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

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Project Summary

- Dissolved gas analysis (DGA) of transformer oil is a critical tool for diagnosing fault conditions, but many traditional solutions tend to be expensive, unselective, slow, or require a technician to travel to the site to take oil samples

- Project aims to develop a real-time, low-cost, fiber-based tool for monitoring dissolved gas species in transformer oil.

- **<u>Overall Objectives:</u>**

    - To develop fiber sensors for targeted detection of relevant gas species (especially acetylene, for detection of discharge faults).
    - Use AI/ML tools to map fiber data to identification of transformer health.
    - Develop a packaged fiber sensor that can be deployed in an operational power transformer.

The Numbers

- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- LOCATION:
  Pittsburgh, PA
- PROJECT TERM:
  01/01/2021 to 06/30/2023
- PROJECT STATUS:
  Ongoing
- AWARD AMOUNT (DOE CONTRIBUTION):
  $450,000
- AWARDEE CONTRIBUTION (COST SHARE):
  $0

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)

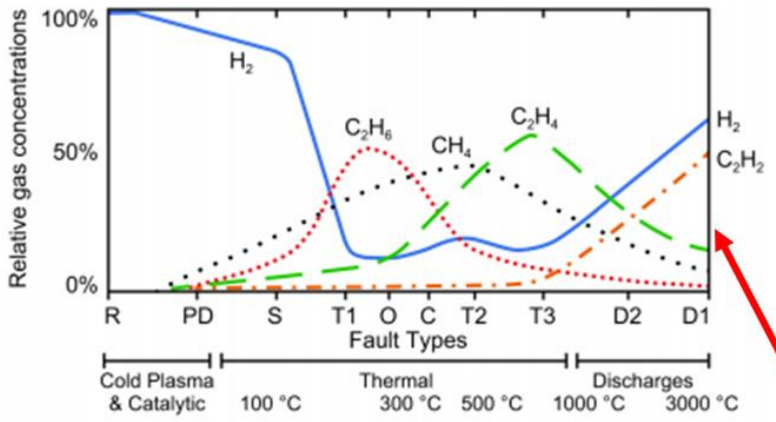
Gas	O_2/N_2 Ratio ≤ 0.2 — Transformer Age in Years: Unknown	1 – 9	10 – 30	>30	O_2/N_2 Ratio > 0.2 — Transformer Age in Years: Unknown	1 – 9	10 – 30	>30
Hydrogen (H_2)	80	75		100	40	40		
Methane (CH_4)	90	45	90	110	20	20		
Ethane (C_2H_6)	90	30	90	150	15	15		
Ethylene (C_2H_4)	50	20	50	90	50	25	60	
Acetylene (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.



NOTE—See 3.2 for faults acronym and Annex C for faults type definition

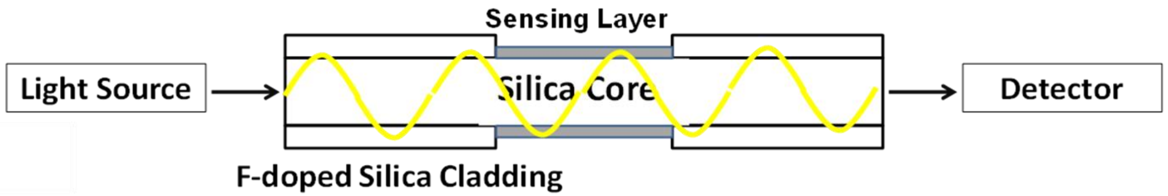
Figure 1—Relative percentage of dissolved gas concentrations in mineral oil as a function of temperature and fault type

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

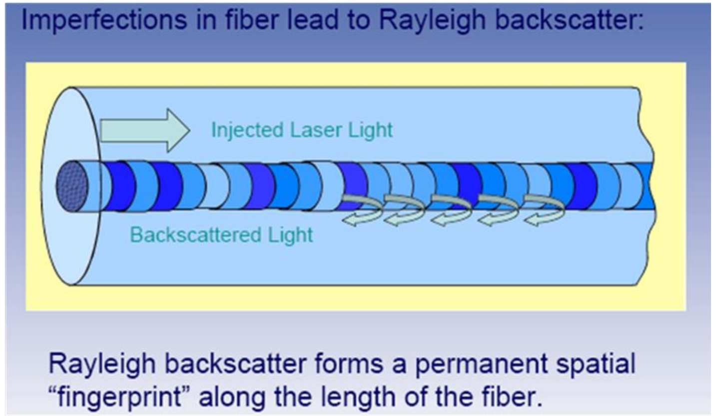
IEEE C57.104-2019 - IEEE Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers

Technical Approach

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



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

Develop thin film materials that respond to target gases and incorporate on optical fiber sensors.
Use AI/ML tools to eliminate cross-sensitivities from broad spectral data (multi-sensor, multi-wavelength approach).

