U.S. DEPARTMENT OF ENERGY
Office of Electricity

Optical Fiber Sensor Technology Development and Field Validation for Distribution Transformer and Other Grid Asset Health Monitoring

TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

Oak Ridge, TN

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Project Overview

Project summary :

- **Low cost optical fiber sensor technology is being developed, demonstrated, and field validated for use in grid asset monitoring applications with an emphasis on distribution grid assets and transformers, in particular.**
- **Internal temperature is being targeted for "hot spot monitoring".**
- **Internal chemistry is being targeted for low-cost "proxy DGA".**

Total value of award : ~$575k over 3 years

Period of performance : 4/1/2016 – 12/31/2019 (no cost time extension)

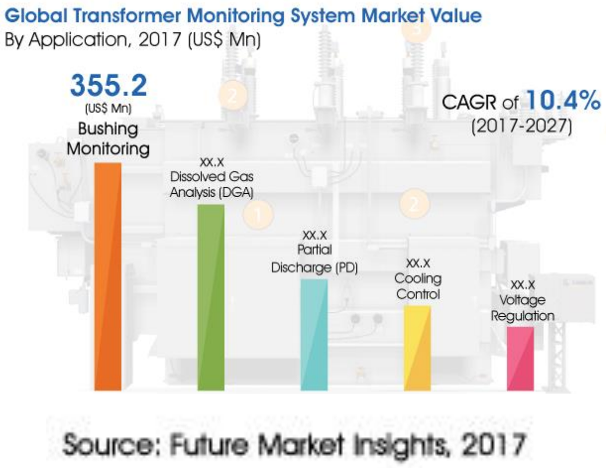
Project lead and partners : NETL (lead on overall subtask), LLNL, U. Pitt.

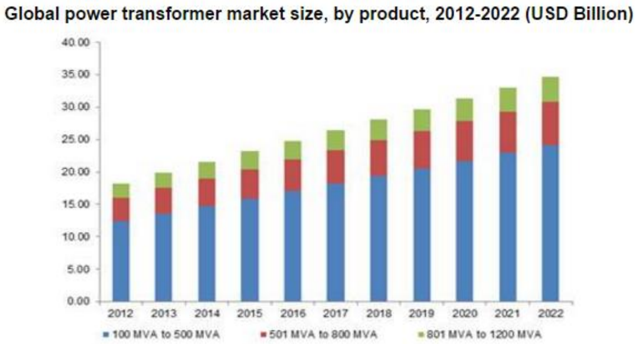
Research Motivation

- **Grid Asset Health Monitoring Enables**
  - Condition based maintenance programs
  - Greater asset utilization prior to replacement
  - Enhanced system reliability and resiliency
  - Used in practice for critical grid assets

- **Example: Large Power Transformers (LPT)**
  - Large associated direct and opportunity costs ($1M-$7.5M)
  - Long replacement times
  - Certain key parameters provide valuable information
  - Clear value proposition for monitoring at asset level
  - A suite of monitoring tools are available commercially

- **Challenges and Economic Opportunity**
  - 75% of power transformers in US more than 25 years old
  - Global market sizes:
    - Power transformers ($35.4 Billion by 2022)
    - Transformer monitoring systems ($2.68 Billion by 2021)





Economic and safety issues drive real-time monitoring needs

Research Motivation

Existing State of the Art (examples)

- Internal temperature monitoring probes
- Dissolved gas analysis (sampling)
- Dissolved gas analysis (real-time monitoring)
- Partial discharge detection
- Bushing monitoring
- Typical costs range from $5,000 (Temp.) - $50,000 (DGA)

Distribution Assets

- Total costs comparable with existing monitoring systems
- Cost prohibitive for real-time monitoring in the field
- Typically run to failure and replaced
- Distribution system visibility can provide grid resiliency and reliability benefits

Challenges and Opportunities

- Monitoring systems should be less than $100-300 installed
- Temperature and DGA are high value targets

Commercial Market Survey (2017-2018)

MODEL	COST
Market Interest for Distribution Transformers	< $100-$300
Single Gas On-line Dissolved Gas Monitor	$6,500-7,500
HYDROCAL	$8,565
SmartDGA for Transformers	$15,000-25,000
On-line Gas Chromatography Dissolved Gas Monitor	$25,000-45,000
Gas Analysers	$46,800
DGA	$40,000
Fiber Optic Temperature Monitor	$5,000-16,000
Electronic Temperature Monitor	$4,000
SAW Temperature sensors	$3,000
Fiber Optic Temperature Sensor	$10,000

Uniqueness of Proposed Solution : Research Targets (Temperature)

Thermal Monitoring Internal to the Temperature Provides Key Information for Transformer Health and Aging

Key Challenges:

1) **Grid Assets Show Significant Temperature Variations Throughout**

2) **Hot-Spot Monitoring is Most Critical**

3) **Temperature Distribution Monitoring Can Provide Additional Information of Value**

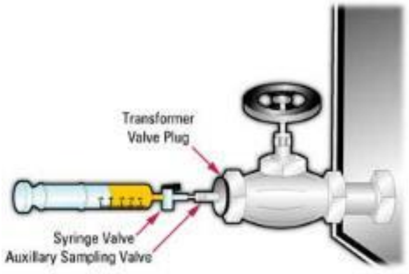
High-Value Targets:

Single-Point Temperature "Hot Spot" Monitoring : 25-110^{o}C, < $100 installed

Multi-Point Temperature Monitoring : 25-110^{o}C, < $10 / node, < $1000 total (can be shared over multiple assets or within a single asset)

Uniqueness of Proposed Solution : Research Targets (Chemical)

“Proxy Dissolved Gas Analysis”
What are Most Critical Parameters to Monitor for Highest Value and Lowest Cost?



PRINCIPLE GASES AND ASSOCIATED FAULT TYPES

Key Gas	Characteristic Fault
H_2, CH_4, C_2H_4, C_2H_6	Thermal fault 150 – 300 °C
H_2, CH_4, C_2H_4, C_2H_6	Thermal fault 300 - 700 °C
H_2, C_2H_2, C_2H_4	Thermal fault >700 °C
CO, CO_2	Thermal decomposition of cellulose
H_2, CH_4	Partial discharge
H_2, C_2H_2	Arcing

Chemical Sensing Strategies for Real-time Monitoring of Transformer Oil: A Review, 2017, IEEE Sensors Journal 17(18), 5786 - 5806.

Highest Value Targets:

H_2 and C_2H_2 most Commonly Produced

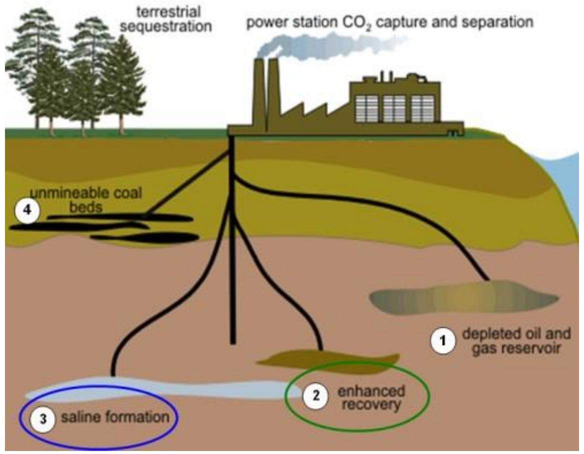
H_2 - thermal faults from 150-700^{o}C, partial discharge
C_2H_2 - thermal faults > 700^{o}C, arcing

Targets:

Analyte ranges < 100ppm to > 1000ppm
Temperature ranges < 25^{o}C to > 110^{o}C
Selectivity across gases (H_2, hydrocarbons, H_2O, etc.)

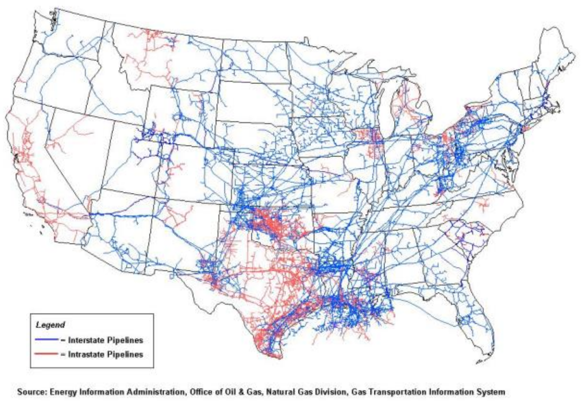
Leveraging Technologies Developed for Other Energy Applications

FE and NE Power Generation Systems (Combustion, Fuel Cells, Turbines, etc.)

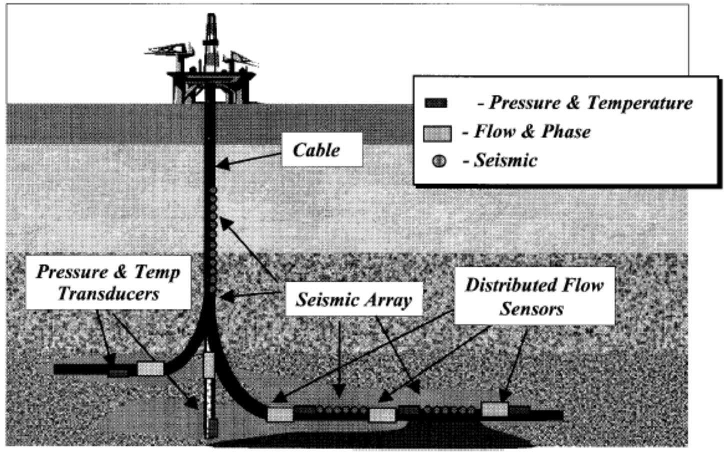


CO_2 Sequestration

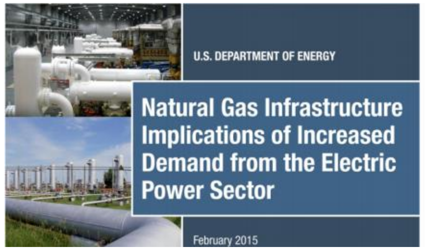
Natural Gas Infrastructure



Unconventional Resource Recovery

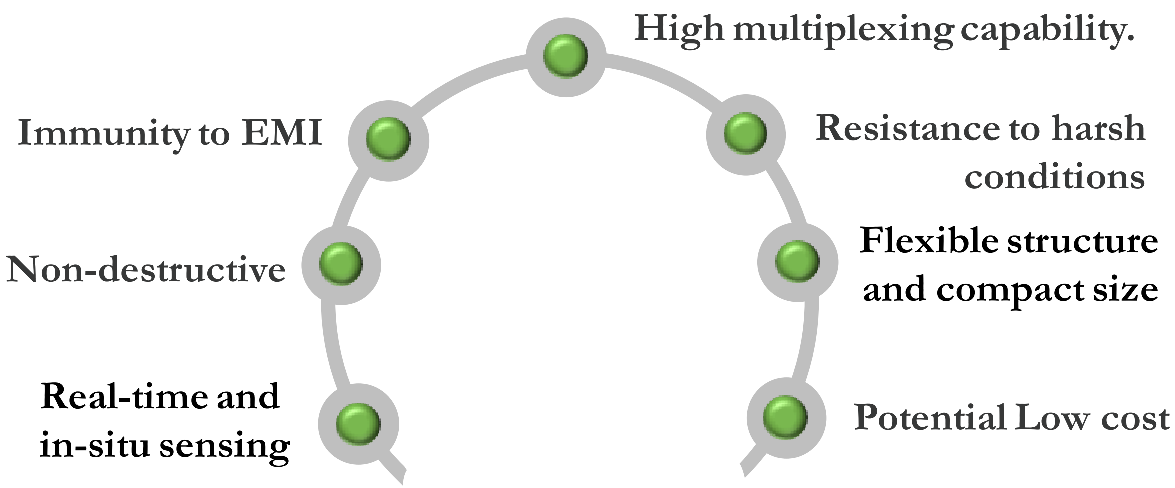


Properties of Methane	
Chemical Formula	CH4
Lifetime in Atmosphere	12 years
Global Warming Potential (100-year)	28-36



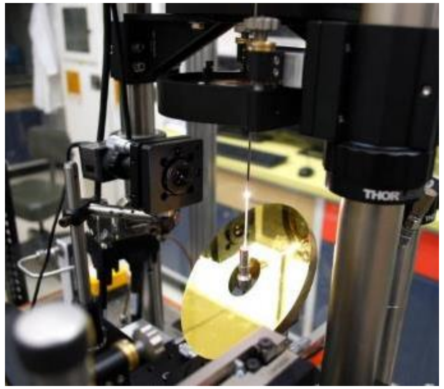
Synergistic Sensor Requirements Can Be Found Across Many Areas of Interest within DOE, and Opportunities Exist to Leverage On-Going Work in the Context of Grid Asset Monitoring.

