DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Optical Fiber Sensors for Selective Detection of Acetylene Dissolved in Transformer Oil

Anticipation and prediction of power transformer faults is a critical component in the task of ensuring electrical grid reliability. The goal of this project is to leverage optical fiber sensing technology combined with advanced data analytics to provide a tool for real-time, spatially distributed transformer monitoring.

PRINCIPAL INVESTIGATORS

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NETL / Leidos

WEBSITE

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The Numbers

DOE PROGRAM OFFICE:
OE – Transformer Resilience and Advanced Components (TRAC)

LOCATION:
Pittsburgh, PA

PROJECT TERM:
01/01/2021 to 07/01/2023

PROJECT STATUS:
Ongoing

AWARD AMOUNT (DOE CONTRIBUTION):
$450,000

AWARDEE CONTRIBUTION (COST SHARE):
$0

Disclaimer

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Primary Innovation

- Development of nanoparticle incorporated oxide thin films for sensing markers of transformer oil degradation (acetylene, hydrogen, etc.).
- Enhanced selectivity through application of MOF protective coatings.
- Coming soon in FY22 – packaged pointwise and distributed sensor and optical interrogator development, with an eye towards field testing.

Impact/Commercialization

- Project seeks to develop low-cost optical fiber sensor and interrogator system to complement dissolved gas analysis (DGA) for monitoring of oil-filled transformer health.
- Fiber based technology offers possibility of real-time monitoring and spatially resolved (distributed) sensing. Can be compiled with fiber-based temperature / acoustic monitoring, advanced data analytics, for more intelligent maintenance scheduling and transformer failure risk assessment.

IP STATUS

Non-provisional patent application filed by NETL for multi-parametric sensing with fiber-optic sensor array (acetylene, hydrogen, temperature) on 4/17/2019. Additional IP on distributed sensor and interrogator design may be developed as project moves forward.

DGA Interpretation Standard for Transformer Faults

Table 1—90th percentile gas concentrations as a function of O_2/N_2 ratio and age in μL/L (ppm)

		O_2/N_2 Ratio ≤ 0.2				O_2/N_2 Ratio > 0.2			
		Transformer Age in Years				Transformer Age in Years			
		Unknown	1 – 9	10 – 30	>30	Unknown	1 – 9	10 – 30	>30
Gas	Hydrogen (H_2)	80	75		100	40	40		
	Methane (CH_4)	90	45	90	110	20	20		
	Ethane (C_2H_6)	90	30	90	150	15	15		
	Ethylene (C_2H_4)	50	20	50	90	50	25	60	
	Acetylene (C_2H_2)	1	1			2	2		
	Carbon monoxide (CO)	900	900			500	500		
	Carbon dioxide (CO_2)	9000	5000	10000		5000	3500	5500	

NOTE—During the data analysis, it was determined that voltage class, MVA, and volume of mineral oil in the unit did not contribute in significant way to the determination of values provided in Table 1.

Table 5— Rogers Ratios Method

Case	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Suggested fault diagnosis
0	< 0.1	0.1 to 1.0	< 1.0	Unit normal
1	< 0.1	< 0.1	< 1.0	Low-energy density arcing—PD[a]
2	0.1 to 3.0	0.1 to 1.0	> 3.0	Arcing—High-energy discharge
3	< 0.1	0.1 to 1.0	1.0 to 3.0	Low temperature thermal
4	< 0.1	> 1.0	1.0 to 3.0	Thermal < 700 °C
5	< 0.1	> 1.0	> 3.0	Thermal > 700 °C

[a] There is a tendency for the ratios C_2H_2/C_2H_4 and C_2H_4/C_2H_6 to increase to a ratio above 3 as the discharge develops in intensity.

