Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

FWP-1022435

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U.S. Department of Energy

National Energy Technology Laboratory

Carbon Capture Front End Engineering Design Studies and CarbonSafe
2020 Integrated Review Webinar

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Project Team

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Additively Embedded Fiber Optic Sensors
Sensor Infused Wellbore Casings

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Intelligent Optical Systems
Field Deployment and Wellbore Testing
Fiber Optic Chemical Sensors

NETL R&IC
Fiber Optic Chemical Sensors
Surface Acoustic Sensors
Chemical Functionalization Layers
Sensor Infused Wellbore Cements
Wellbore Materials Characterization

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Industry Partnership Engagement

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Silicon Integrated Circuit Sensors
Wireless Energy Harvesting and Telemetry

Carnegie Mellon University
Surface Acoustic Wave Device Sensors
Wireless Telemetry in Wellbore & Geological Environments

Prof. David Greve,
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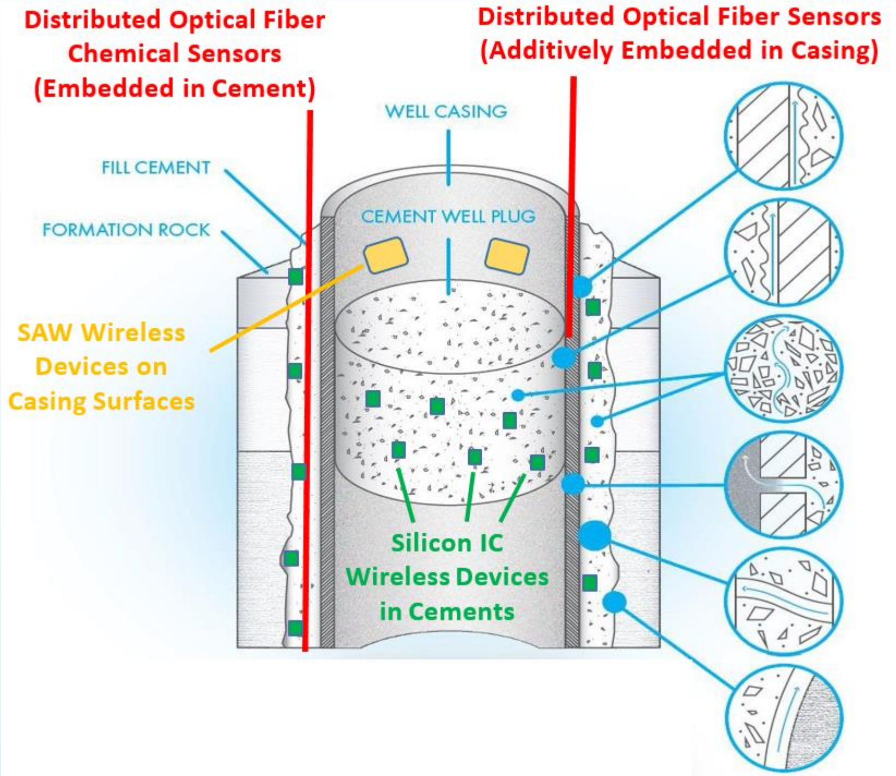
Overall Project Performance Dates: 04/2018-03/2021

Project Objective



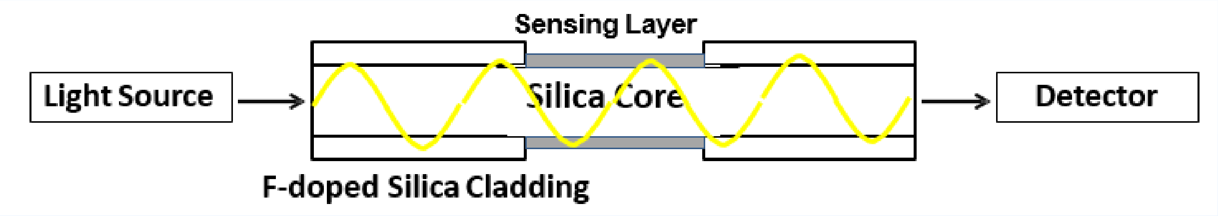
Develop and Demonstrate:

- A suite of complementary technologies for wellbore integrity monitoring
- Chemical sensing of high priority parameters (pH, corrosion onset, etc.)
- Optical fiber and passive wireless (SAW, SiIC) technologies

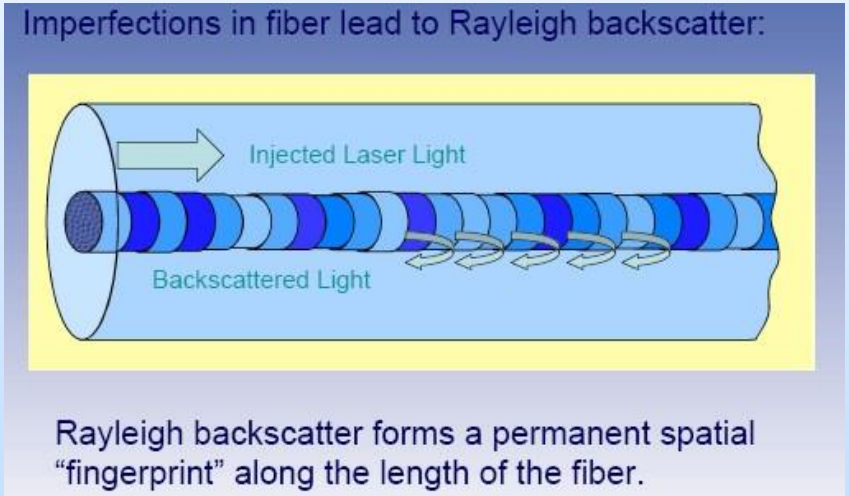
Overall Goal: A suite of technologies functionalized for chemical sensing and identification of wellbore integrity risks BEFORE they result in failures.