Uniqueness of the Proposed Solution : Fiber Optic Sensing

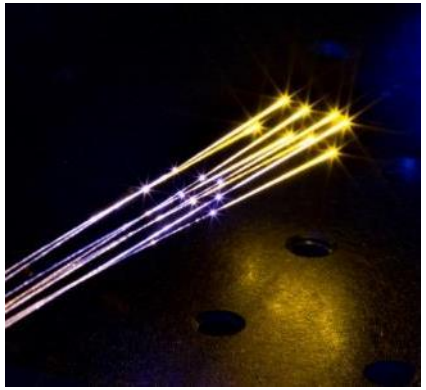


- ❑ **Key Research Needs:**
  - ❑ Functional sensor material research
  - ❑ Great advantages of fiber-optic sensors over their electrical equivalents such as immunity to EMI and high voltages, usable under harsh environment
  - ❑ Multi-variate analysis for multi-component gas analysis
  - ❑ Sensor telemetry and interrogation

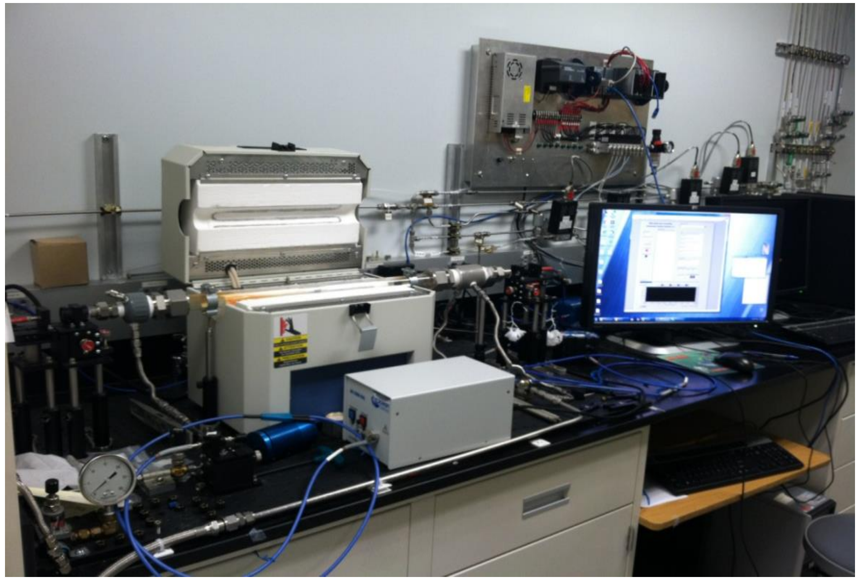
Novel Single Crystal Fiber Growth



Fiber Sensing Layer Functionalization

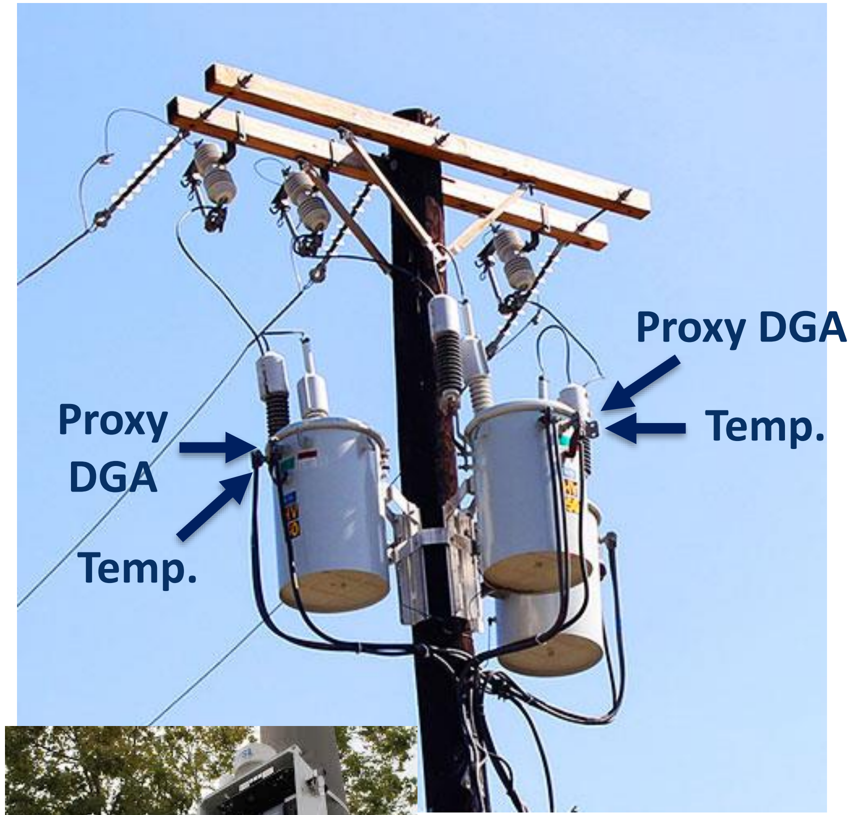


Gas Sensing Reactors



Significance of the Results, If Successful

Primary Target:
Real-Time Distribution Asset Monitoring

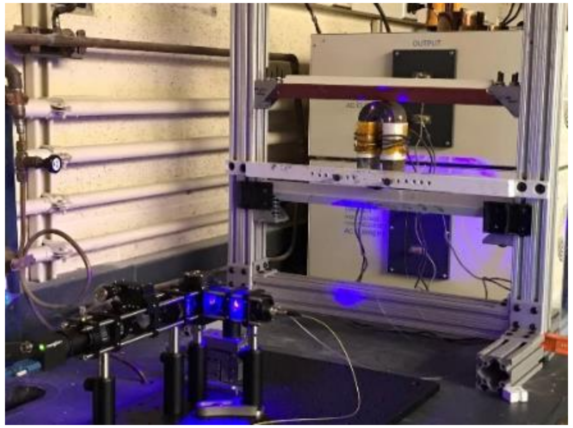


MicroPMU
Comms + GPS
+ Time Synch.

New Low-Cost Sensors Integrated with MicroPMUs

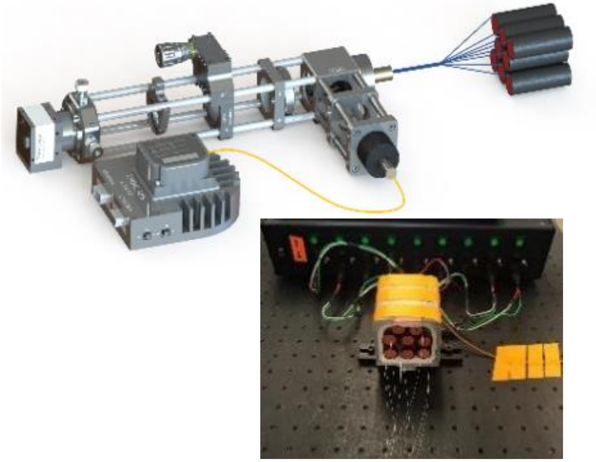
Examples of Other Relevant Applications for Low Cost Temperature Monitoring

Solid-State Transformer Monitoring



Power Electronics Converter Monitoring

Battery Array Monitoring



Advanced Grid Research
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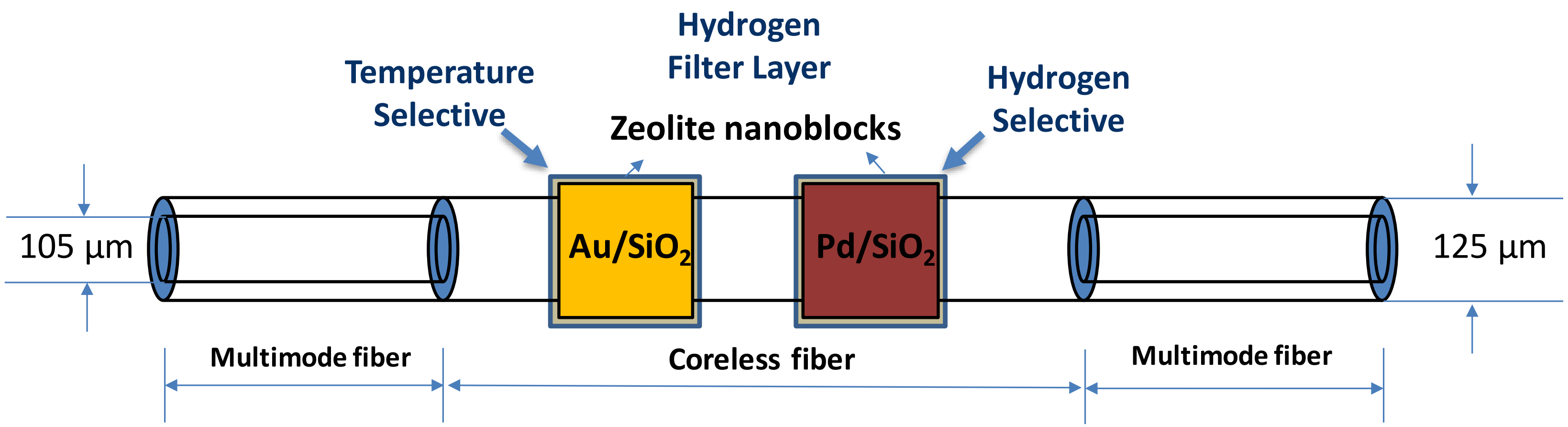
US DEPARTMENT OF ENERGY

Specific Research Questions Being Addressed : Sensor Development

Functional Sensing Layers Integrated with Low-Cost Optical Fibers



1) Develop Sensing Layers Specific to Analytes of Interest with Unique Optical Responses