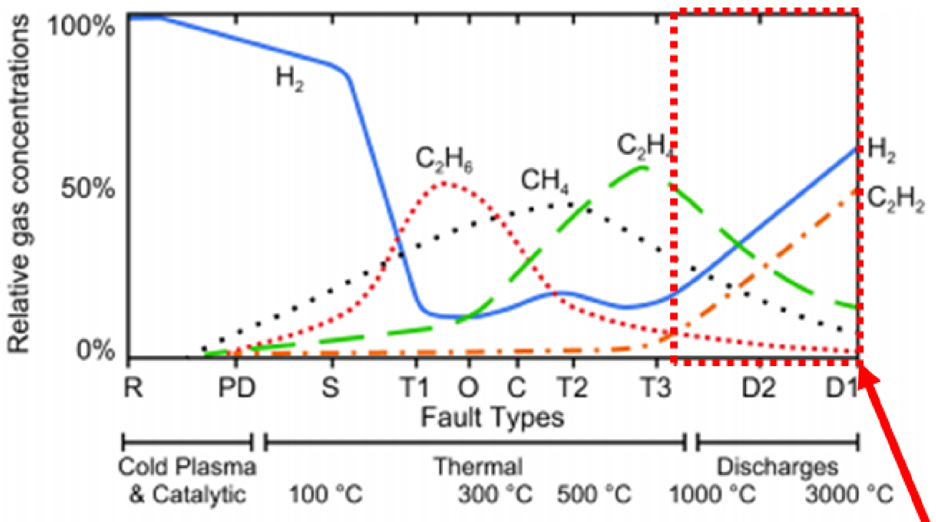


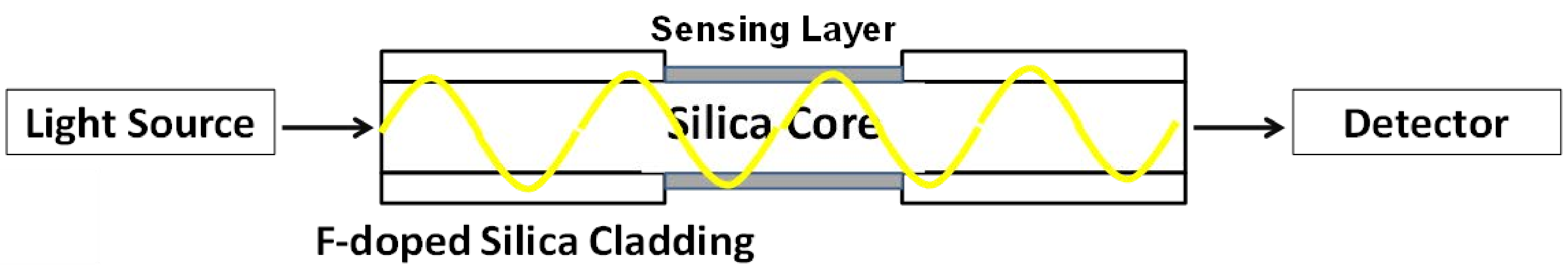
Figure 1—Relative percentage of dissolved gas concentrations in mineral oil as a function of temperature and fault type

In presence of arcing, acetylene concentration increases dramatically – can be 0.1 – 3.0x ethylene concentration (> 100 ppm).

IEEE C57.104-2019 - IEEE Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers

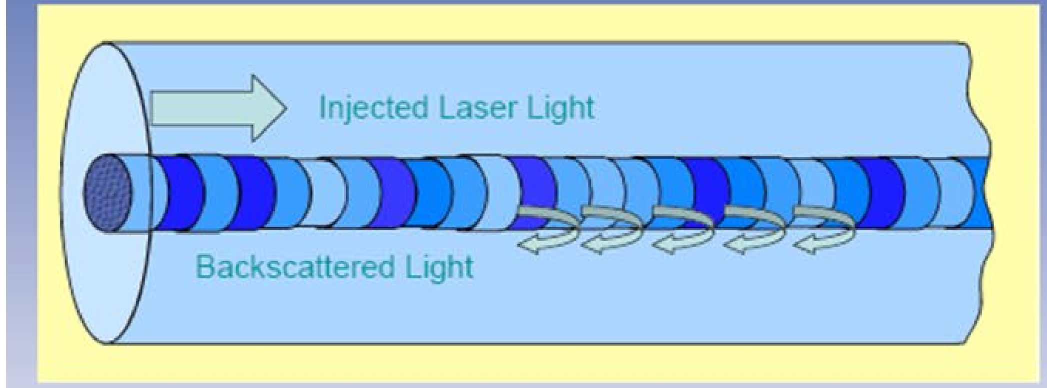
Optical Fiber Based Sensor Technology

Evanescent Wave Sensors



- → **Eliminate Electrical Wiring and Contacts at the Sensing Location**
- → **Tailored to Parameters of Interest Through Functional Materials**
- → **Eliminate EMI and Potential Interference with Electrical Systems**
- → **Compatibility with Broadband and Distributed Interrogation**

Imperfections in fiber lead to Rayleigh backscatter:

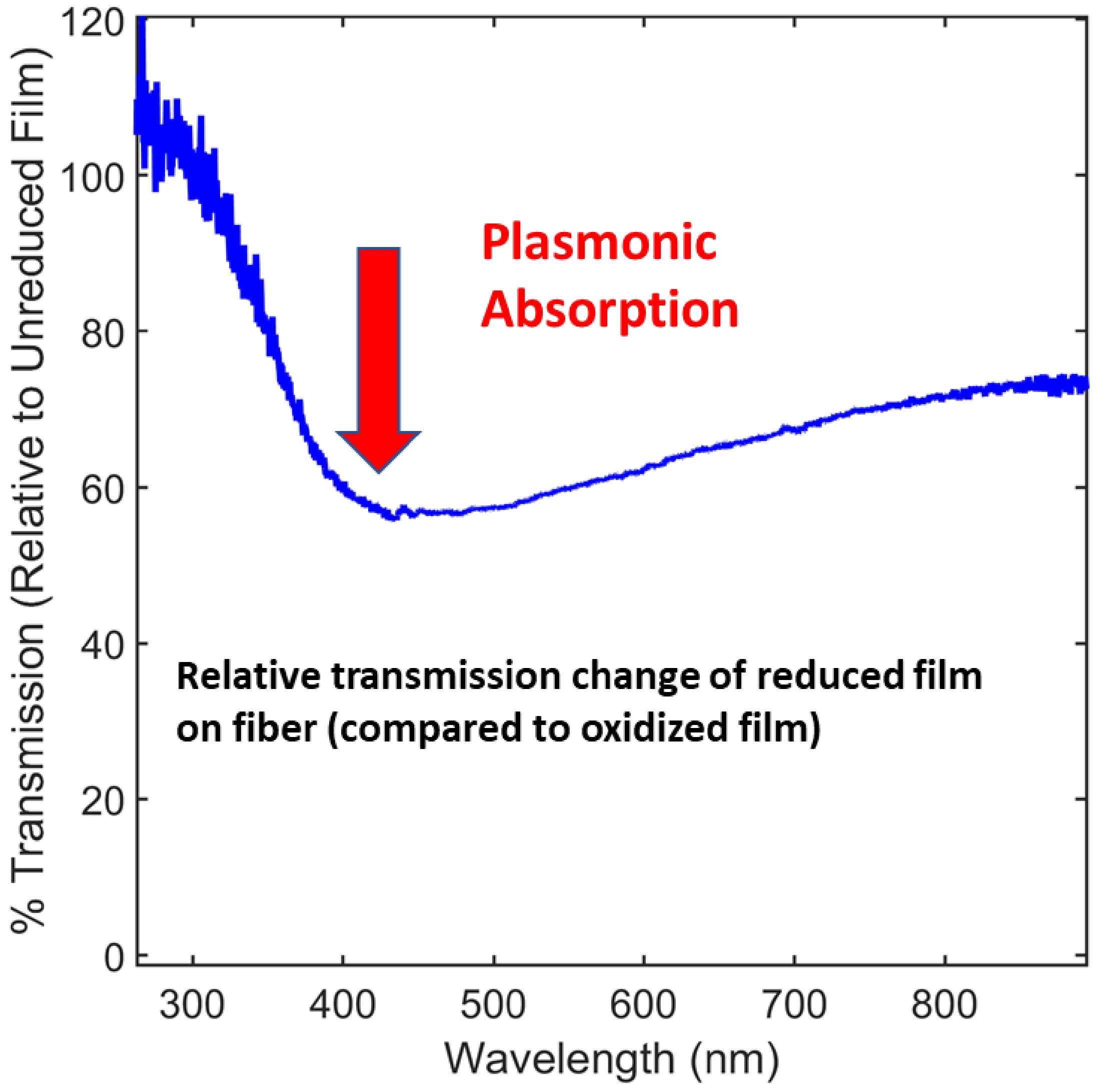


Rayleigh backscatter forms a permanent spatial "fingerprint" along the length of the fiber.

Optical fiber-based sensors are particularly well-suited for harsh environment and electrified system applications.

Innovation Update

- Nanoparticle-incorporated, plasmonic sensing layers have been developed for selective, ppm-level acetylene detection at elevated temperature (up to 80°C).
- Enhanced selectivity has been demonstrated through utilization of a metal organic framework (MOF) overlayer, ZIF-8.
- Working in close collaboration with other projects at NETL and elsewhere: fiber-based temperature sensing, vibration sensing, complementary gas sensors.

