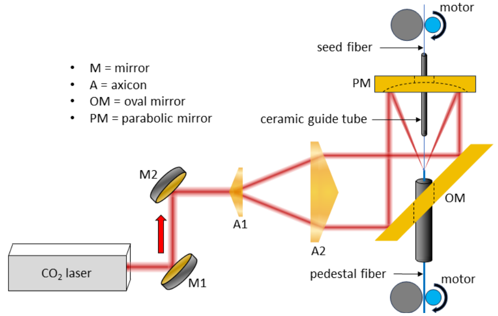
UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

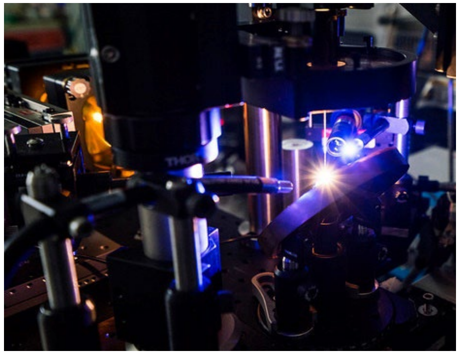
COLLABORATION WORKSHOP

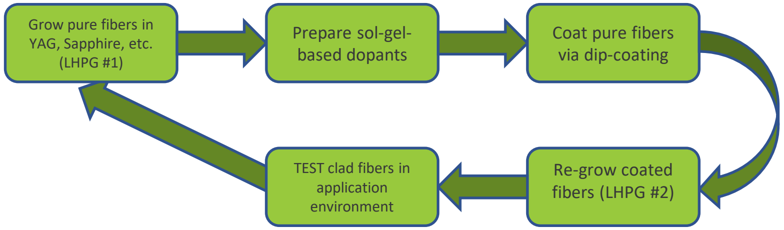
NATIONAL ENERGY TECHNOLOGY LABORATORY

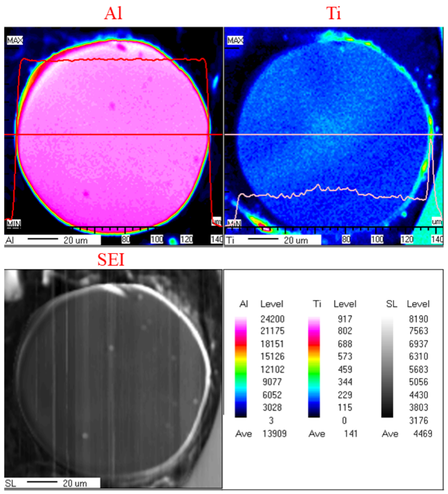
Laser-heated Pedestal Growth and Raman DTS for Harsh-environment Applications

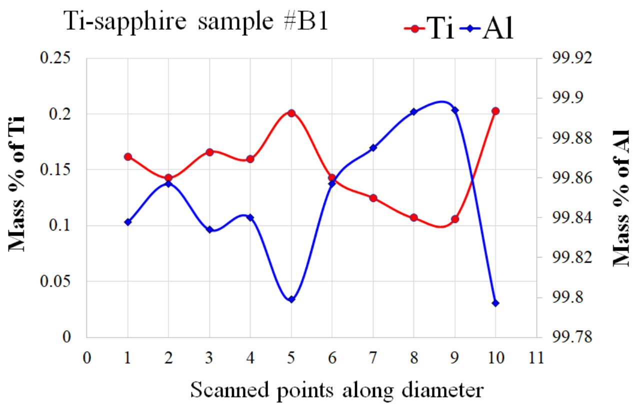
- Single crystal fiber (SC) superior to silica fiber in regard to stability under harsh conditions.
- Grow SC fiber via laser-heated pedestal growth (LHPG).
- Sol-gel coated fiber used in two-step LHPG process to create cladding layer.
- Raman DTS system can use grown fiber for distributed temperature sensor.











UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

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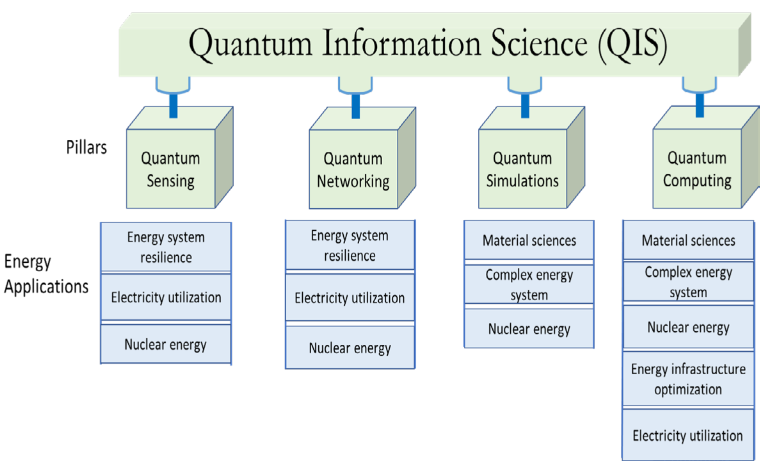
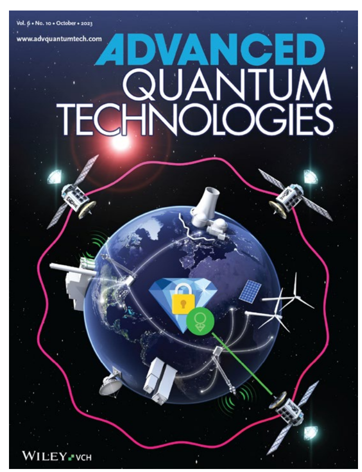
Email: Yuhua.Duan@netl.doe.gov

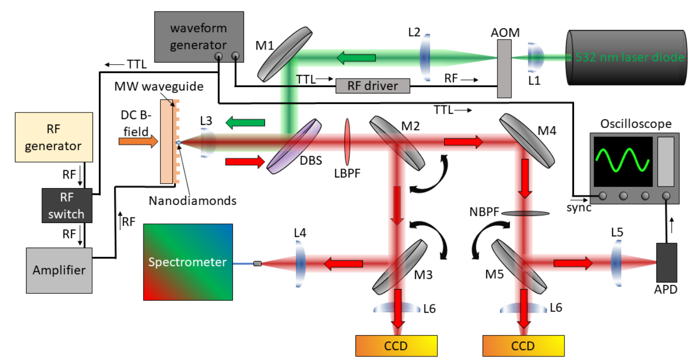
NATIONAL ENERGY TECHNOLOGY LABORATORY

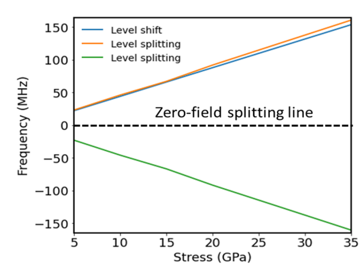
Quantum for Energy Systems and Technologies

- Growing interest in quantum sensing, quantum computing and quantum networks for processes pertaining to energy production, distribution, and consumption.
- Published three open-access comprehensive review articles on quantum computing, quantum networking, and quantum sensing for energy sector applications, with a fourth in preparation.
- Constructed apparatus capable of optically detected magnetic resonance and spin relaxometry using NV centers in nanodiamonds for ultra-sensitive magnetic field, electric field, temperature, and pressure sensing.
- Perform *ab initio* density functional theory (DFT) calculations on the bulk and surface properties of the N and NV defective bulk and diamond surfaces.

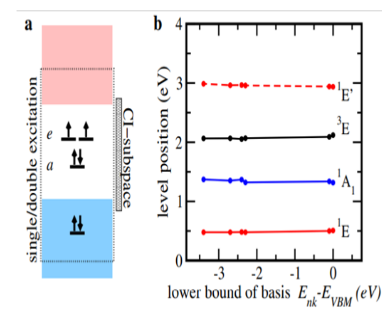








NV center oriented along [111] direction with applied stress along [100]



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Email: Ruishu.Wright@netl.doe.gov

UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

Grid Research, Integration, and Deployment for Quantum (GRID-Q): Quantum Sensing Thrust