2) Leverage Low Cost Optical Sources and Detectors (LEDs, Photodiodes)

3) Utilize Multi-Wavelength Interrogation Methods for Simultaneous Monitoring of Multiple High Value Parameters (Temperature, H_2, …)

4) Apply Advanced Data Analytics to Identify Key Wavelengths for Monitoring

Technical Targets:

Single Point Measurement

Temp. Range > 25 – 110^{o}C
Temp. Resolution <= Δ1^{o}C

H_2 Range <100ppm to >1000ppm
H_2 Resolution <= Δ10ppm

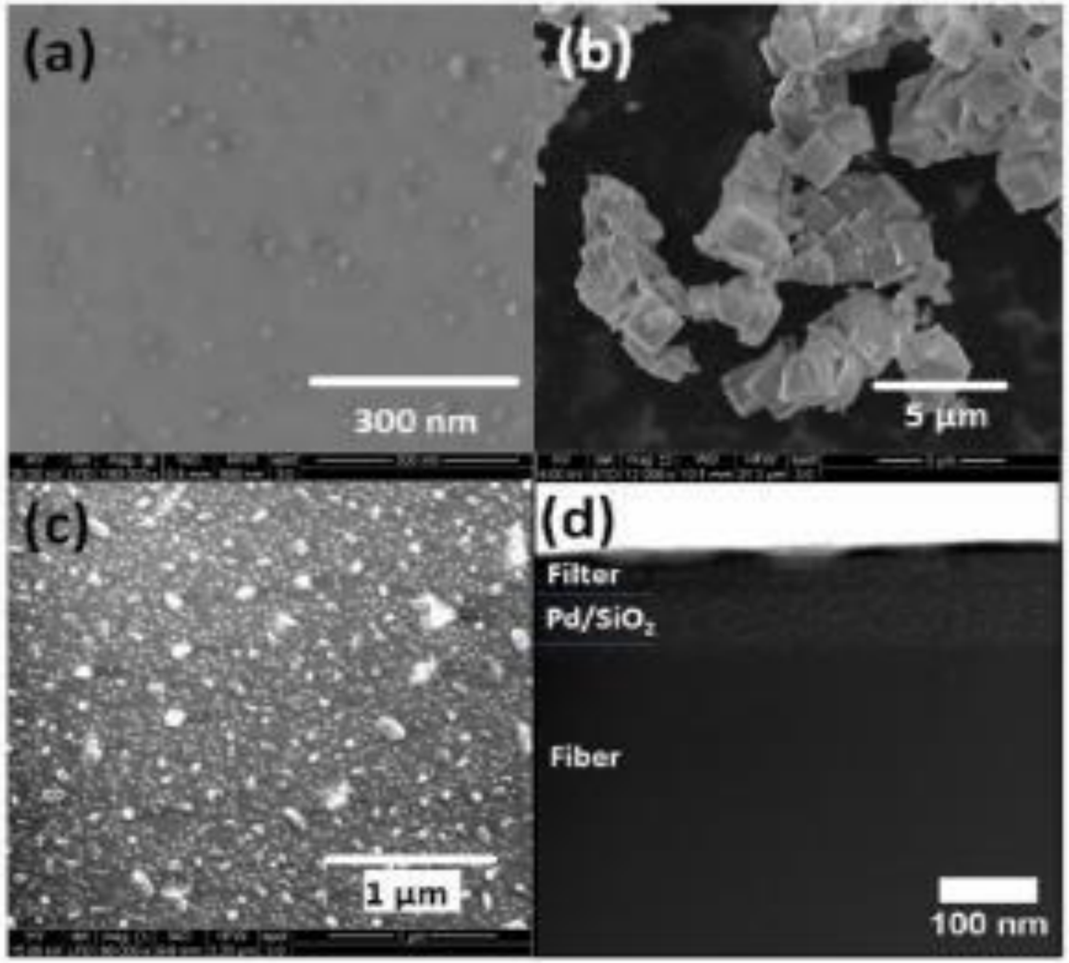
Cost Targets:

Total Installed < \$100

Technical Explanation of the Proposed Approach : Sensor Development

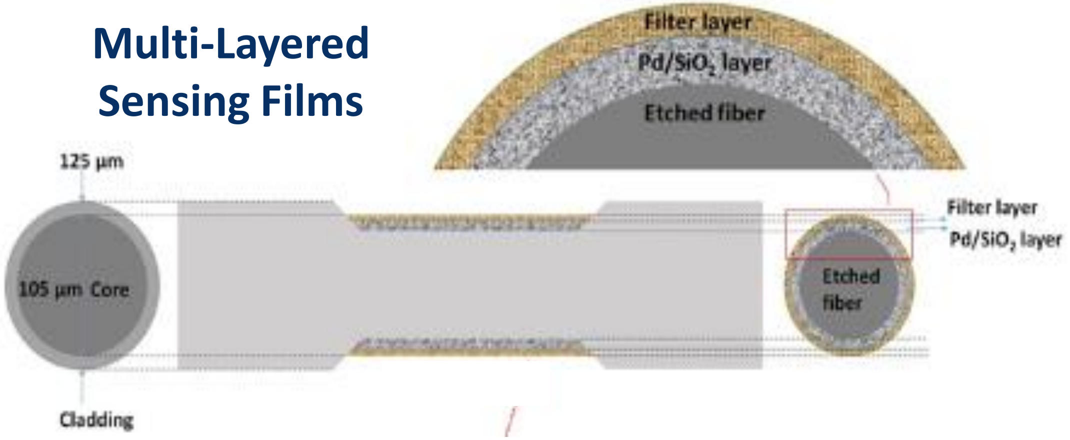
Selective H_2 Sensing

Pd Nanoparticles in Silica and Zeolitic Derived Filter Layers

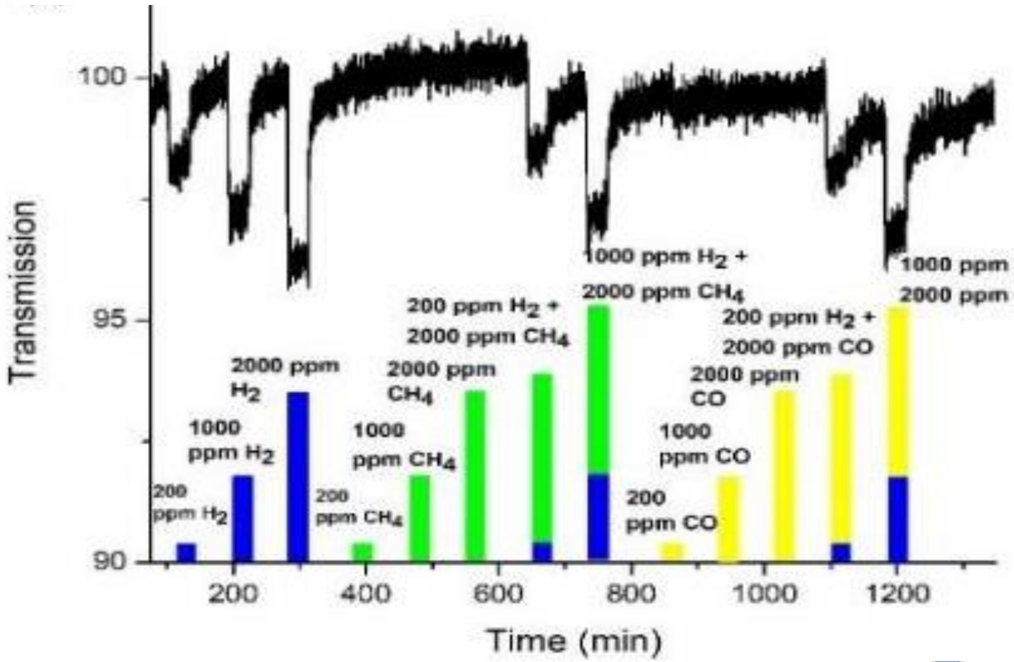


IEEE Sensors Letters, 1(5) 1-4 (2017)

Multi-Layered Sensing Films

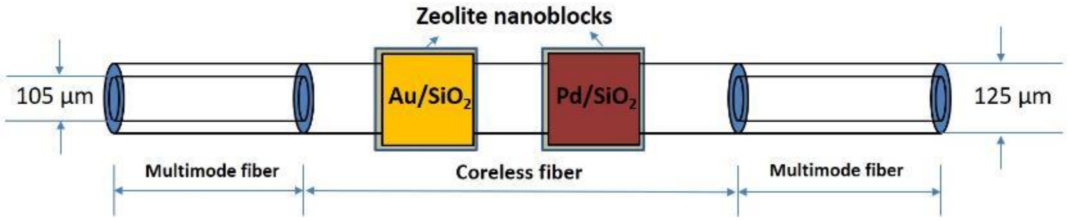


H_2 Sensitivity and Selectivity Over Relevant Ranges

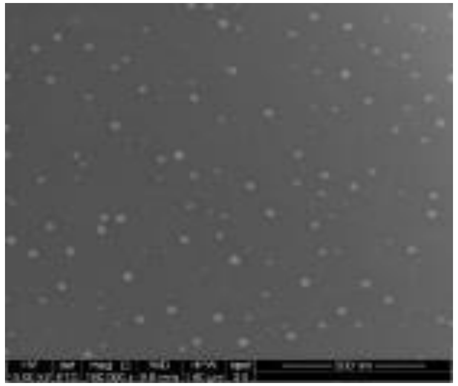


Technical Explanation of the Proposed Approach : Sensor Development

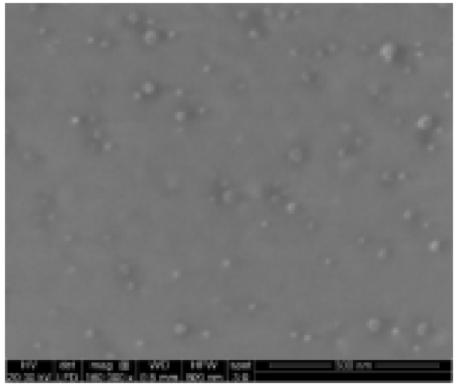
Low-cost Fiber Optic Sensor Array for Simultaneous Detection of H_2 and Temperature