Technology #1: Distributed Optical Fiber Sensors

Sensing Principle : Evanescent Wave Sensors



Distributed Sensing

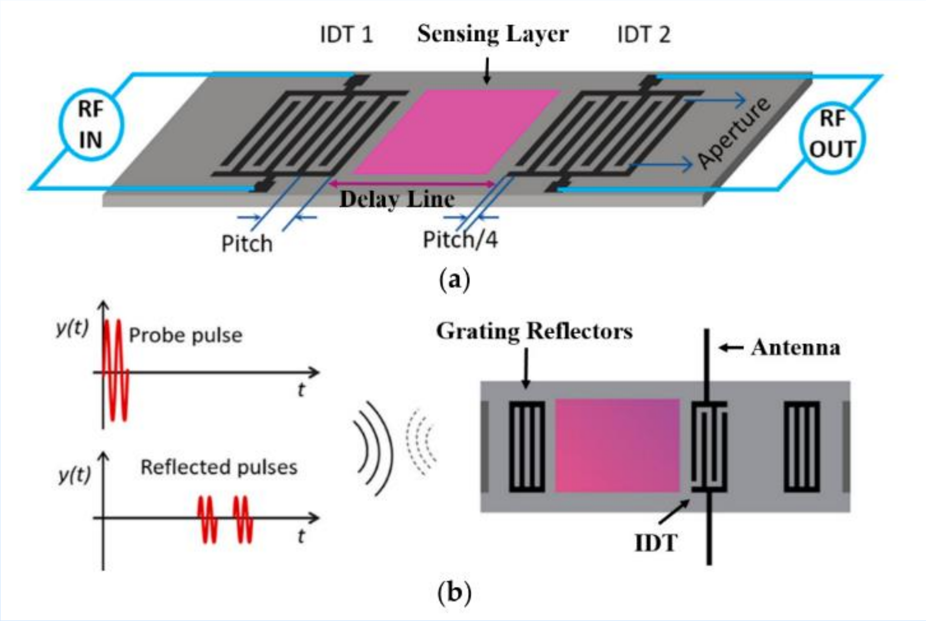


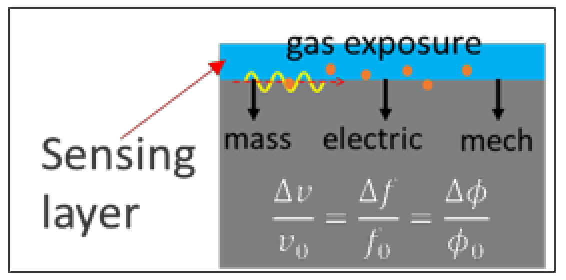
- Eliminate Electrical Wiring and Circuitry at the Sensing Location (Stability)
- Tailored to Parameters of Interest Through Functional Materials (Functionalization)
- Compatibility with Broadband and Distributed Interrogation (Geospatial / Multi-parameter)

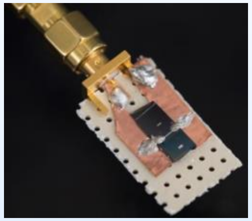
Deployment Scenario: Embedded Within Wellbore Cements and Casing Metals

Technology #2: Passive and Wireless SAW Devices

Sensing Principle : Functionalized Surface Acoustic Wave Devices





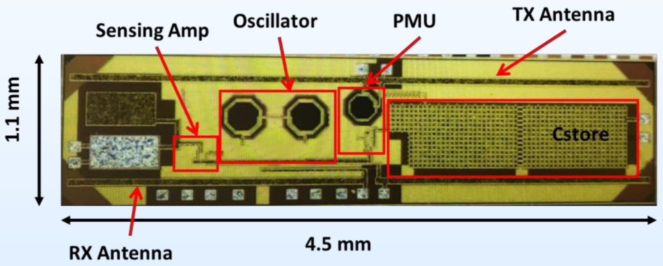


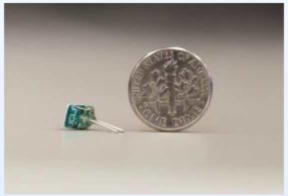
- Passive and wireless operation
- Rugged and stable for harsh environment applications
- Telemetry is a primary challenge, must be addressed in parallel

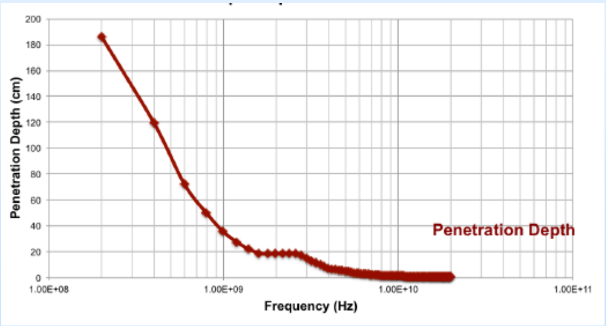
Deployment Scenario: Embedded on Interior and Exterior Casing Surfaces