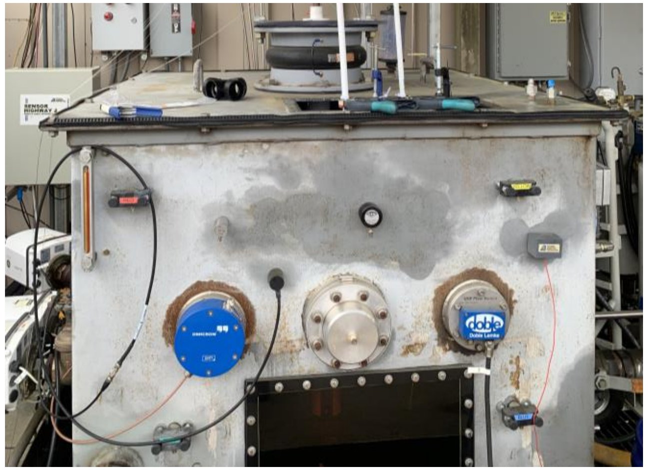
Accomplishments

- Nanocomposite sensing layers were developed that could detect acetylene down to 10-ppm level.
- A multi-sensor probe was developed, combined with AI/ML tools to identify target gas species in calibrated oil samples.
- Oil-resistant, gas-permeable sensor packaging was designed and deployed in a model transformer system at the Electric Power Research Institute (EPRI) site in Charlotte, NC to demonstrate detection of arcing.

Lab Scale (Flowing Gas)

Lab Scale
(Dissolved Gas in Oil)

Field Testing (Model System)



Timeline (Task 2.0)

➢ Milestones

- Successfully demonstrate properties of silica coating embedded with metal cation and gold nanoparticles to meet required sensor specifications.

Completed – 10/31/2021

- Successfully identify the most appropriate sensing materials that show reversible and highly selective adsorption for acetylene.

Completed - 12/31/2021

➢ Deliverables

- Technical report outlining results of identifying the most appropriate acetylene sensing materials.

Completed – 12/31/2021

Timeline (Task 3.0)

➢ Milestones

- Successfully demonstrate point-wise fiber acetylene sensors with high-sensitivity at elevated temperatures. (Go/No-Go, if attempts to integrate C_2H_2 sensing materials into fiber sensor structures to form a fiber C_2H_2 sensor do not succeed, then a decision will be made to divert the R&D toward other materials.)

Go – 12/31/2021 (Ni-NP / ZIF-8 composite)

- Successfully demonstrate OFDR-based distributed fiber-optic sensors for constant measurement of acetylene concentration gradients.

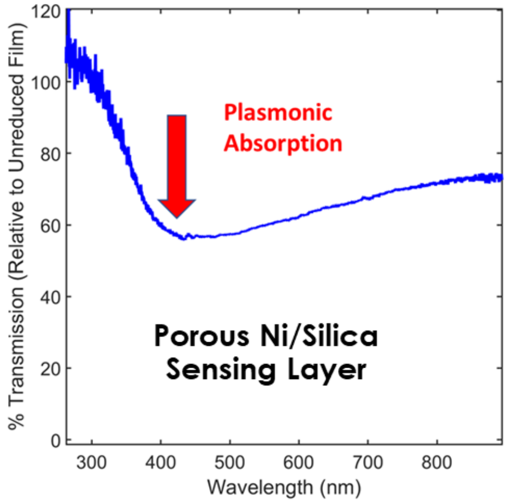
Completed – 8/30/2022

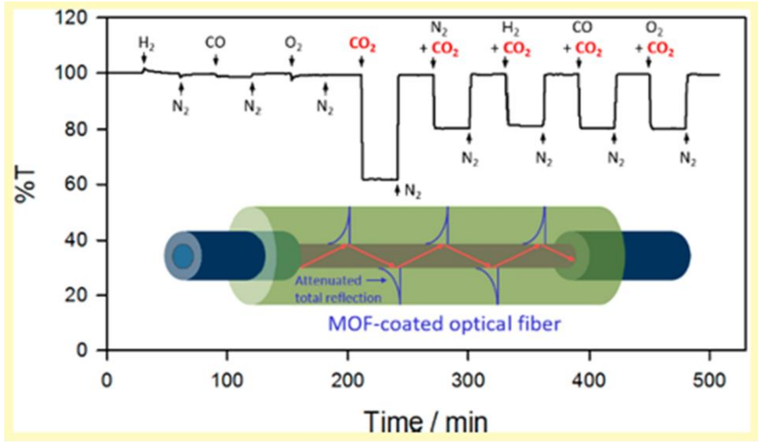
➢ Deliverables

- Technical report outlining results of development point-wise C_2H_2 sensor and distributed C_2H_2 sensor.