5-30 nm noble metal NPs

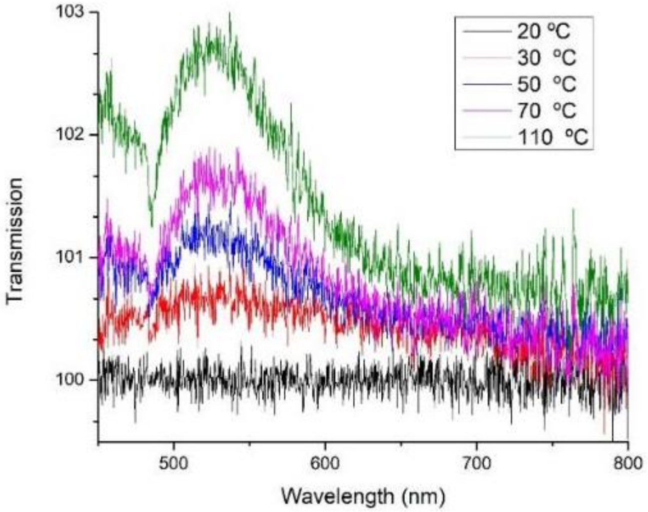


Au / SiO_2 Films

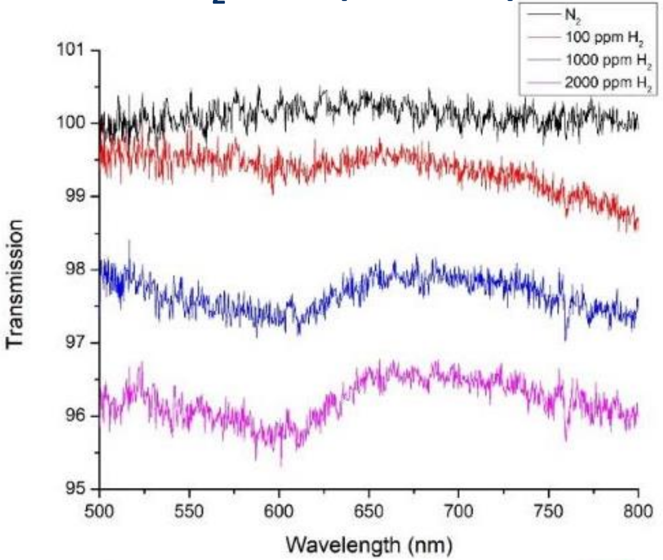


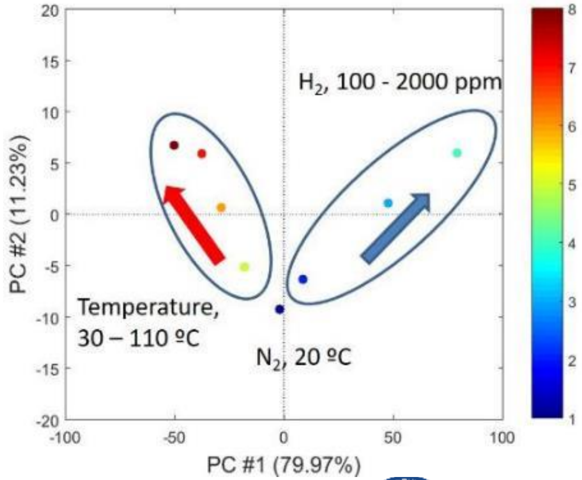
Pd / SiO_2 Films

Au Temp. Absorption Response



Pd H_2 Absorption Response



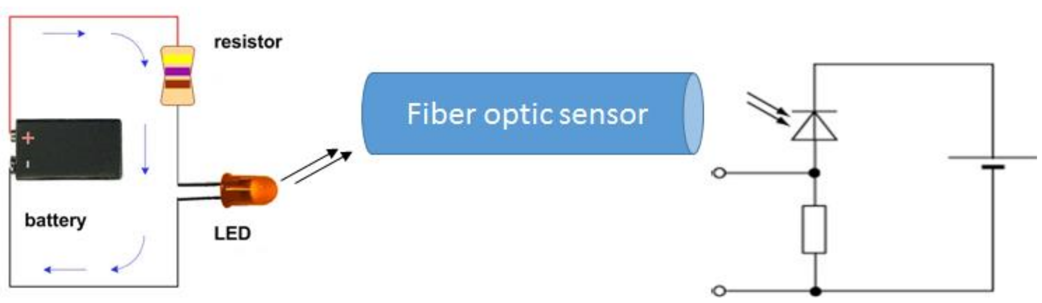


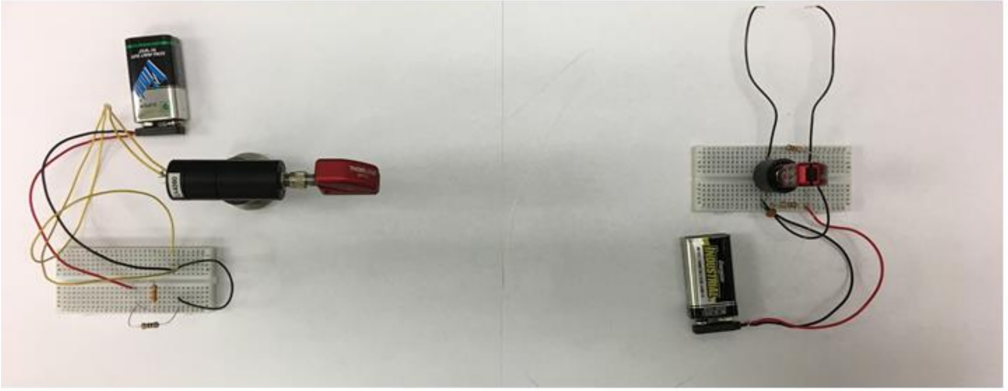
Proc. SPIE, Fiber Optic Sensors and Applications XV 10654, 1065405

- ❑ **Unique wavelength dependences of responses to temperature and H_2**
- ❑ **Two clusters of H_2 and temperature separated by principle component analysis**
- ❑ **Confirms discrimination by multiple wavelength interrogation**

Technical Explanation of the Proposed Approach : Sensor Development

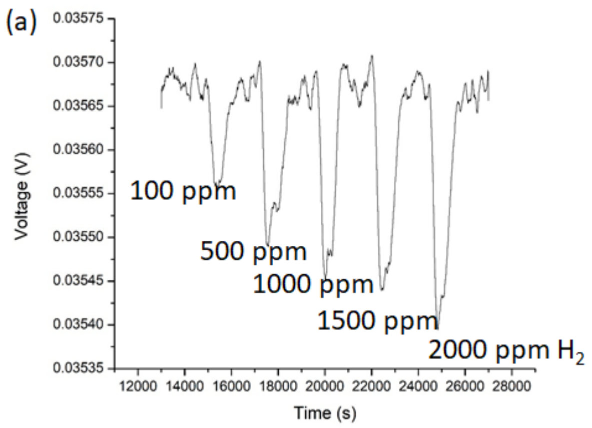
Low-cost Fiber Optic Sensor Array Prototype

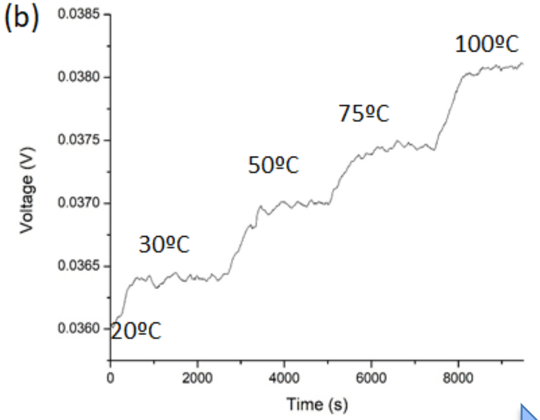




LED Input

Photodiode Output





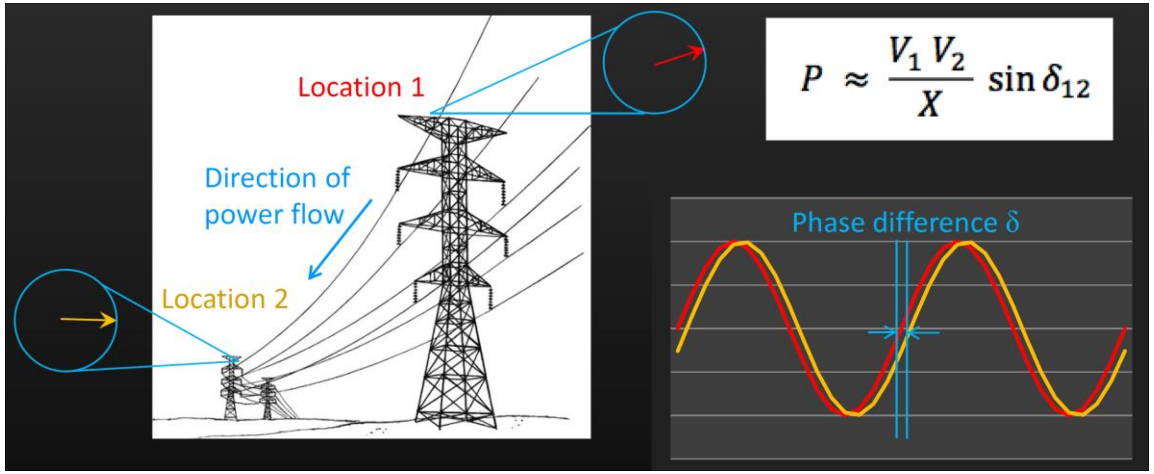
Experimental Prototypes

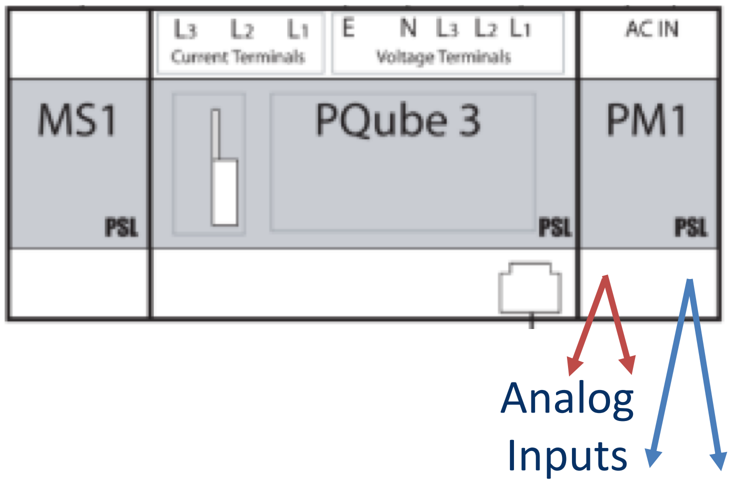
MODEL	COST
Distribution Transformer Market interest	< $100
Single Gas On-line Dissolved Gas Monitor	$6,500-7,500
HYDROCAL	$8,565
SmartDGA for Transformers	$15,000-25,000
On-line Gas Chromatography DG Monitor	$25,000-45,000
Dissolved Gas Analysers	$46,800
DGA	$40,000
Fiber Optic Temperature Monitor	$5,000-16,000
Advanced Electronic Temperature Monitor	$4,000
SAW Temperature Sensors	$3,000
Fiber Temperature Sensor	10,000
Deuterium Halogen Source + Spectrometer	$12,000
Mounted LED + Power Meter	$2,100
Unmounted LED + Photodiode Circuit	<$100

- ❑ Low-cost prototypes developed using LEDs, filters, and photodiode detectors
- ❑ Demonstrated feasibility for low-cost implementation

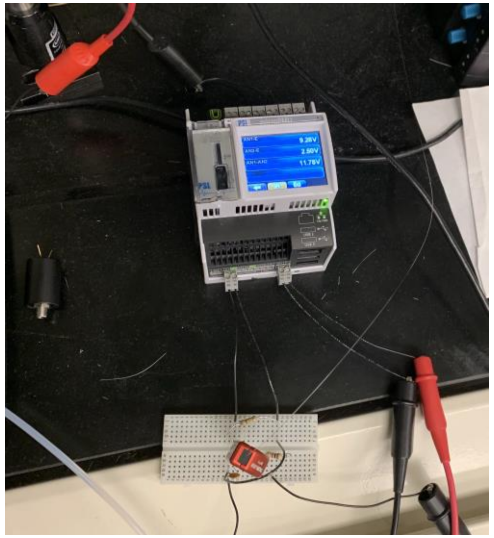
Technical Explanation of the Proposed Approach : Sensor Development