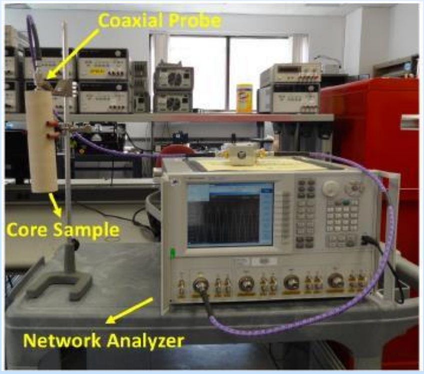
Technology #3: Wireless Miniature SiIC Devices

Sensing Principle : Functionalized Silicon Integrated Circuit Devices









- ➢ Miniaturized devices with active functions through IC processing
- ➢ Wireless energy harvesting and storage to eliminate batteries
- ➢ Telemetry is again a major challenge to be addressed

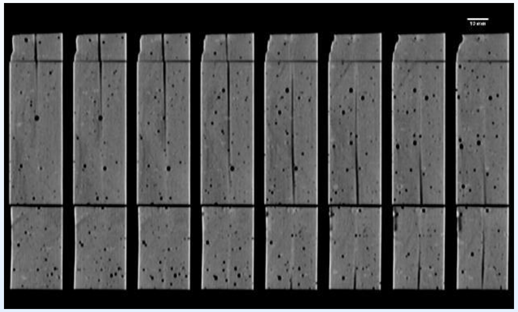
Deployment Scenario: Embedded Within the Wellbore Cements

Additional Efforts: Sensor Embedding

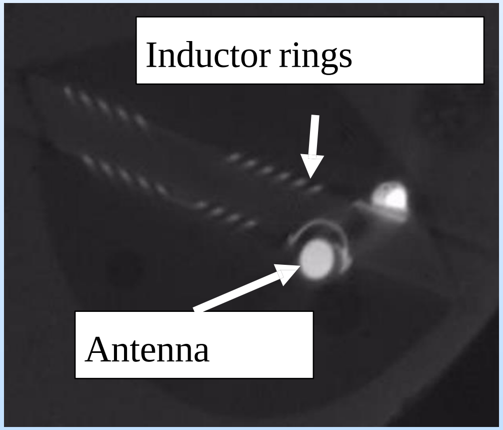
Wellbore Cements

Mechanical Testing

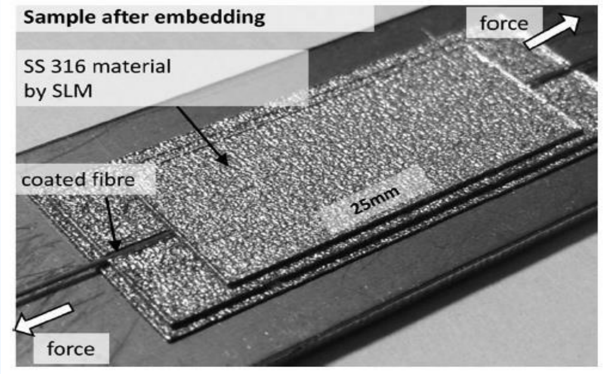
CT Scans of Embedded Optical Fibers

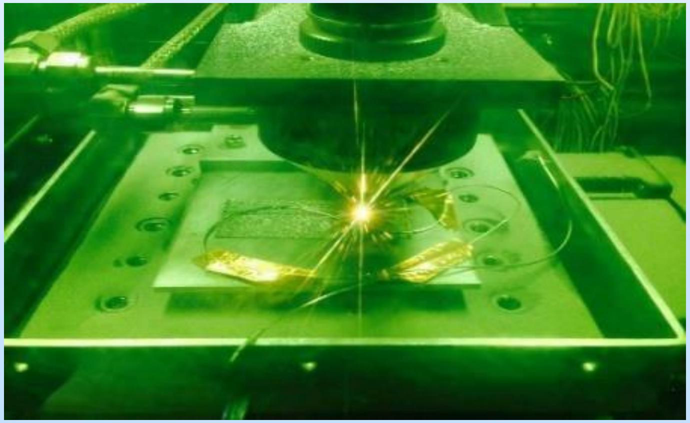


SiIC Sensors



Embedded in Casing Alloys





Proof-of-Concept Sensor Embedding Efforts Combined with Structural and Performance (CT scans, Permeability, Porosity, Corrosion) Benchmarking.