Completed – 10/30/2022

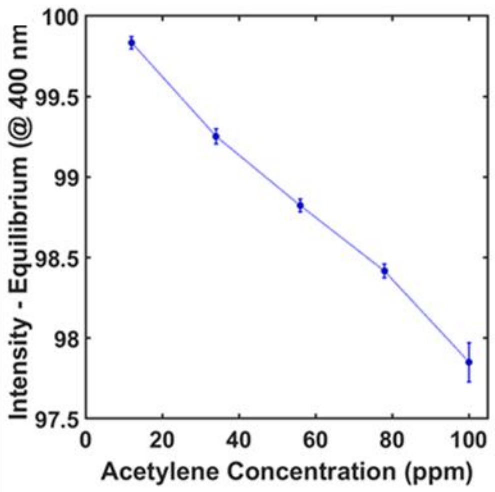
Sensing Material Development

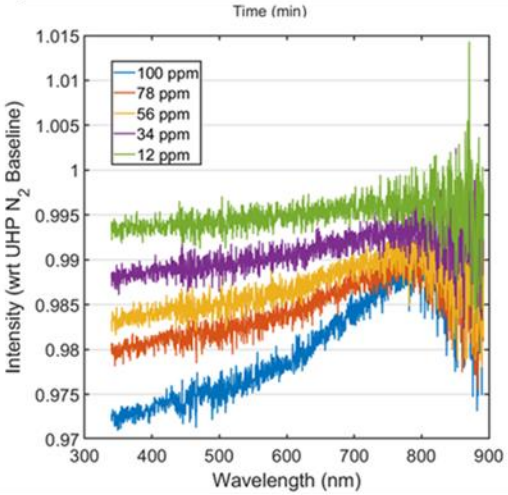




Kim, Ki-Joong, et al. "Metal–organic framework thin film coated optical fiber sensors: a novel waveguide-based chemical sensing platform." ACS sensors 3.2 (2018): 386-394.

- Nickel / silica composite sensing layer provides optical response through catalytic interaction with acetylene.
- Metal organic framework (MOF) was used as an overcoat to improve selectivity to acetylene.





Target Gas	Room Temperature	Elevated Temperature (80°C)
Acetylene (100 ppm)	1.85% (185×10^{-4} %/ppm)	0.56% (56×10^{-4} %/ppm)
Carbon Monoxide (1000 ppm)	5.52% (55.2×10^{-4} %/ppm)	0.52% (5.2×10^{-4} %/ppm)
Methane (1000 ppm)	12.2% (122×10^{-4} %/ppm)	0.75% (7.5×10^{-4} %/ppm)
Hydrogen (2500 ppm)	4.22% (16.9×10^{-4} %/ppm)	0.53% (2.1×10^{-4} %/ppm)

Multi-Sensor Probe

Sensor #1:

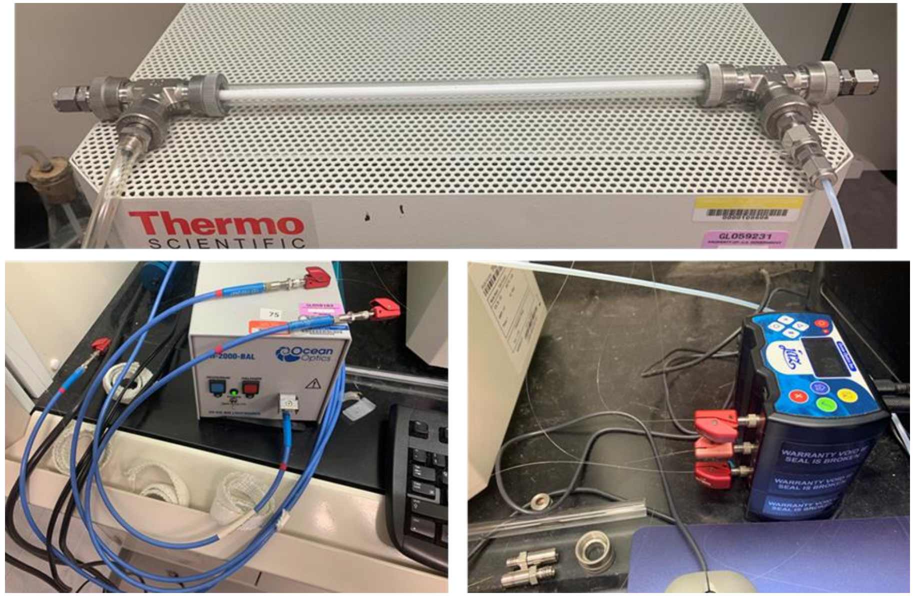
Ni/Silica

Sensor #2:

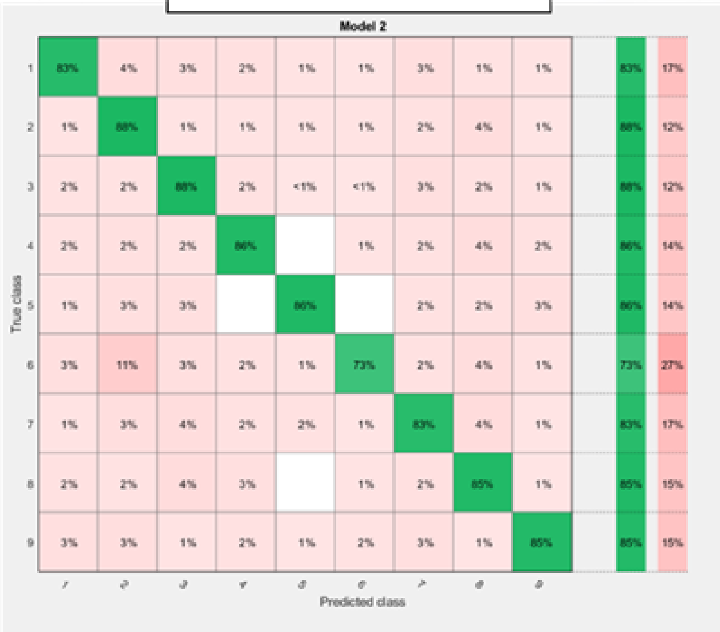
AuPd (Hydrogen)

Sensor #3:

PIM-1/ITO (Methane)



Combined Sensor



Combined spectral dataset used to train support vector machine (SVM) model. Performed dramatically better (83-97%) at identifying gas species vs. any individual sensor (36-86%).

Test ID#	Gas Exposure	Concentration
1	UHP N_2	(Control)
2	Low Concentration Hydrogen	500 ppm
3	High Concentration Hydrogen	5000 ppm
4	Low Concentration Methane	250 ppm
5	High Concentration Methane	2500 ppm
6	Low Concentration Acetylene	10 ppm
7	High Concentration Acetylene	100 ppm
8	Low Concentration Carbon Monoxide	250 ppm
9	High Concentration Carbon Monoxide	2500 ppm

Timeline (Task 4.0)

➢ Milestones

- Successfully demonstrate fiber-optic acetylene sensors for monitoring oil decomposition and gas generation due to partial discharge or arcing.

Completed - 11/30/2022

- Successfully field validate sensor for early failure detection in oil-immersed transformers by detecting dissolved acetylene concentration and other parameters.

Completed - 4/30/2023

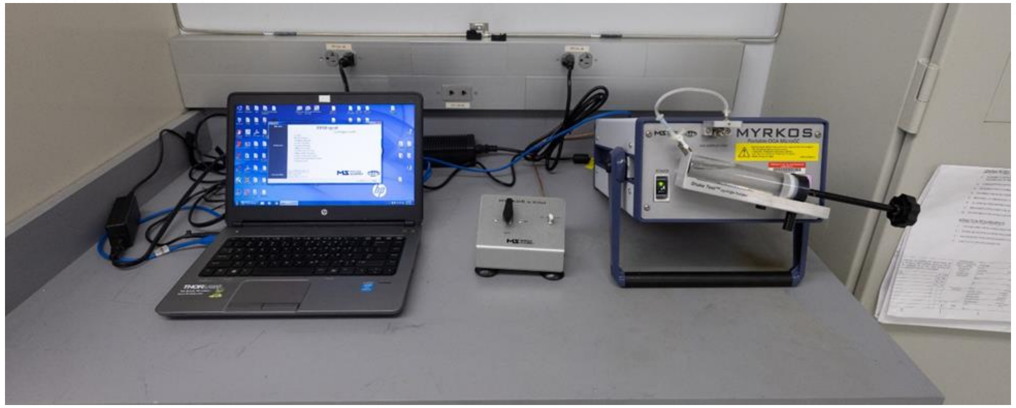
➢ Deliverables

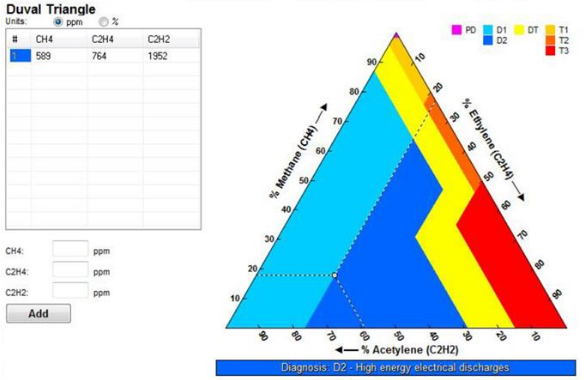
- Technical report outlining results of monitoring dissolved gas generation due to partial discharge or arcing in oil-immersed transformers.