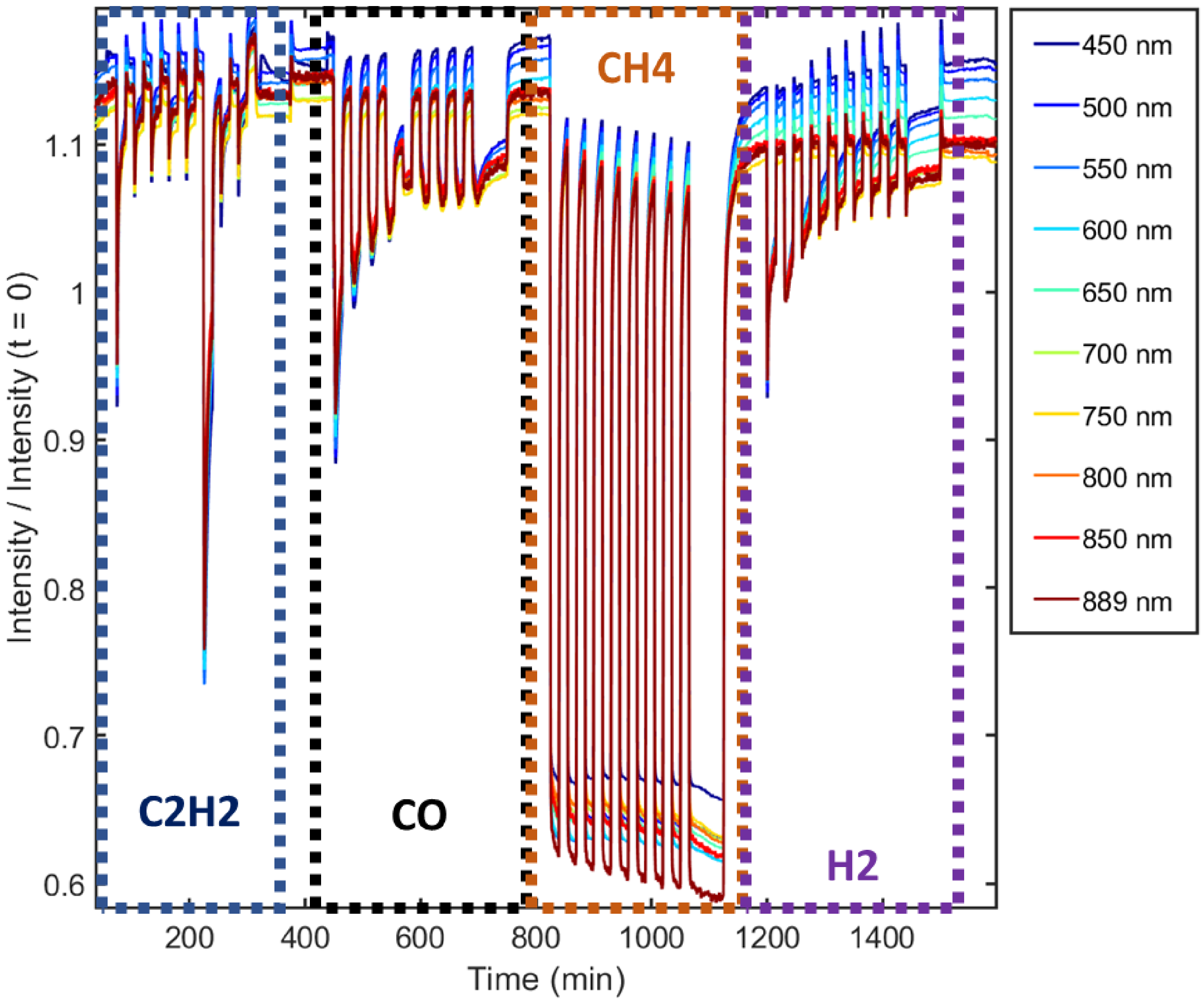


Nickel-NP Incorporated Oxide Sensing Layer

Cross-sensitivity at Room Temperature

- Acetylene: Cycle between 0 and 100 ppm
- CO: Cycle between 0 and 1000 ppm
- CH4: Cycle between 0 and 1000 ppm
- H2: Cycle between 0 and 2500 ppm

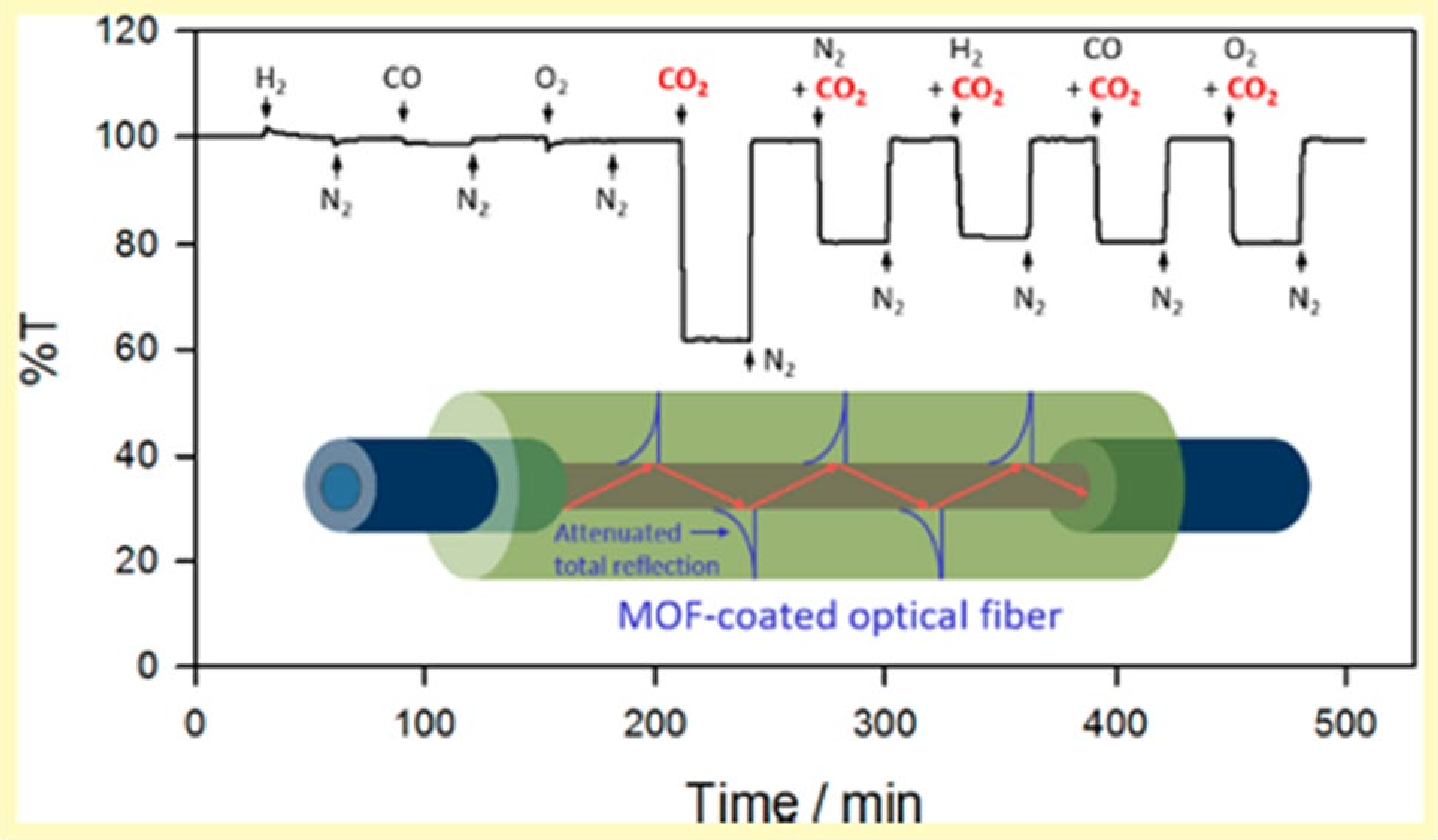
Gas	Peak Response @ Target Level(%)	Peak Response / Conc (%/ppm)
Acetylene	4.2%	**4.2×10^{-2}**
CO	8.6%	8.6×10^{-3}
Methane	46%	**4.6×10^{-2}**
H2	7.2%	2.9×10^{-3}



- Sensor is able to detect changes in acetylene concentration 1-100 ppm.
- Some selectivity to acetylene relative to other species but can be improved on! (See next slides.)

Selective Gas Sensing with a Metal-Organic Framework (MOF)

- Prior work in NETL sensors group based for CO_2 sensing on optical fiber.
- Acetylene uptake in ZIF-8 shown to be high (~1.0 mmol/g, compared to 0.68 mmol/g for CO_2).
- Expected to have good selectivity relative to larger molecules.