Project Structure: Tasks and Outcomes

Overall Task Structure

Task 1: Project Management

Task 2: Technology Maturation Plan & Industry Engagement

Task 3: Chemical Sensing Layer Research & Development

Task 4: Multi-Functional Optical Fiber Sensor Development & Deployment

Task 5: Multi-Functional Wireless Based Sensor Device Development

Task 6: Sensor-Infused Wellbore Material Performance Characterization

Key Project Deliverables and Outcomes

#1: New Chemical Sensing Layers for High Alkalinity / High T in Wellbore Relevant Conditions

#2: Maturation of New Wireless / RF Sensing Technology for Subsurface

#3: Field Validation of New Fiber Optic pH Sensing Technology

Project Progress: Industry Advisory Group

Advisory Group Members

Name	Company	Expertise
Glen Benge	Benge Consulting	Wellbore isolation & well cementing
Dennis Dria	Myden Energy Consulting, PLLC	Fiber-optic technology development & implementation
George Koperna	Advanced Resources International, Inc.	CO_2 EOR & storage, reservoir engineering
Igor Kosacki	WellDiver	Sensor development
John Lovell	MicroSilicon Inc.	Temp & pressure measurement systems, Wellhead asphaltenes sensor
Tim Ong	BHP Billiton	Strategy planning- technology & innovation
Pierre Ramondenc	Schlumberger	Coiled tubing well interventions, real-time fiber-optics
Austin Vonder Hoya	Pioneer Natural Resources USA	Geophysical technology
David Wagenmaker	Southern Company Gas	Reservoir engineering

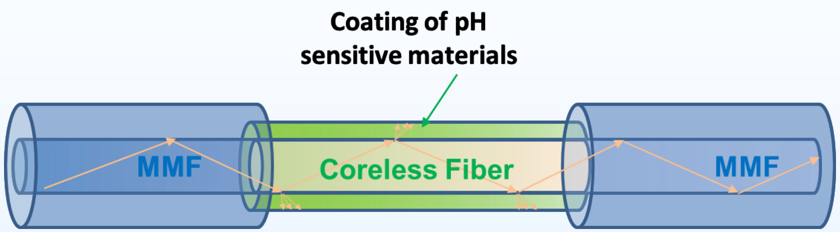
Ranking of Geochemical Parameters to Be Monitored

Rank	Geochemical paramters
1	pH
2	H_2S, HS^-
3	Dissolved CH_4 and CO_2
4	Corrosion ions (Mn^{2+}, Fe^{2+}, etc.)
5	Ionic strength, Solution conductivity
6	TDS
7	Dissolved oxygen
8	Cl^-
9	Na^+
10	Ca^{2+}

- Advise on matters that directly concern the technology developed for industry:
  - Wellbore environment for different applications
  - Hierarchy of sensing applications to industries represented
  - Deployment challenges
  - Wellbore integrity
  - Longevity (sensor and power)
- Industries represented:
  - CO_2 Storage
  - Geothermal
  - Waste Water Disposal
  - Oil Industry
- Field demonstrations are still in early stages

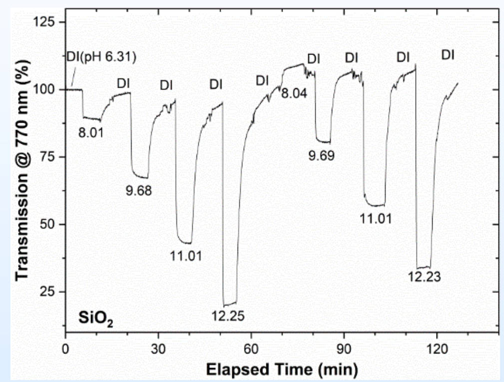
Regular Meetings Have Occurred with the Industry Advisory Group to Provide Feedback and Guide Technology Maturation Plans for the Overall Project.

Project Progress: Chemical Sensing Layers

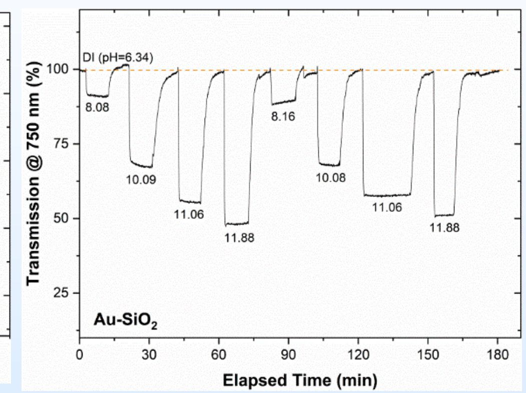


Oxides	Room Temp.	80 °C, high pH
SiO_2	✓	
$Au\text{-}SiO_2$	✓	
TiO_2		✓
$Au\text{-}TiO_2$		✓
ZrO_2		✓