Preliminary Integration with MicroPMU Hardware (Proof of Concept)





Power Input: 24VDC – 48VDC



Changes in analog inputs as a function of H_2 concentration:

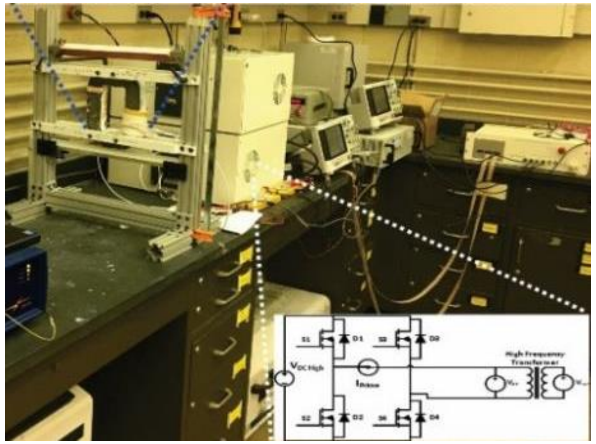
→ 9.24 V (N_2)

→ 9.28 V (2000 ppm H_2)

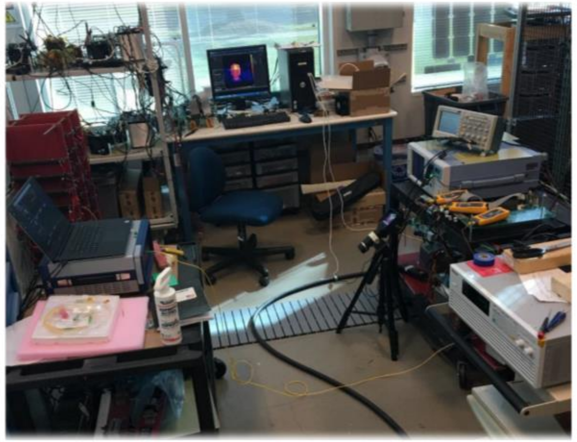
→ 9.24 V (N_2)

Specific Research Questions Being Addressed : Field Validation

Temperature Sensors Advance from Laboratory Test to Field Validation



NETL



NCSU

TRANSFORMER TEST FACILITY

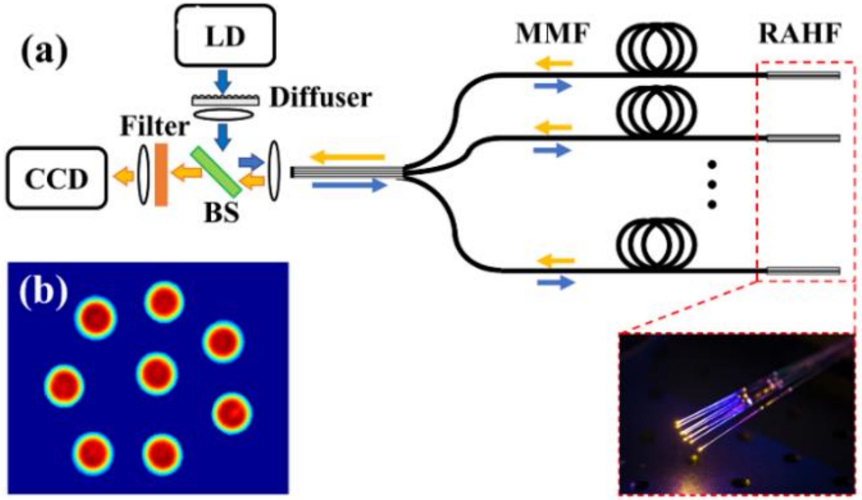
1) Push Forward the R&D on Low-cost Prototype Optical Fiber Temperature Sensing Systems in Validating Field Trials

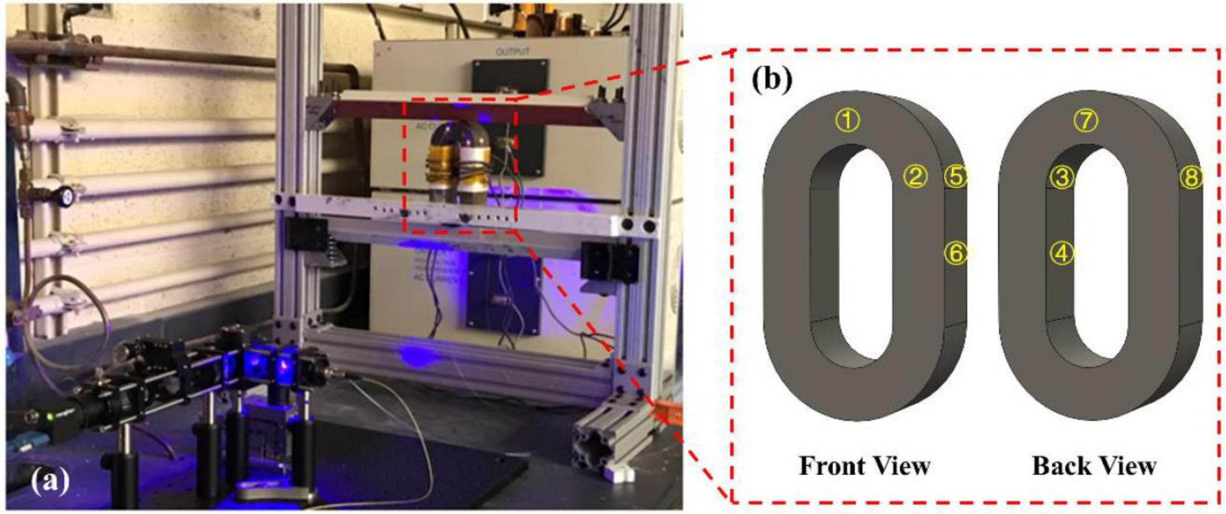
2) Package and On-site Deploy the Sensing Fiber and Interrogator in an Industrial Environment, and Evaluate Performance

3) Distributed Optical Fiber Sensor Demonstration for Real-time High Spatial Resolution High-accuracy Temperature Monitoring of Transformers, Identifying Locations of Hot Spots

Technical Explanation of the Proposed Approach : Field Validation

Field Test Demonstration of a Low-cost Multi-point Sensor



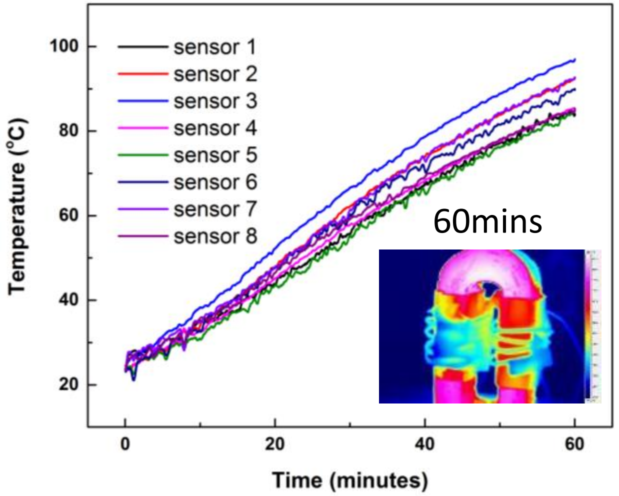


- Point-wise multi-point sensing by using quantum dots infiltrated random air hole fibers and image-based detection.
- Low-cost packaged optical fiber sensor prototype demonstrated for real-time temperature monitoring

A 80-point sensing systems: $560.

- Diode control electronics - $70/unit (5 units)
- Diode lasers (405 nm) - $10/unit
- Control, computation, and communication units - $220/unit (5 units)
- CCD Camera - $30
- 3D printed Optomechanic systems - $100
- Fibers and nano-particles - $50

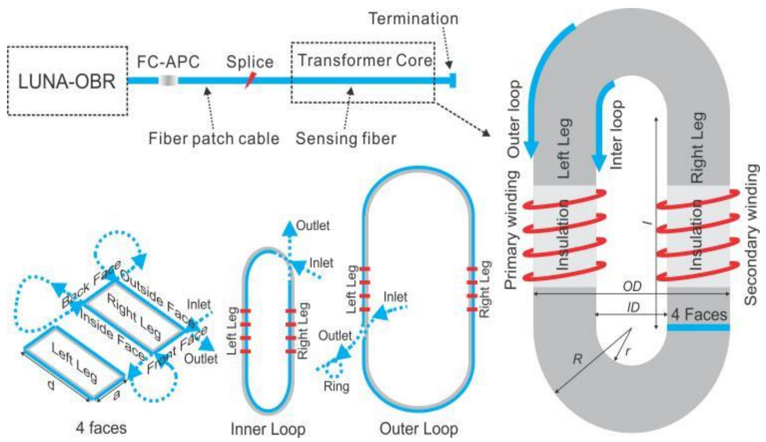
Total Estimated Cost Per Sensor : <~$10



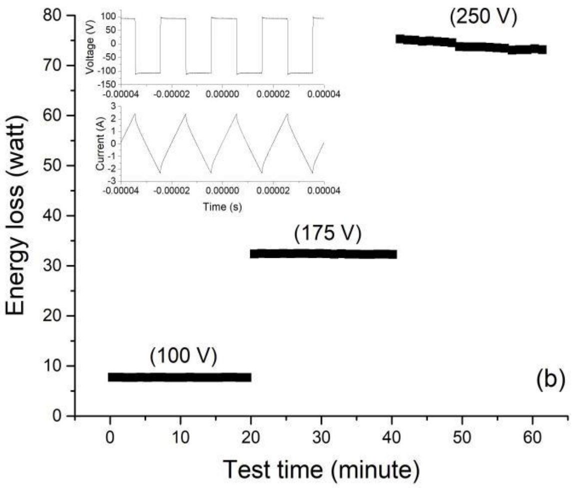
Technical Explanation of the Proposed Approach : Field Validation

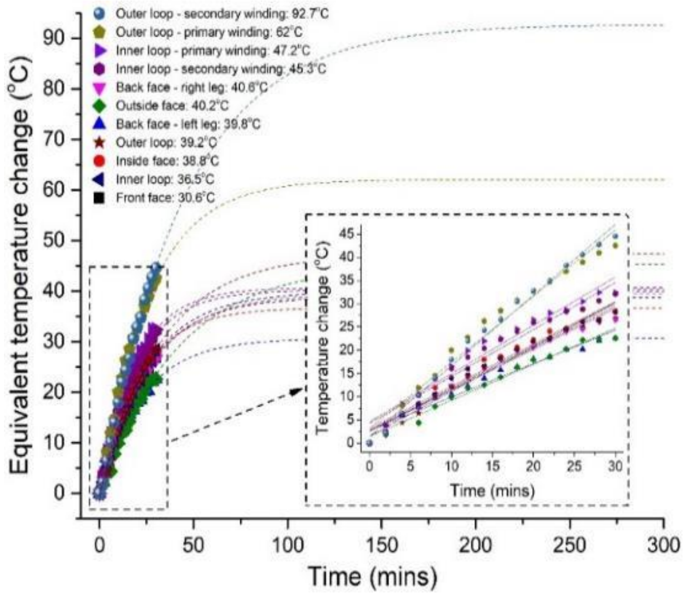
Temperature Monitoring of SuNLaMP Transformer Core at NETL