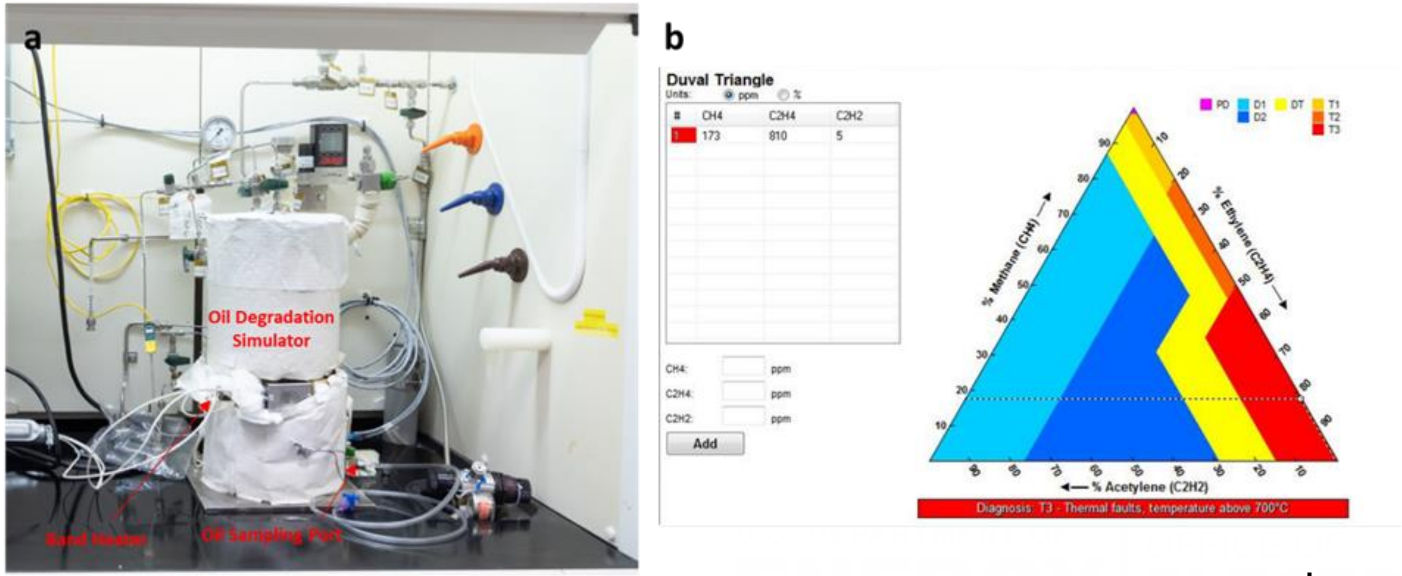
In Progress

Tracking Dissolved Gas in Oil

- Generation of oil samples with specific dissolved gas profiles.
- Thermally degraded oil generated with lab scale heater tank.
- Target acetylene concentrations reached with calibrated oil samples (Morgan Schaffer True North).
- Cross-checked with Myrkos Dissolved Gas Analyzer.