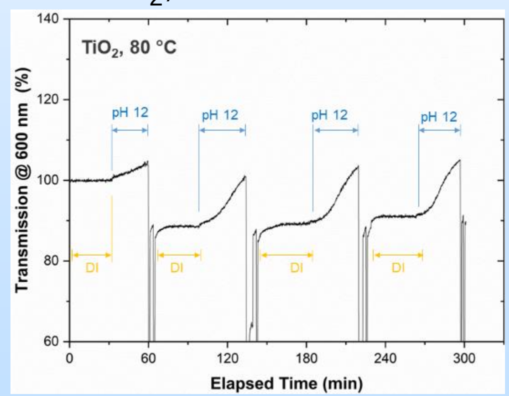
SiO_2, Room Temperature



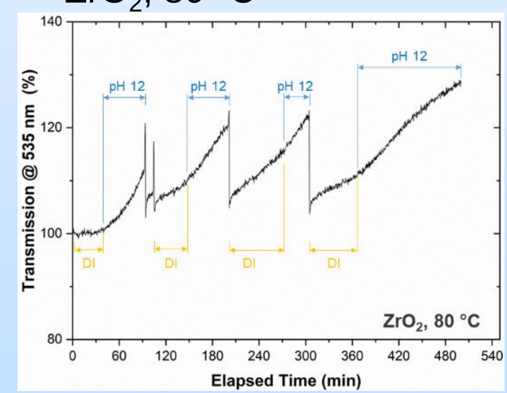
$Au\text{-}SiO_2$, Room Temperature



TiO_2, 80 °C

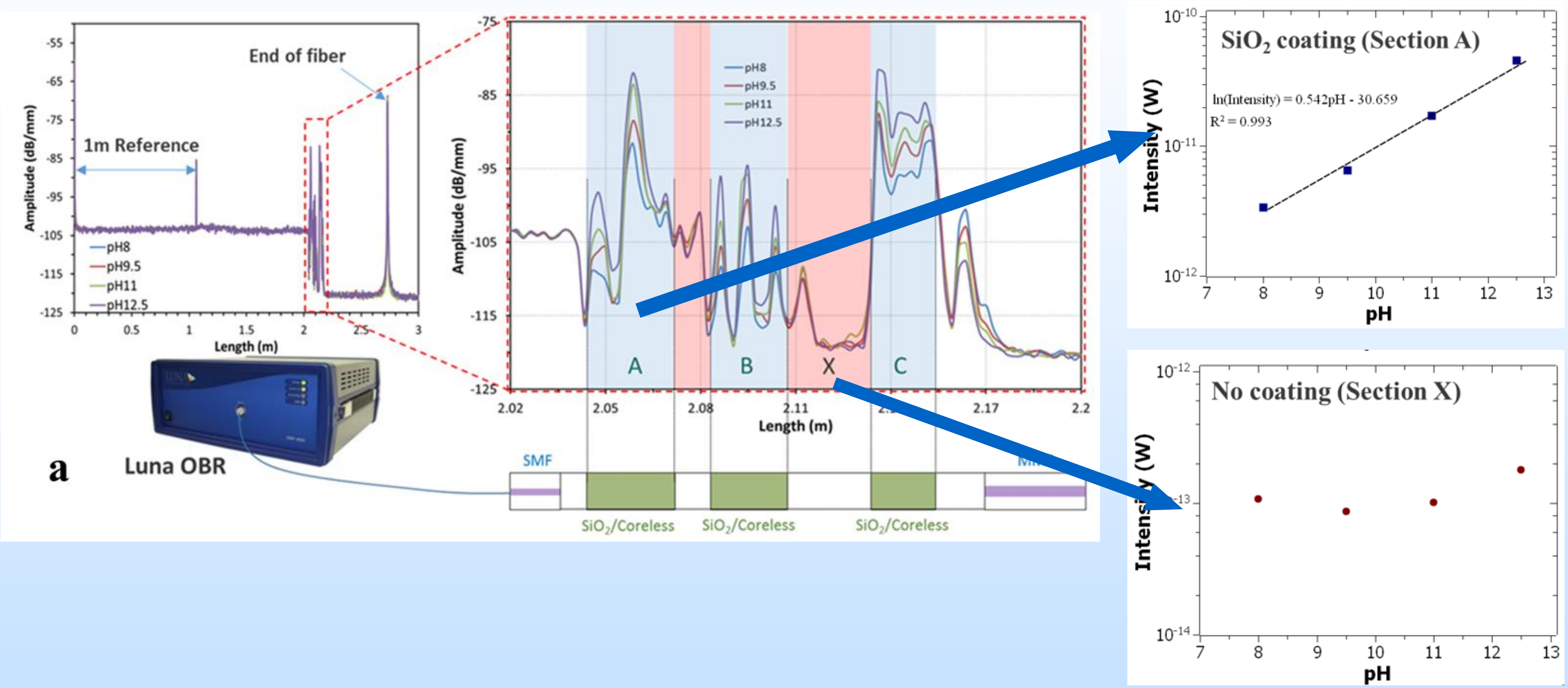


ZrO_2, 80 °C



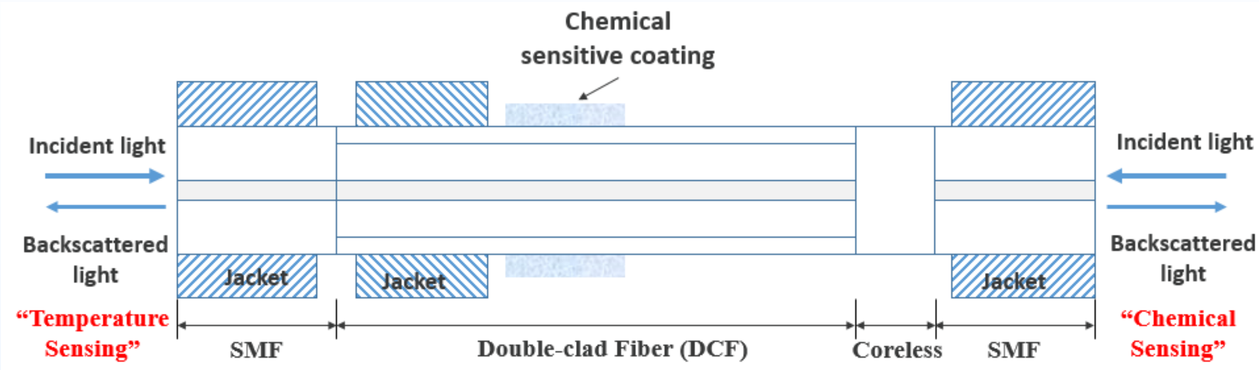
Oxide Based Sensing Layers Have been Demonstrated for pH Sensing with Stability in Elevated Temperature and High Alkalinity Environments.