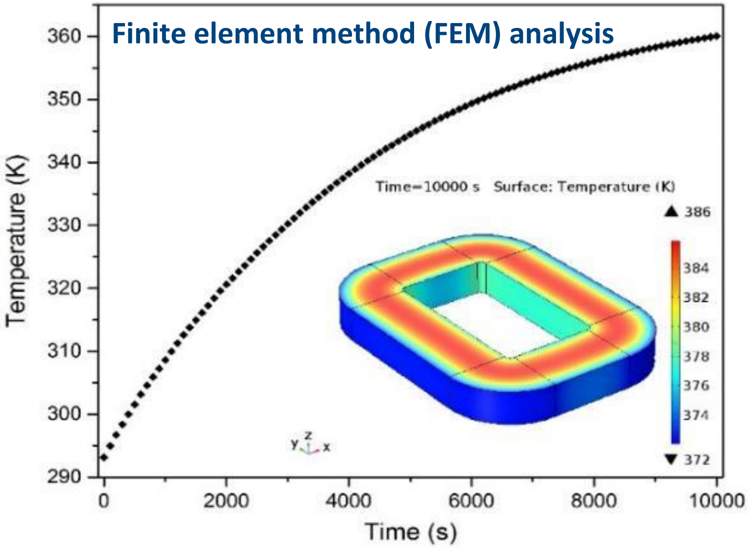
Distributed optical fiber sensor

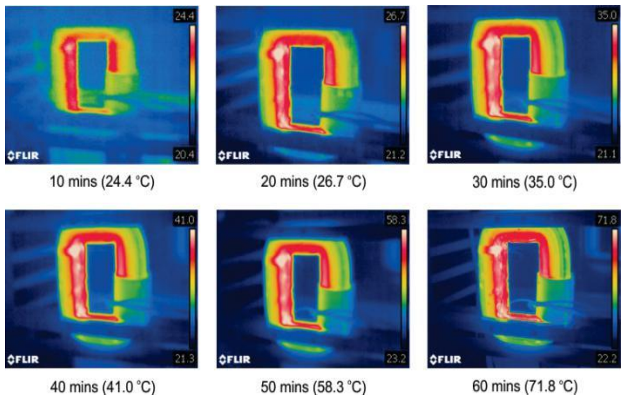


Energy loss measurement







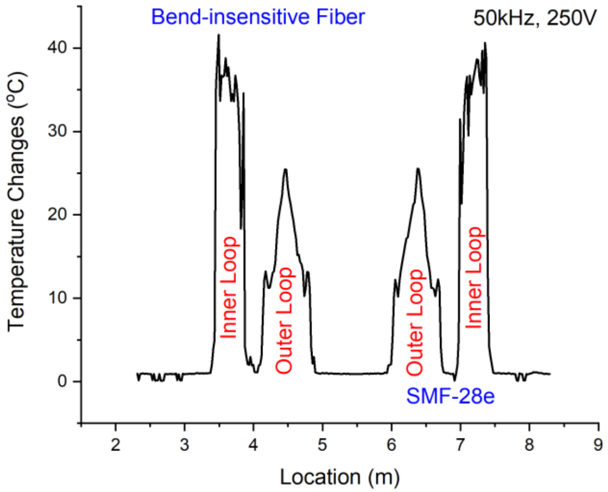


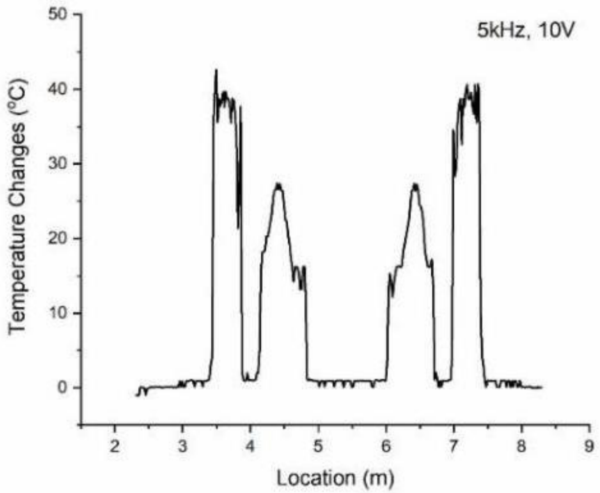
Standard IR-based thermal imaging measurement

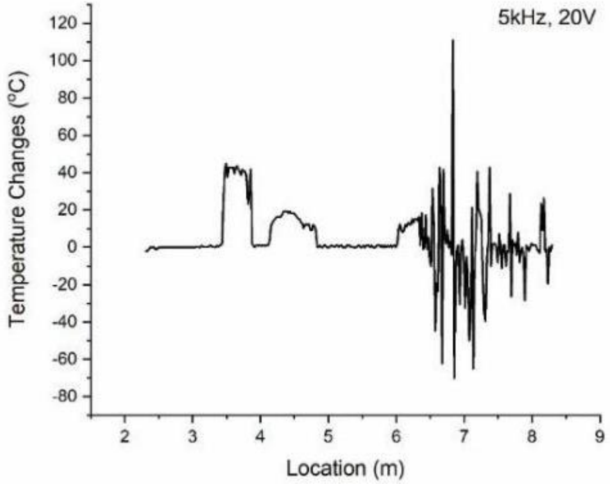
- **Distributed Optical Fiber Temperature Sensor Based on Optical Frequency-Domain Reflectometry shows great advantages over other conventional temperature sensing techniques.**
- **Real-time continuous temperature sensing is demonstrated with 0.1°C resolution and 1 cm spatial resolution.**

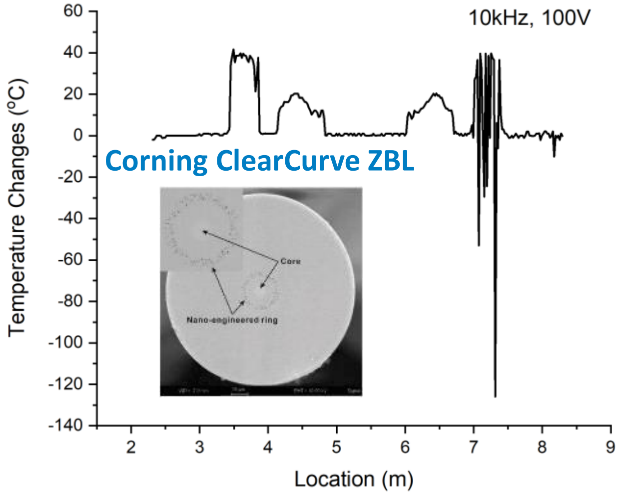
Technical Explanation of the Proposed Approach : Field Validation

Effective Temperature Measurement in a Vibration Environmental Condition









- A specialty fiber with nano-engineered design (Corning ClearCurve ZBL) is designed to reduce bending induced loss while fully compatible with the standard single-mode fiber
- Use of this bend-insensitive fiber in this study can effectively mitigate impact by the transformer core vibration due to magnetostriction

Corning SMF-28e

Maximum Attenuation

Wavelength (nm)	Maximum Value* (dB/km)
1310	0.33 – 0.35
1383**	0.31 – 0.35
1550	0.19 – 0.20
1625	0.20 – 0.23

Mandrel Diameter (mm)	Number of Turns	Wavelength (nm)	Induced Attenuation* (dB)
32	1	1550	≤0.05
50	100	1310	≤0.05
50	100	1550	≤0.05
60	100	1625	≤0.05

Corning ClearCurve ZBL

Maximum Attenuation

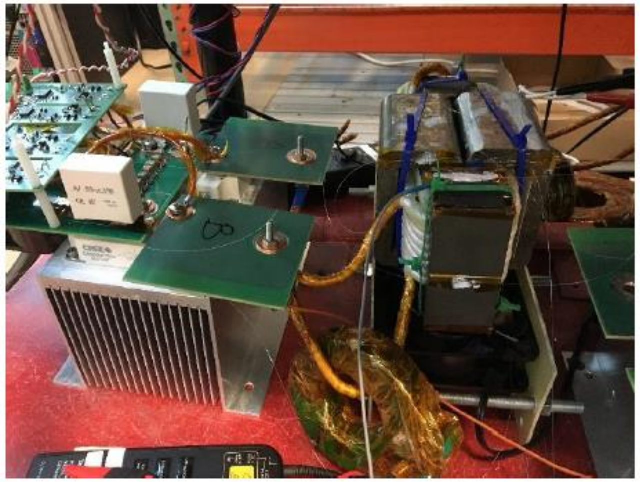
Wavelength (nm)	Maximum Value* (dB/km)
1310	≤ 0.35
1383**	≤ 0.35
1490	≤ 0.24
1550	≤ 0.20

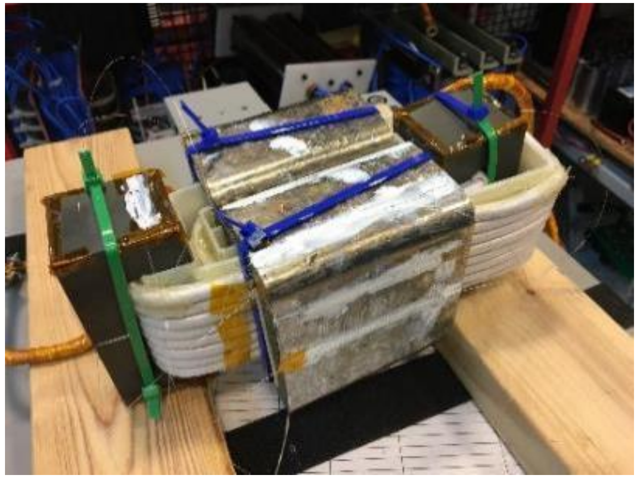
Macrobend Loss

Mandrel Radius (mm)	Number of Turns	Wavelength (nm)	Induced Attenuation* (dB)
5	1	1550	≤ 0.10
5	1	1625	≤ 0.30

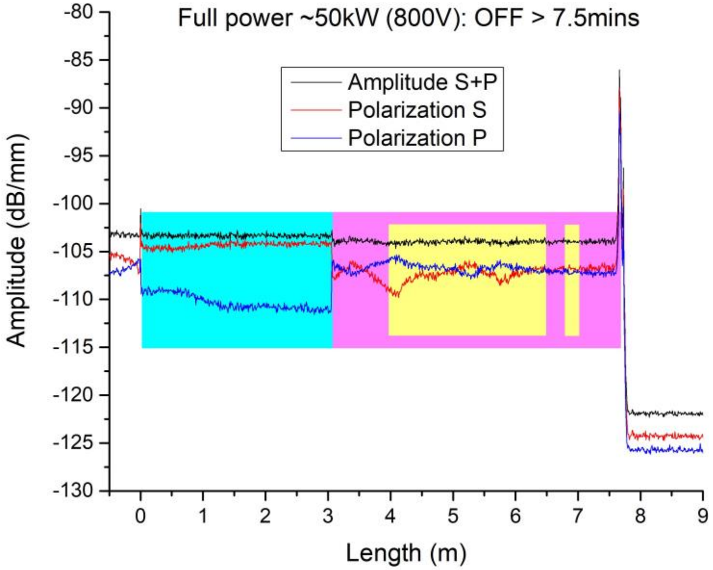
Technical Explanation of the Proposed Approach : Field Validation