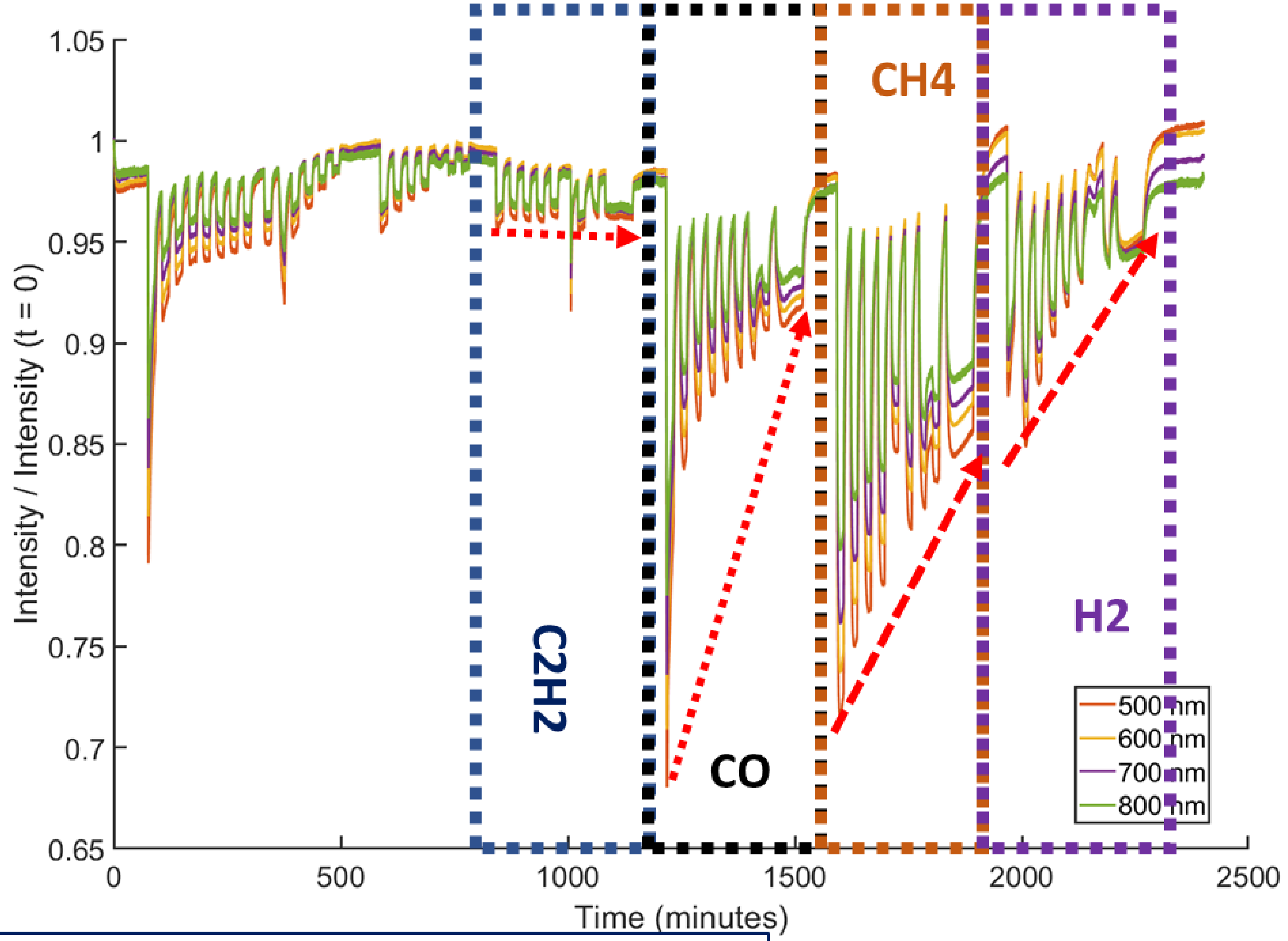
Kim, Ki-Joong, et al. "Metal–organic framework thin film coated optical fiber sensors: a novel waveguide-based chemical sensing platform." ACS sensors 3.2 (2018): 386-394.

Selective Gas Sensing with a Metal-Organic Framework (MOF)

Gas	Peak Response @ Target Level(%)	Peak Response / Conc (%/ppm)
Acetylene	**4.2%**	**4.2×10^{-2}**
CO	8.6%	8.6×10^{-3}
Methane	**46%**	**4.6×10^{-2}**
H2	7.2%	2.9×10^{-3}

with MOF

Gas	Peak Response @ Target Level(%)	Peak Response / Conc (%/ppm)
Acetylene	**1.4%**	**1.4×10^{-2}**
CO	3.2%	3.2×10^{-3}
Methane	**9.8%**	**9.8×10^{-3}**
H2	3.9%	1.6×10^{-3}



Dramatic reduction in methane sensitivity. All other gases (except acetylene) had diminishing response over time (see dashed red arrows - selectivity may be improved more in equilibrium).