Project Progress: Chemical Sensing Layers

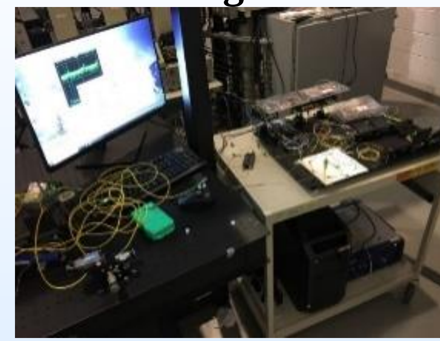


Silica Coated Optical Fiber Sensors Have Been Used to Demonstrate Multi-Point Distributed pH Sensing at the High pH conditions.

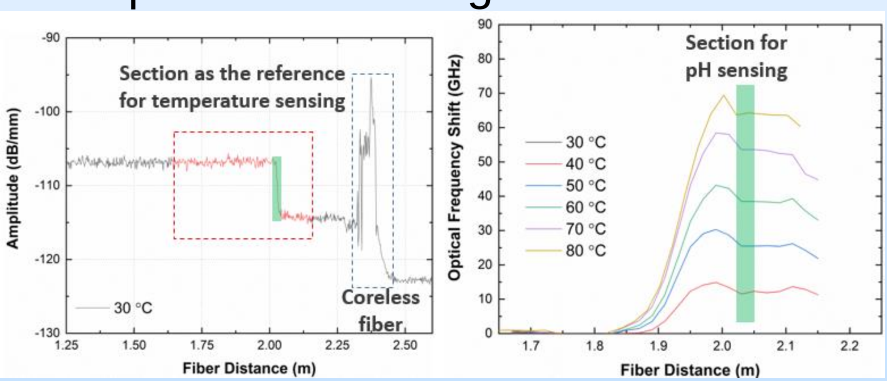
Project Progress: Chemical Sensing Layers



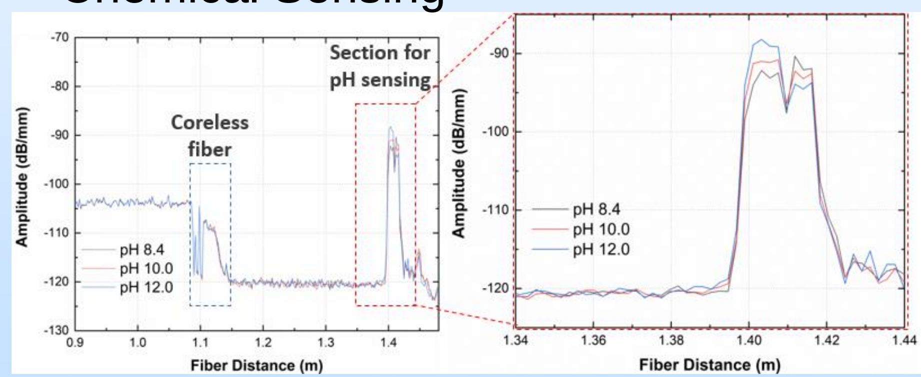
A Custom Low-cost Benchtop Interrogator



Temperature Sensing



Chemical Sensing

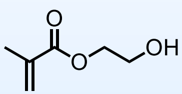


Multi-parameter sensing (temperature and pH) using the same optic fiber (double-clad fiber) for temperature compensated pH sensing.

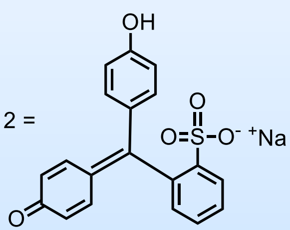
Project Progress: Chemical Sensing Layers

Polymer network with covalently bonded pH indicator reduces the leaching-out.