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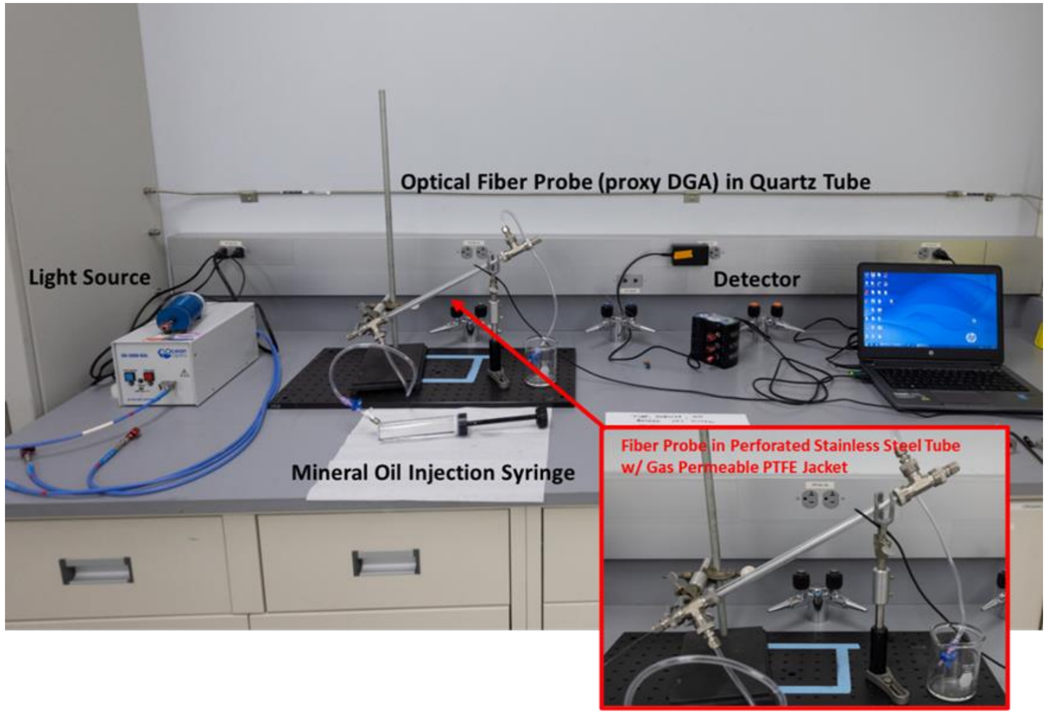
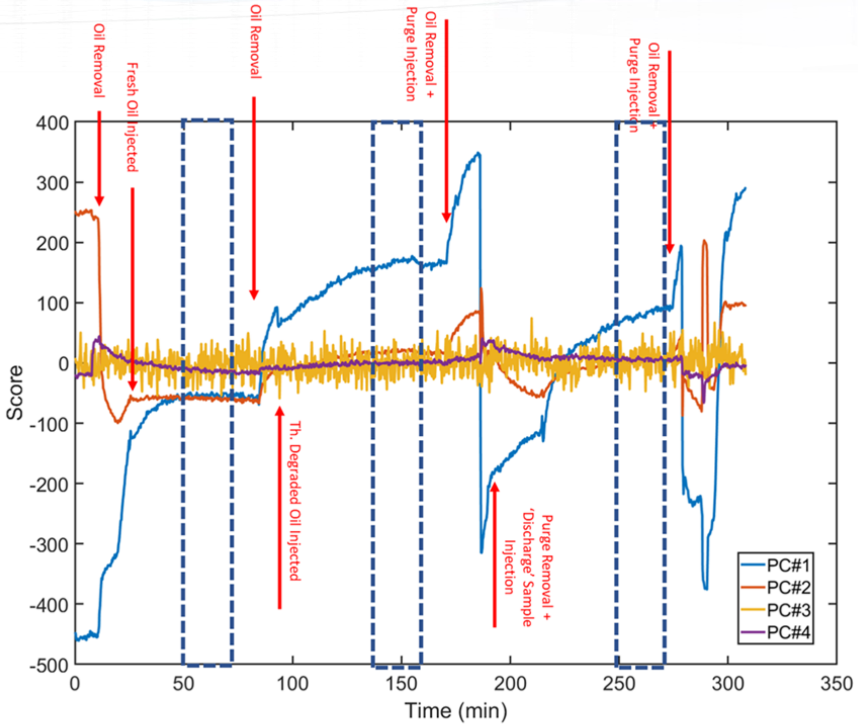
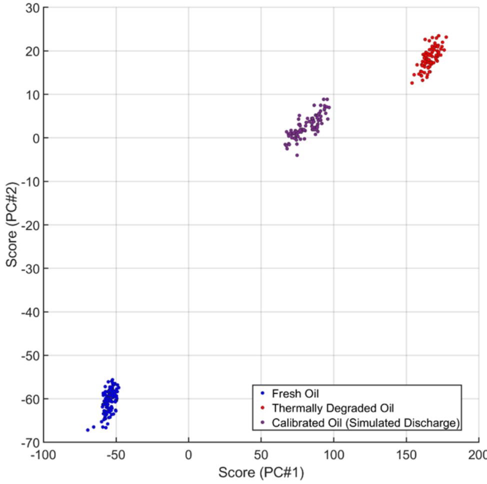
Tracking Dissolved Gas in Oil







- Multi-fiber sensor probe was exposed to multiple target oil samples.
- Dimensionality of full spectral dataset was reduced with principal component analysis (PCA).
- Clustering of data in terms of different associated “fault states” observed in PCA plot.