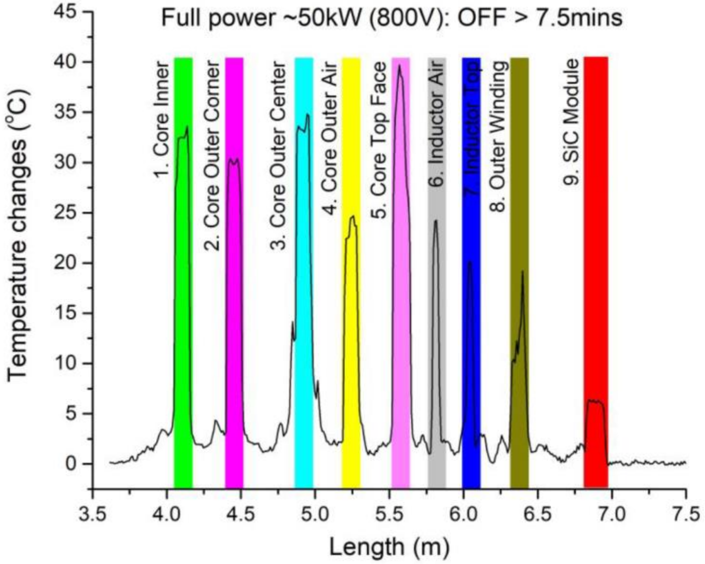
Temperature Monitoring of SuNLaMP Power Electronics Converter at NCSU





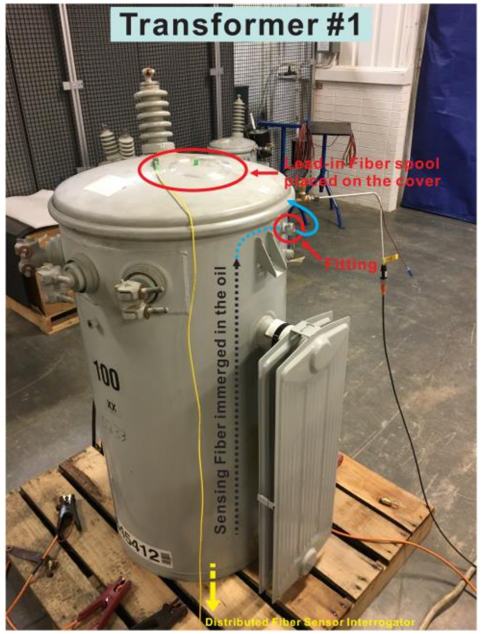
- Real-time monitoring of temperature rises of a 50kW prototype transformer core and SiC module with the OFDR system
- Solve local overheating problems to obtain an optimized thermal design



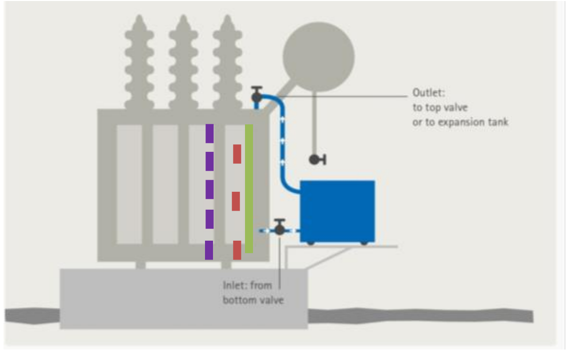


Technical Explanation of the Proposed Approach : Field Validation

Internal Transformer Temperature Monitoring of Commercial Transformer



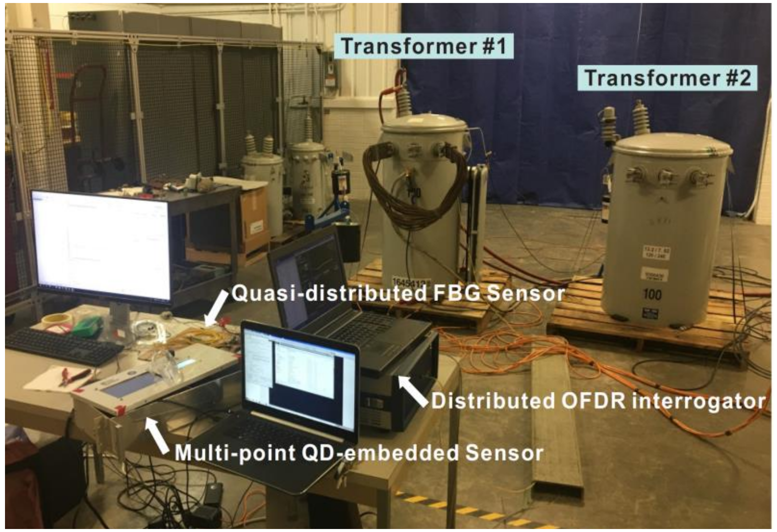
- **Three types of optical fiber sensors are integrated into operational distribution transformers for internal temperature monitoring during standard thermal runs.**

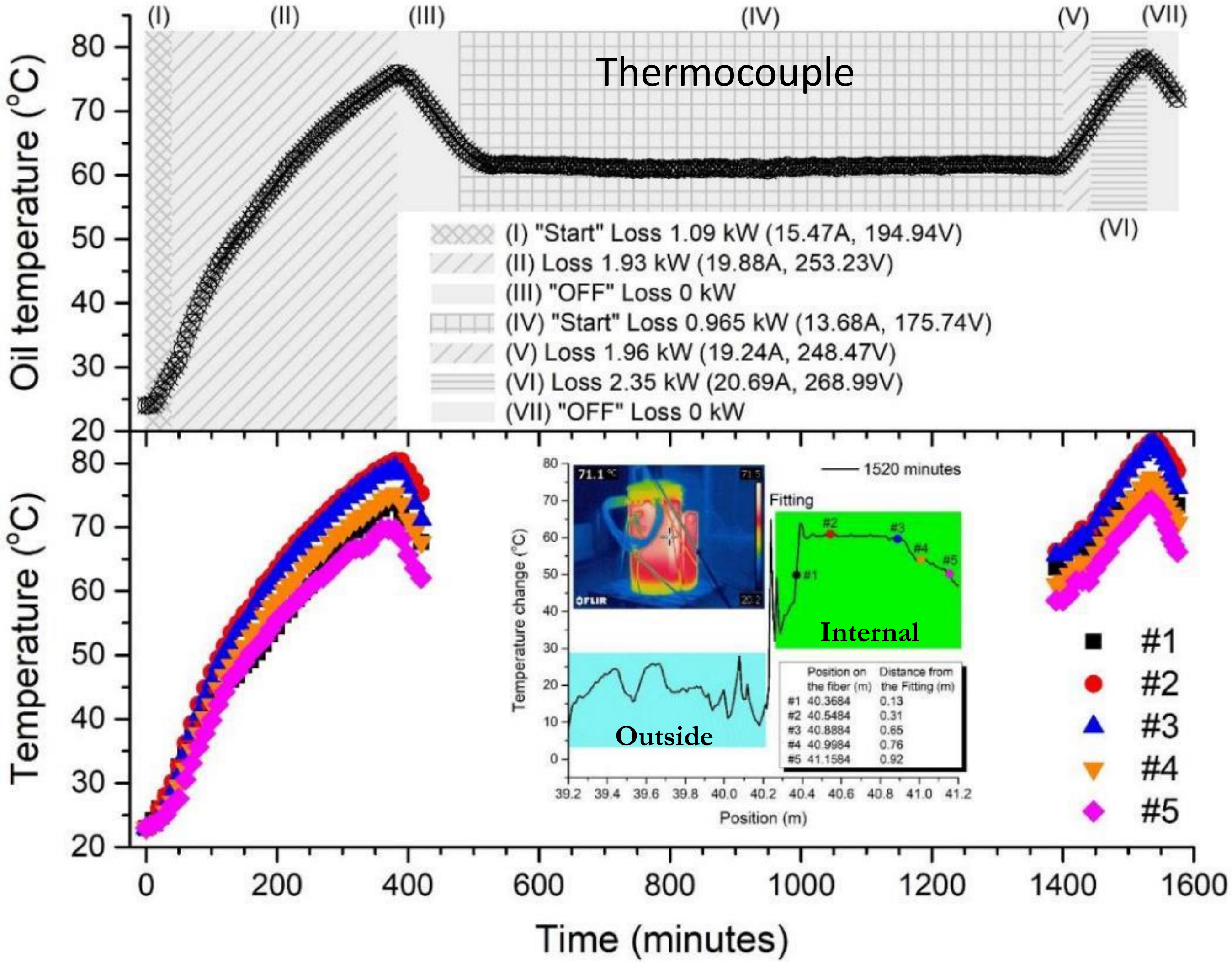


- **Distributed temperature sensing by using BIF and a commercial OFDR system.**
  - Standard telecom single-mode fiber, complex interrogator, ~$100,000 for a 30-m system
- **Quasi-distributed FBG sensor array and its interrogator.**
  - Conventional wavelength division multiplexing FBG, broadband spectrum measurement, ~$10,000 for a 20-point system
- **Point-wise multi-point sensing by using quantum dots infiltrated random air hole fibers and image-based detection.**
  - Specialty fiber and sensing materials, intensity-based interrogation realized by a diode laser and a CCD camera, ~$500 for a 20-point system