Monomer 1 =



Monomer 2 =



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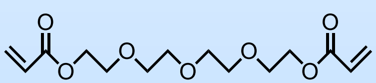
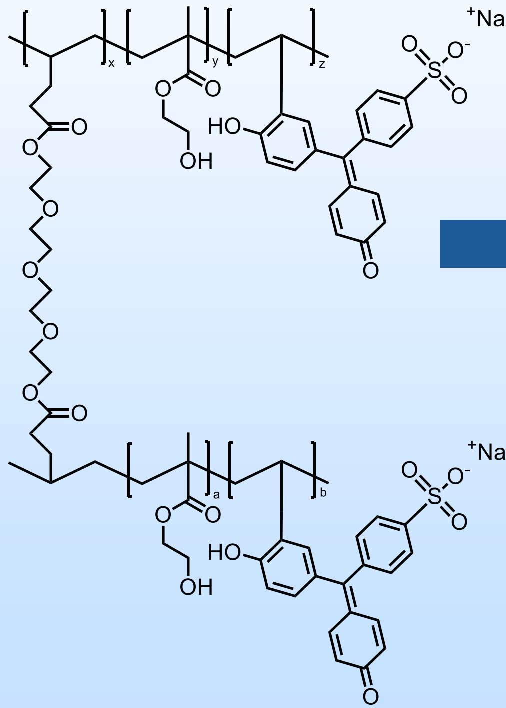
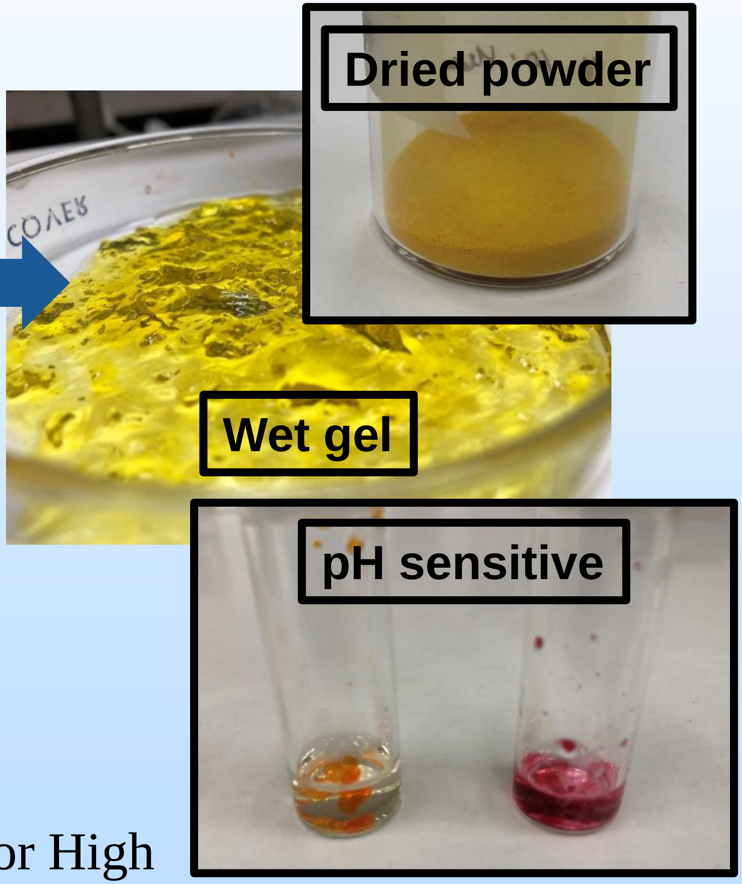


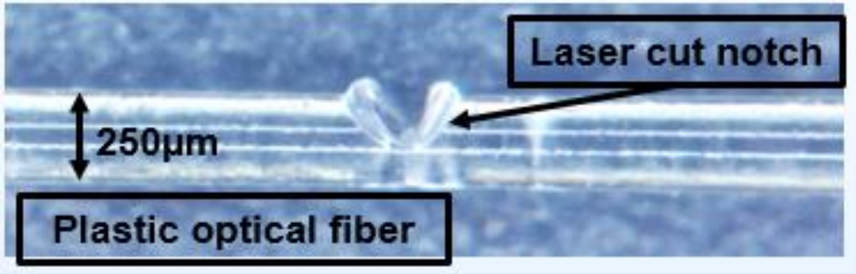


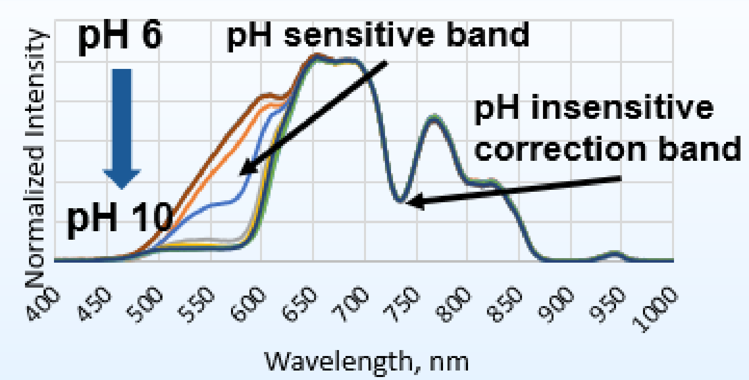


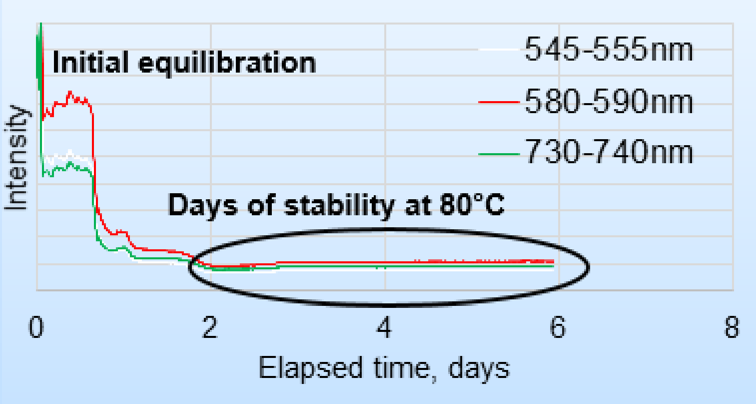
Polymers with pH Indicators are Also Developed for High Temperature and High Alkalinity Environments.