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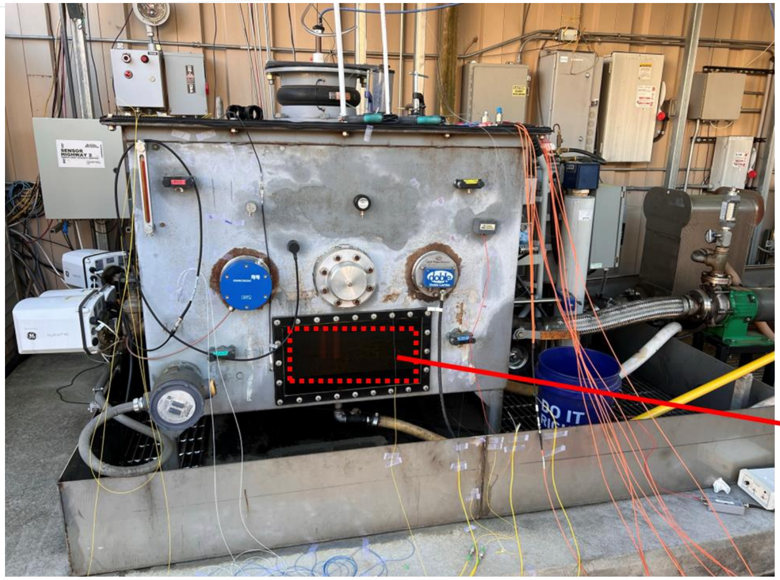
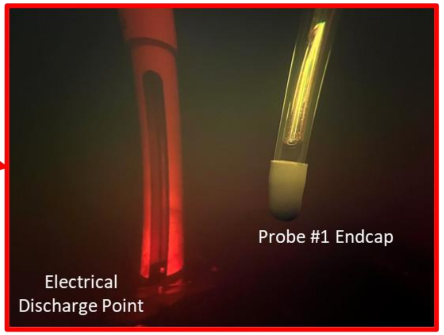
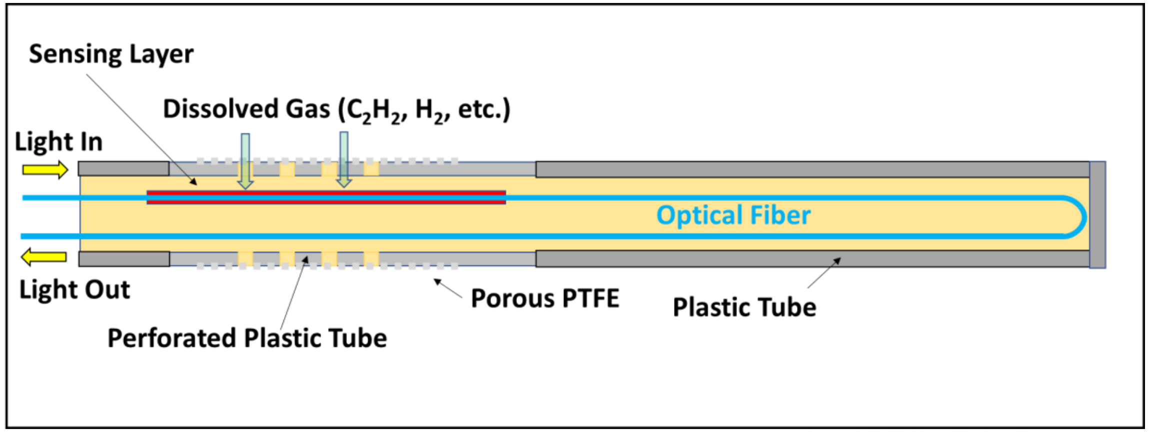
Field Testing



Probe #1:
Four sensors, deployed near arc (see below).
Probe #2:
Three sensors, deployed near top of tank.



- Sensors deployed at model oil-filled transformer facility at Electric Power Research Institute in Charlotte, NC.
- System was able to simulate arcing events in oil.
- Demonstrated ability to detect arcing events in real time (chemically and acoustically).