Technical Explanation of the Proposed Approach : Field Validation

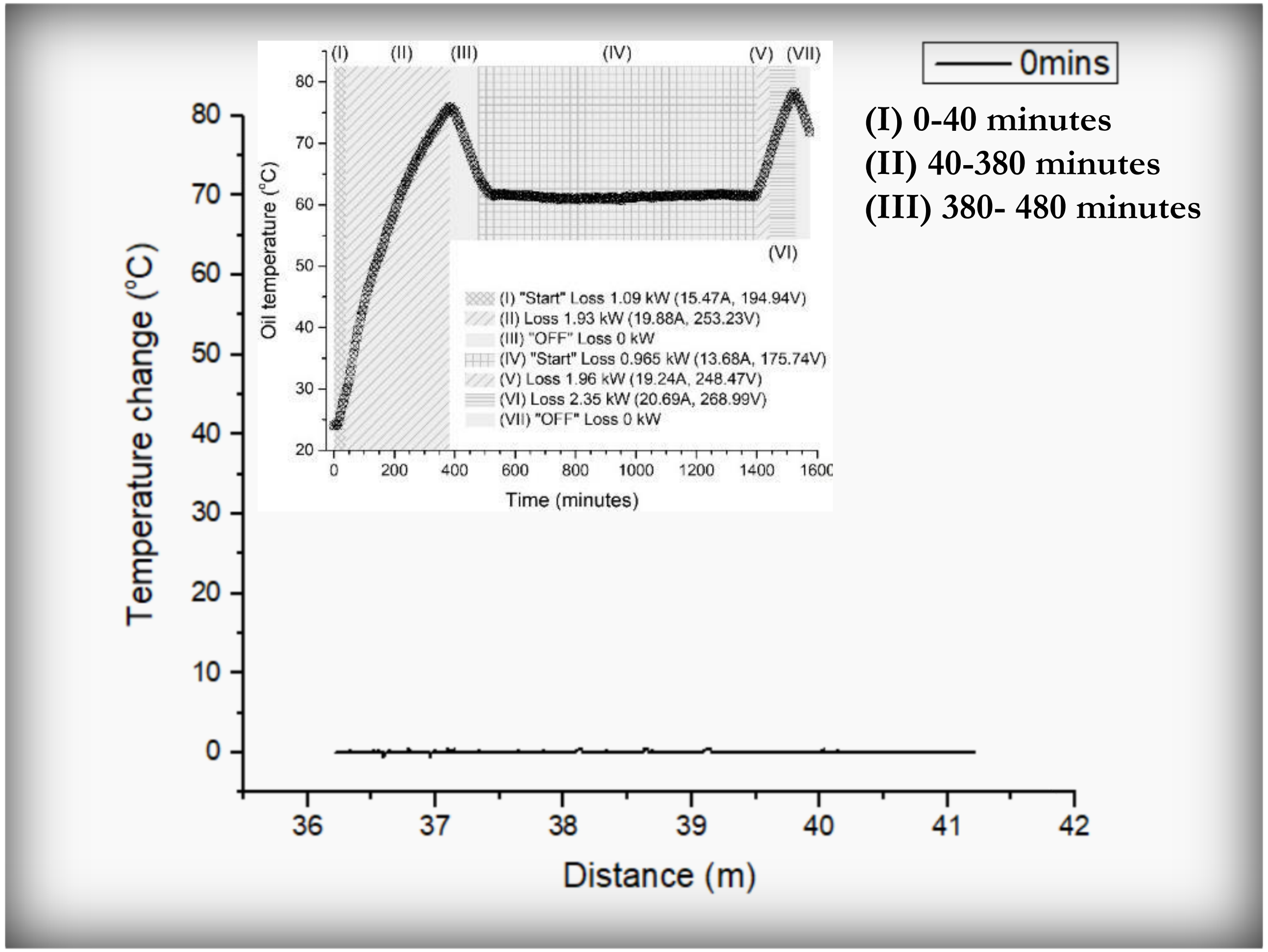
Internal Transformer Temperature Monitoring of Commercial Transformer

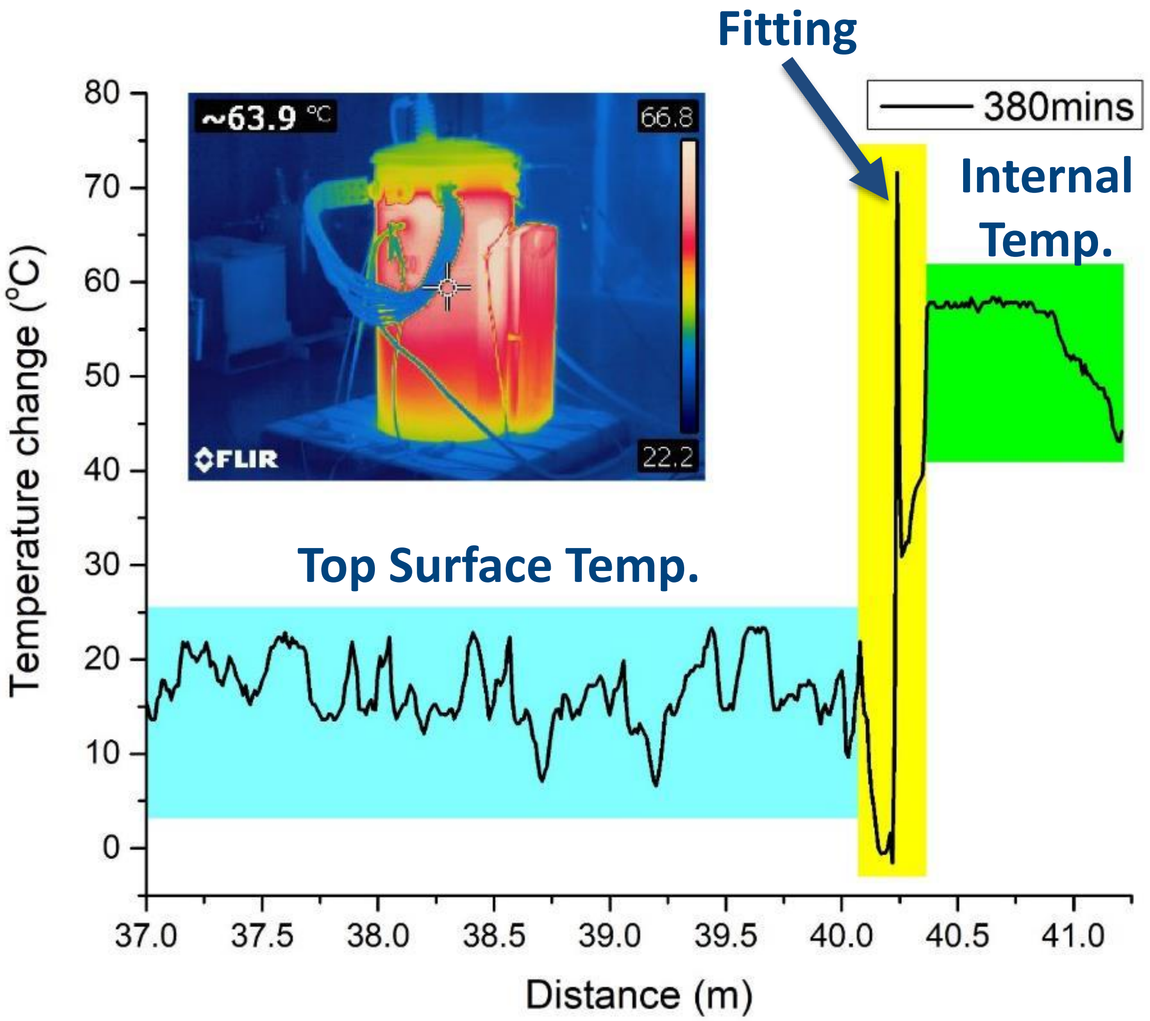




- ❑ Aging and failure of distribution transformers primarily dictated by peak and average internal temperature.
- ❑ New information provided about internal transformer temperatures not previously accessible.

Example Testing Results : Day 2 Field Validation Efforts





In-situ Thermal characterization of Transformers Approaching Steady State After Energizing

Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

Project Schedule, Deliverables, and Current status

Task	Expected Completion Date	Deliverables	Status
1.1	09/30/2017	Literature review to determine temperature and chemical sensing strategies for real-time monitoring of transformer	Completed
1.2	09/30/2018	Transformer monitoring system commercial market survey	Completed
2.1	09/30/2018	Functional sensing layers integrated with low-cost optical fibers: selective H_2 sensing	Completed
2.2	09/30/2018	Functional sensing layers integrated with low-cost optical fibers: temperature sensing	Completed
2.3	09/30/2019	Develop low-cost fiber optic sensor array prototype for simultaneous detection of H_2 and temperature	Completed
2.4	09/30/2019	Functional sensing layers integrated with low-cost optical fibers: selective C_2H_2 sensing	Completed
3.1	09/30/2017	Field test of the distributed optical fiber temperature sensor at CMU/NETL	Completed
3.2	09/30/2018	Field test of the distributed optical fiber temperature sensor at NCSU	Completed
3.3	09/30/2019	Field test of the distributed optical fiber temperature sensor in commercial transformer	Completed

The project is on a no-cost extension as funds have been spent down and publications are in progress.

Anticipated Challenges and Risk Mitigation Strategies

- **Complex Measurement Environment with Changing Temperature, Multi-Component Gases:**

  Mitigation #1: Develop Selective Sensing Layers for Specific Analytes
  Mitigation #2: Utilize Multi-Wavelength Interrogation Methods for Simultaneous Monitoring of Multiple Parameters

- **Further Cost Reduction for Low Cost Temperature / Proxy DGA:**

  Mitigation: Optimize Sensor Design and Adopt Advanced Data Processing Techniques to Improve Sensing Performance by Using Low-Cost Components

- **Intrinsic Temperature and Strain (Vibration) Cross-talk Effects in Optical Fiber Sensors:**

  Mitigation: Stress-free Installation of Sensing Fiber and Usage of Specialty Fiber to Minimize External Disturbance

Next Steps (Future Projects)

- ❑ Demonstrate Integration of Data Streams with the Micro PMU System
- ❑ Demonstrate a Low-cost Distributed Fiber Sensor Interrogator
- ❑ Field Validate Low Cost Temperature / Proxy DGA in a Distribution Transformer
- ❑ Field Validation of an Instrumented Transformer on the Distribution System
- ❑ Field Validation of Distributed Sensing on Distribution Lines

Broader Impact

Publications Over the Project Duration:

- ❑ Real-time monitoring of temperature rises of energized transformer cores with distributed optical fiber sensors, 2019, IEEE Transactions on Power Delivery 34 (4) 1588-1598.
- ❑ Low-cost fiber optic sensor array for simultaneous detection of hydrogen and temperature, 2018, Proc. SPIE, Fiber Optic Sensors and Applications XV 10654, 1065405.
- ❑ Double-Layer Zeolite Nano-blocks and Palladium-based Nanocomposite Fiber Optic Sensors for Selective Hydrogen Sensing at Room Temperature, 2017, IEEE Sensors Letters 1 (5), 1-4.
- ❑ Chemical Sensing Strategies for Real-time Monitoring of Transformer Oil: A Review, 2017, IEEE Sensors Journal 17 (18), 5786 – 5806.
- ❑ Distributed fiber-optic sensor for real-time monitoring of energized transformer cores, 2017, Micro-and Nanotechnology Sensors, Systems, and Applications IX 10194, 101941S.

Patent Applications Submitted or Awarded Over the Project Duration:

- ❑ Low-cost fiber optic sensor array for simultaneous detection of multiple parameters, 2019, US Patent App. 16/387,359.
- ❑ Distributed Sensing of Electromagnetic Components Using Optical Fiber Based Methods, 2019, US Patent App. 16/123,786
- ❑ Palladium and platinum-based nanoparticle functional sensor layers and integration with engineered filter layers for selective H2 sensing, 2017, US Patent 15/641,193.
- ❑ Noble and Precious Metal Nanoparticle-Based Functional Sensor Layers for Selective H2 Sensing, 2017, US Patent 9696256.
- ❑ Temperature Sensing Using High Temperature Stable Plasmonic Nanocomposite Films in Optical Fiber Based Sensors, 2017, US Patent 9568377.

Design improvement

– Sensor integration

2017

Prototyping

- Packaging
- Field Validation

2018-2019

Evaluating potential start-up

- DOE/NSF I-corps

2019

If business case seems reasonable:

Develop a New Product Line Around the Concept

- SBIR phase I, SBIR phase II

2020+

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