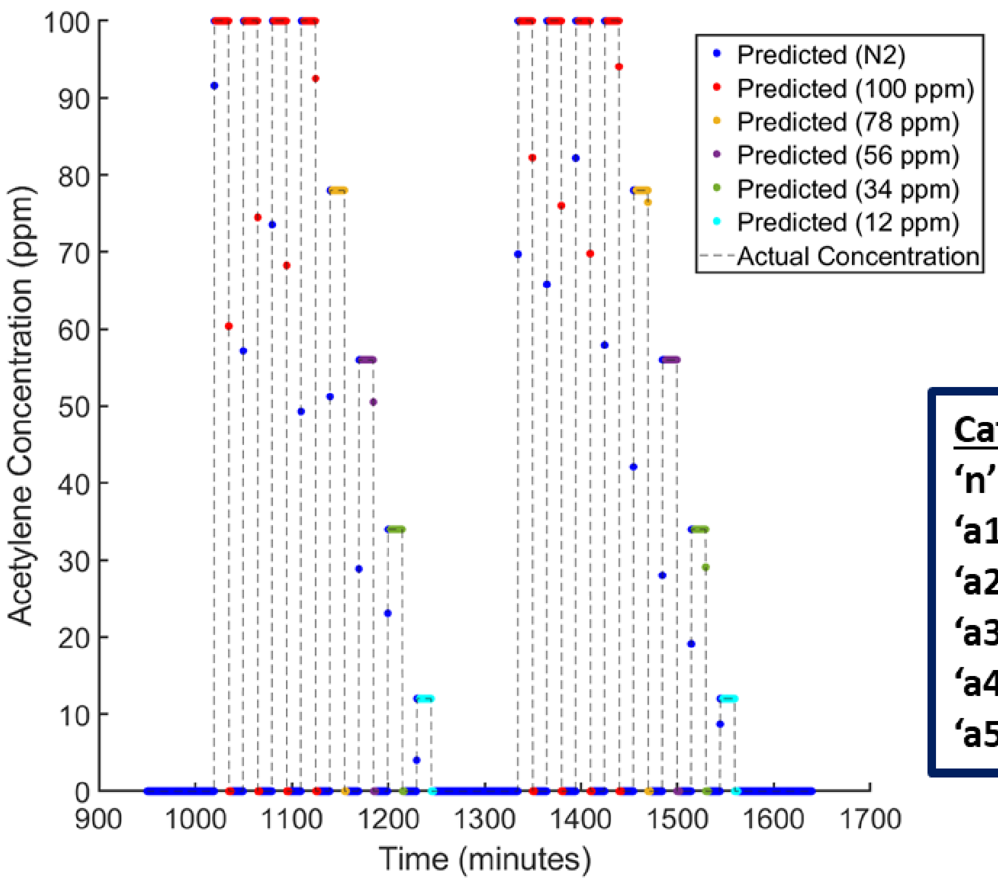
Advanced Data Analytics for Fault Detection

- **Applying Matlab classification learner app to spectral data.**
- Data was labeled based on six discrete concentration levels.
- Cubic support vector machine (SVM) applied with 25% data holdout for training.
- Simple example based on preliminary data but illustrates approach.