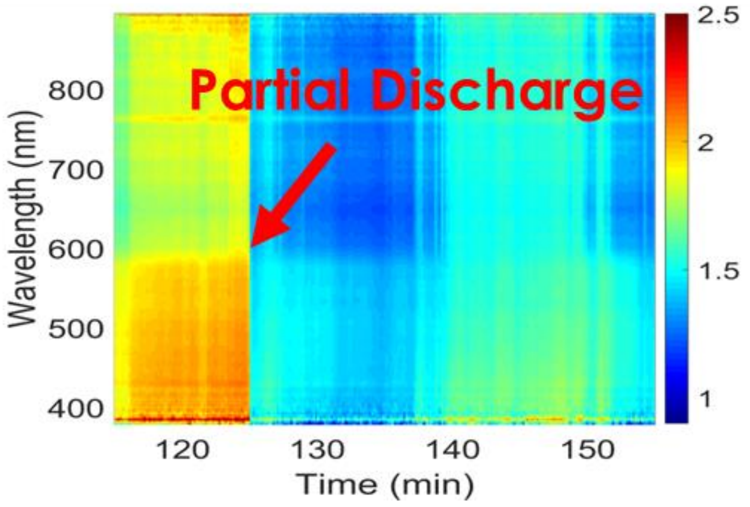


Impact/Commercialization

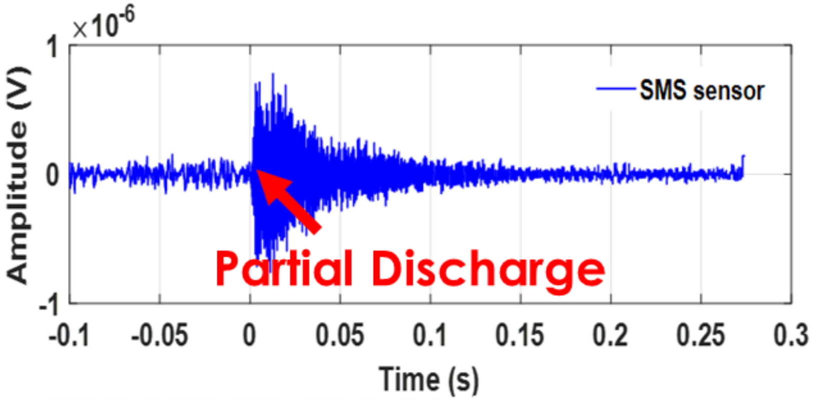
- Sensor suite being developed combining fiber-based acoustic and temperature sensing technology (co-developed under work associated with Grid Modernization Lab Consortium) in collaboration with University of Pittsburgh.

- Patent granted to NETL on multi-parametric sensing with fiber-optic sensor array 3/8/2022.

Gas Sensing Results



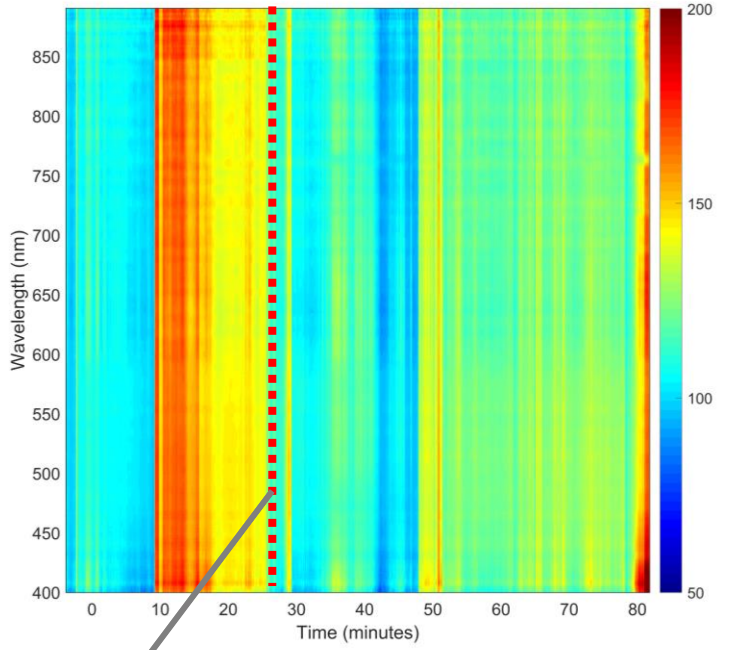
Acoustic Sensing Results

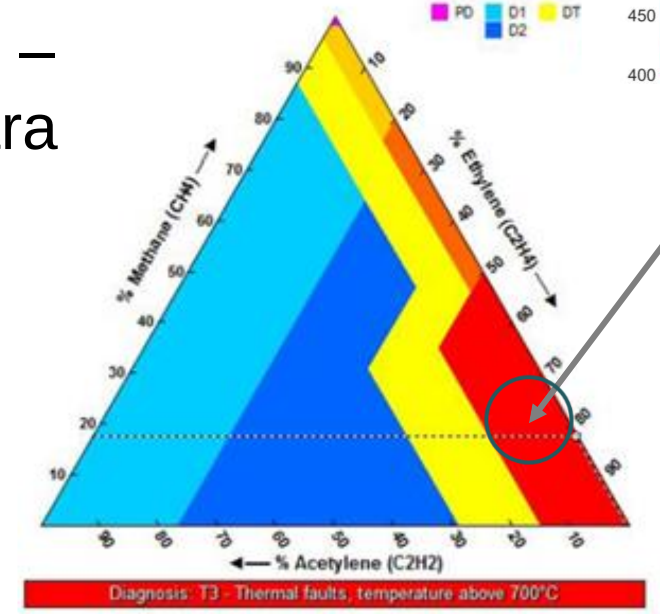


Future Work

- Re-design of sensor package for convenient deployment at oil sample port of power transformer.
- Longer time-scale testing at pilot facilities, observe cross-correlations with full environmental picture (humidity, temperature).
- Refinement of design to target other relevant species (ethane, ethylene) – more precisely map real-time spectra to Duval triangle.

Spectral Data





THANK YOU

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Acronyms

NETL – National Energy Technology Laboratory

EPRI – Electric Power Research Institute

DGA – Dissolved Gas Analysis

AI / ML – Artificial Intelligence / Machine Learning

EMI – Electromagnetic interference

PIM – Polymer of Intrinsic Microporosity

ITO – Indium Tin Oxide