Ruishu Wright (PI)[1], Yuhua Duan (co-PI)[1], Michael Buric (co-PI)[3], Hari Paudel[1,2], Gary Lander[3,4], Matthew M. Brister[1,2], Jeff Wuenschell[1], Scott Crawford[1], Nageswara Lalam[1,2], Hari Bhatta[1,2], Richard Pingree[1,2], Paul Ohodnicki (co-PI)[5], Jun Young Hong[5]

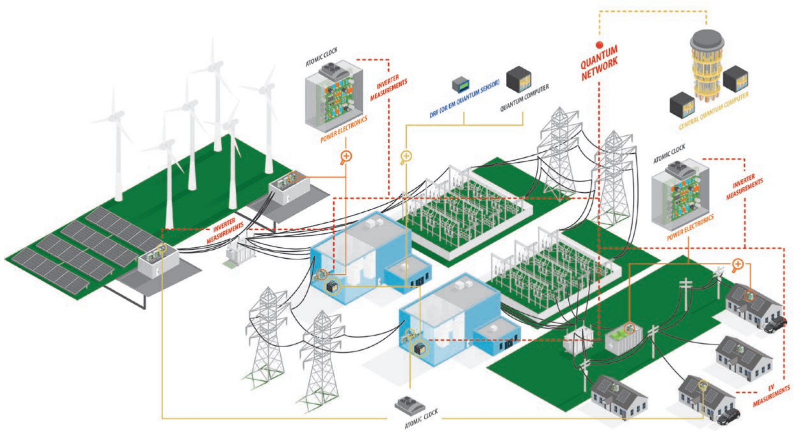
[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA; [3]National Energy Technology Laboratory, 3610 Collins Ferry Road, Morgantown, WV 26505, USA; [4]NETL Support Contractor, 3610 Collins Ferry Road, Morgantown, WV 26505, USA; [5]. Department of Mechanical Engineering & Materials Science, University of Pittsburgh, Benedum Hall, Pittsburgh, PA 15261.

GRID MODERNIZATION INITIATIVE U.S. Department of Energy

GRID-Q project NL team – ORNL, NETL, LANL, LLNL, ANL.
Performance Period: December 1, 2023 to November 30, 2026

GRID-Q Objectives

Thrust 1: Design a User Facility of Quantum Information Science (QIS) for power grids.
Thrust 2: Engage stakeholders, perform gap analysis, and define roadmap
Thrust 3: Use Cases of QIS for Power Grid:
(1) Quantum computing [ORNL, LLNL];
(2) Integrated quantum security/communication [LANL, ORNL];
(3) Secure quantum sensing [NETL/UPitt]



UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING

COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL Poster Presentation Slide Summaries

Natural Gas Pipeline and Methane Leak Sensors

- **Advanced Distributed Optical Fiber Sensor Systems for Pipeline Integrity Monitoring (Dr. Nageswara Lalam)**
- **Reduced order model for Guided Wave propagation on gas pipelines to enable real time simulation (Dr. Sandeep Bukka)**
- **Multi-parameter optical fiber for distributed sensing of humidity, methane, CO_2 and corrosion (Dr. Badri Mainali)**
- **Passive Wireless Surface Acoustic Wave Sensors for Methane Leakage and Corrosion Monitoring in Pipelines (Richard Pingree)**

Hydrogen Sensors for Subsurface Storage Wells

- **H_2 Sensing with an Optical Fiber Sensor in the Subsurface H_2 Storage Conditions (Dr. Daejin Kim)**

Carbon Capture System Monitoring

- **Advanced Sensors for In-Situ Amine Degradation Monitoring in Post-Combustion Carbon Capture (Dr. Alexander Shumski)**

Rare Earth Element and Critical Metals Sensors

- **Materials and Platforms for Luminescence-Based Sensing of Economically Critical Metals (Dr. Scott Crawford)**

High Temperature and Harsh Environment Sensing

- **Laser-heated Pedestal Growth and Raman DTS for Harsh-environment Applications (Dr. Gary Lander)**

Quantum Sensing

- **Quantum Sensing for Energy Applications (Dr. Yuhua Duan)**
- **Grid Research, Integration, and Deployment for Quantum (GRID-Q): Quantum Sensing Thrust (Dr. Ruishu Wright)**