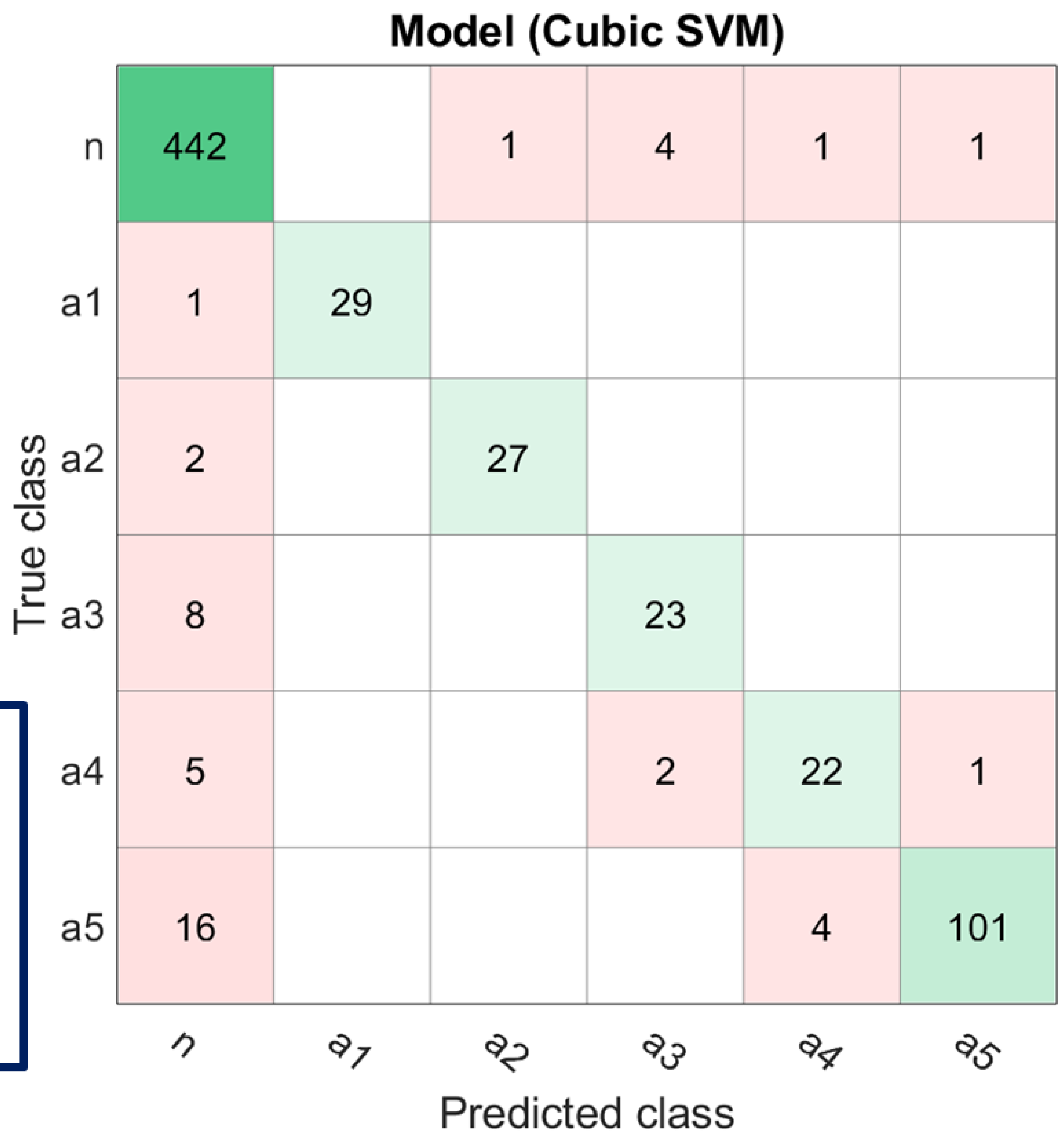
Results

Accuracy	93.3%
Prediction speed	~1100 obs/sec
Training time	13.414 sec

Model Type
Preset: Cubic SVM
Kernel function: Cubic
Kernel scale: Automatic
Box constraint level: 1
Multiclass method: One-vs-One
Standardize data: true



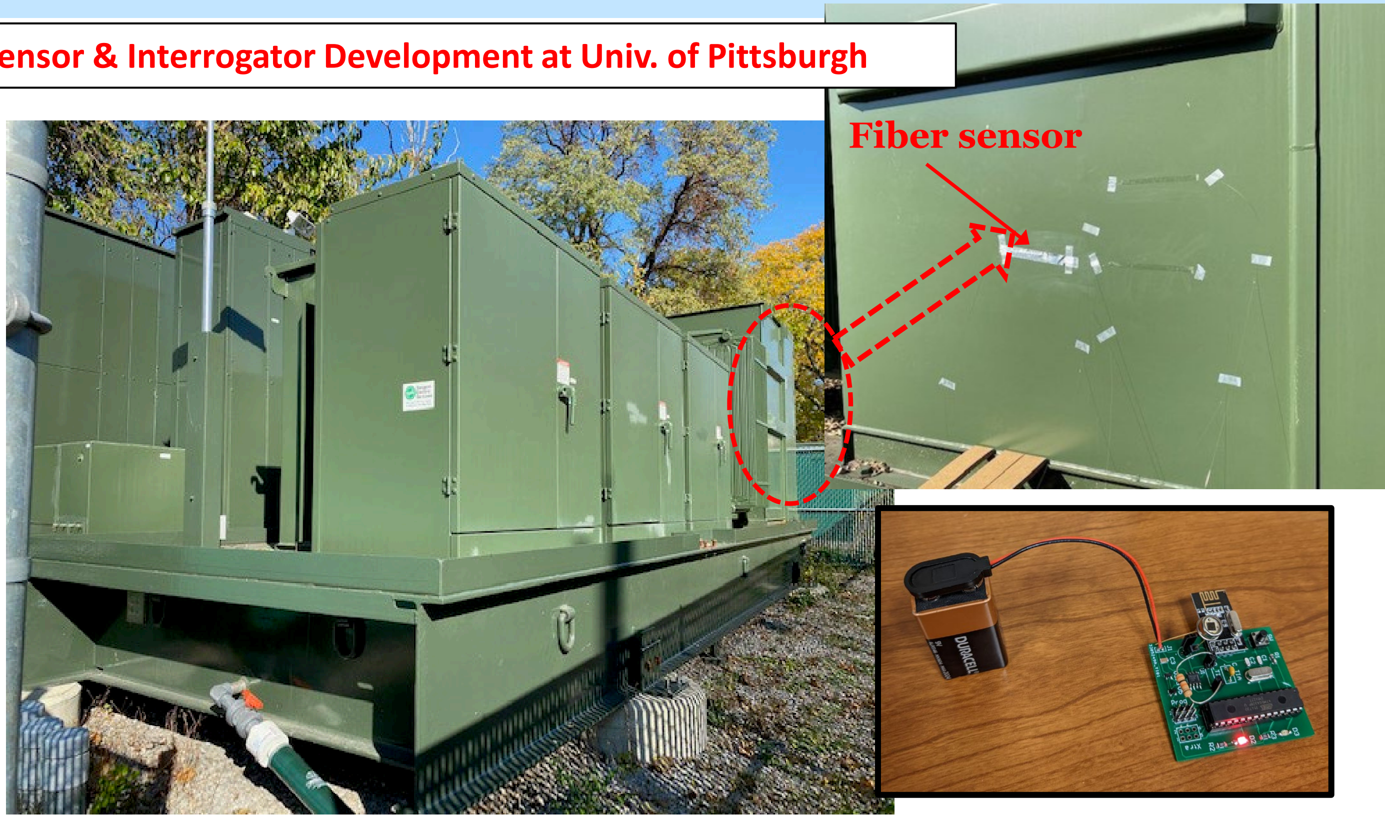
Categories
'n' = Nitrogen
'a1' = 12 ppm
'a2' = 34 ppm
'a3' = 56 ppm
'a4' = 78 ppm
'a5' = 100 ppm

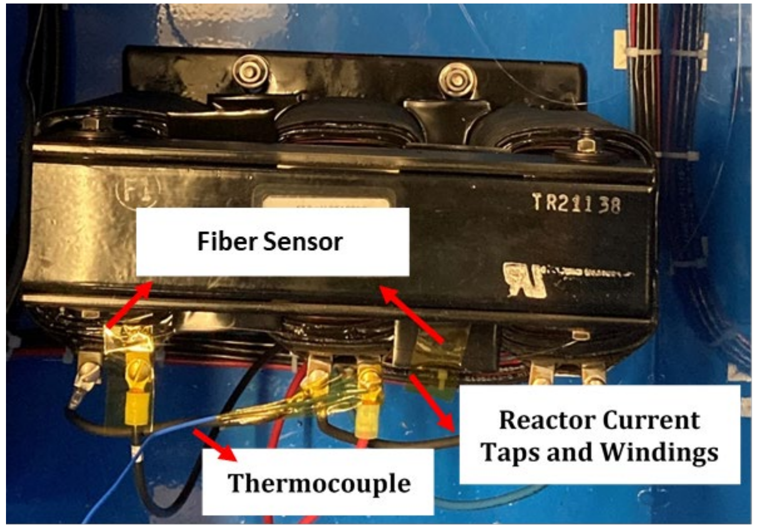


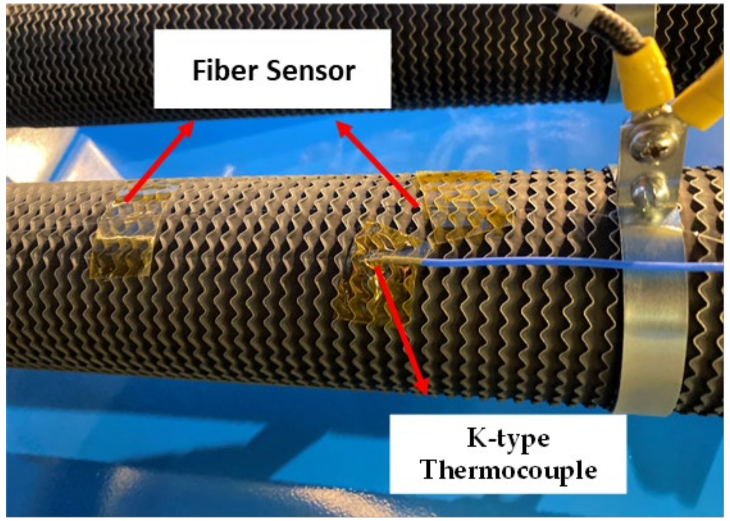
Collaborations and Related Work

- Related work ongoing at NETL through Grid Modernization Lab Consortium (GMLC) on fiber-based temperature and acoustic sensing.
- Ongoing / upcoming collaborations at Univ. of Pittsburgh on low-cost interrogators (Ohodnicki group) and new approaches to distributed sensing (Chen group).
- Close collaboration with ongoing and new work at NETL developing gas sensors for natural gas and hydrogen infrastructure.

Fiber Sensor & Interrogator Development at Univ. of Pittsburgh



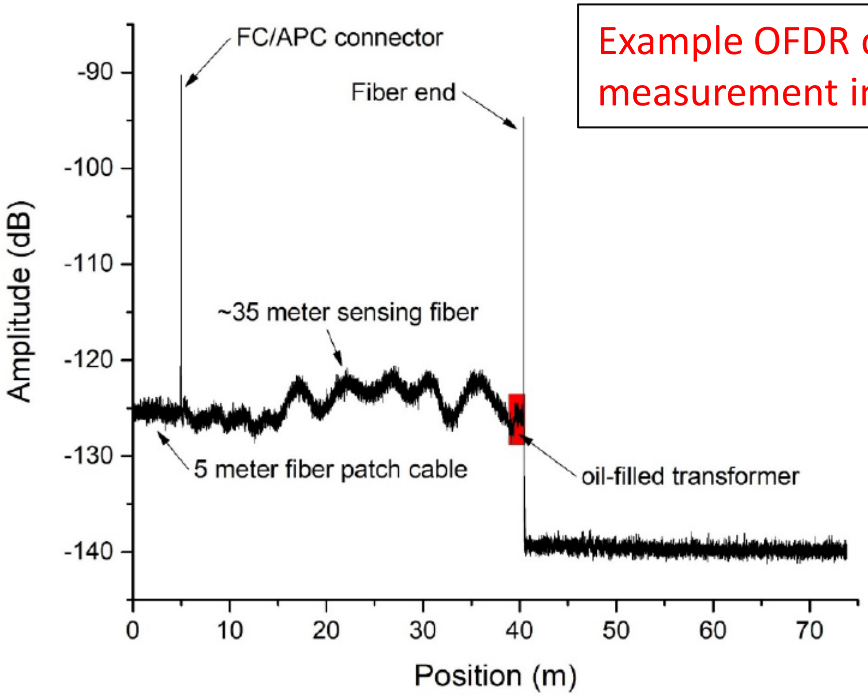




Innovation Update (Coming Soon)

- Work will move forward in FY22 to improve fiber sensor and interrogator for point and distributed sensing under field conditions.
- Use with complementary gas sensors (hydrogen, methane), combined with ML/AI can lead to composite sensors with boosted selectivity ("photonic nose").
- Moving towards deployment for field testing - installation in simulated and (eventually) operational oil-filled transformer.

Lab Scale Simulated Transformer (NETL)



Example OFDR distributed measurement in transformer

Acronyms

NETL: National Energy Technology Laboratory

DGA: Dissolved gas analysis

MOF: Metal organic framework

PPM: Parts per million

ML/AI: Machine learning / artificial intelligence

GMLC: Grid Modernization Lab Consortium

OFDR: Optical Frequency Domain Reflectometry

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