Project Progress: Packaging Development

Sensing materials incorporated optical fiber pH sensors with temperature stability demonstrated over days.



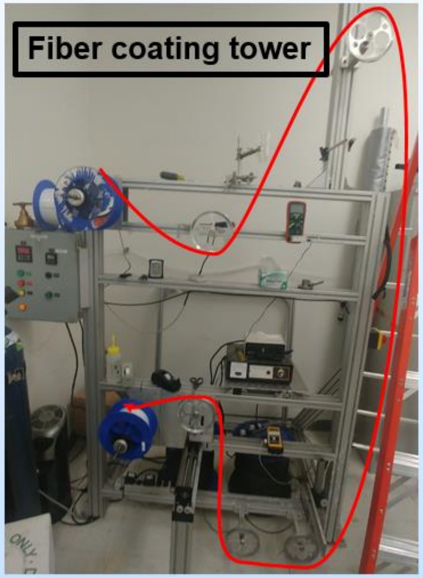


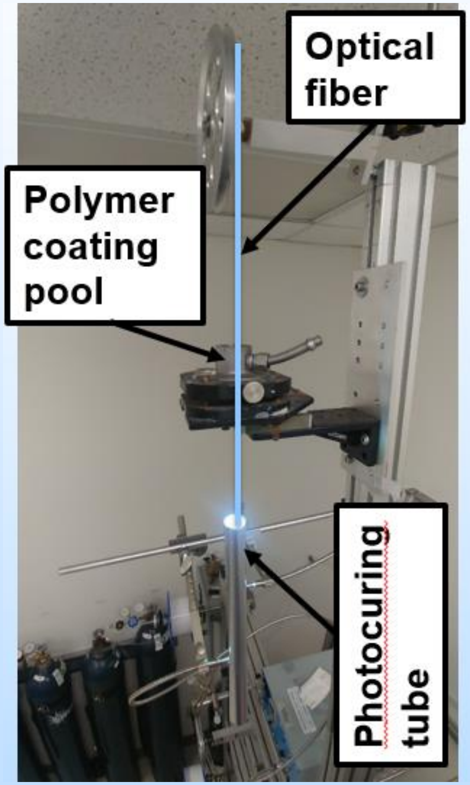


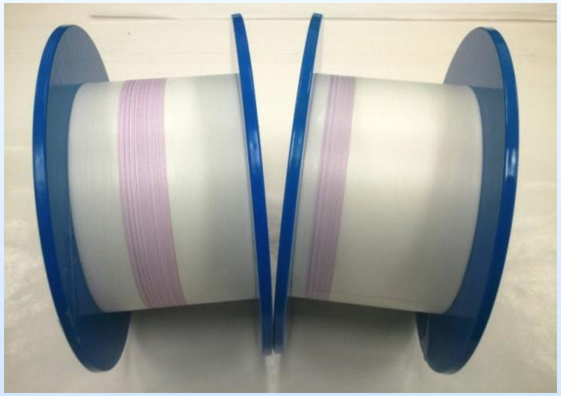
Various Types of Packaging were Explored to be Compatible with Installation within Wellbore Cements for Chemical Monitoring

Project Progress: Sensing Layer Scale-Up

Optical fibers are passed from the feed spool, through a polymer coating pool, into the photocuring tube, and rolled onto the collection spool at the base of the coating tower.







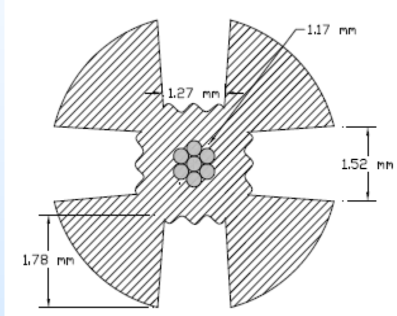
Fiber optic chemical sensor rolled on a spool.
40 m coated fiber demonstrated on this project.

Established Fiber Recoating Facilities are Being Leveraged to Scale Promising Inorganic and Organic Sensing Layers to m- and Eventually km-Scale Lengths.

Project Progress: Optical fiber sensor deployment and field validation

Fiber sensor protection

4 optical fiber channels

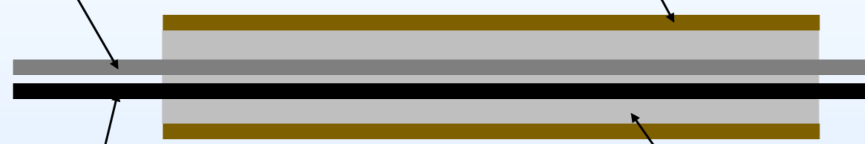


6 mm diameter

Fiber sensor cement integration

Steel tubing (gas delivery and strength member)

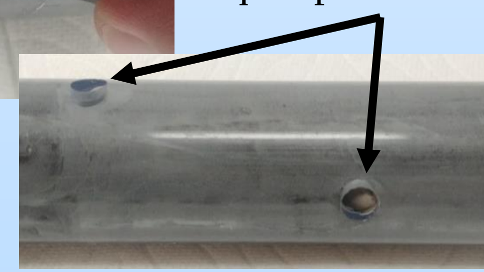
Support pipe



Optical cable (Draka) (sensors and light distribution)

Cement core (3 – 5 m length)

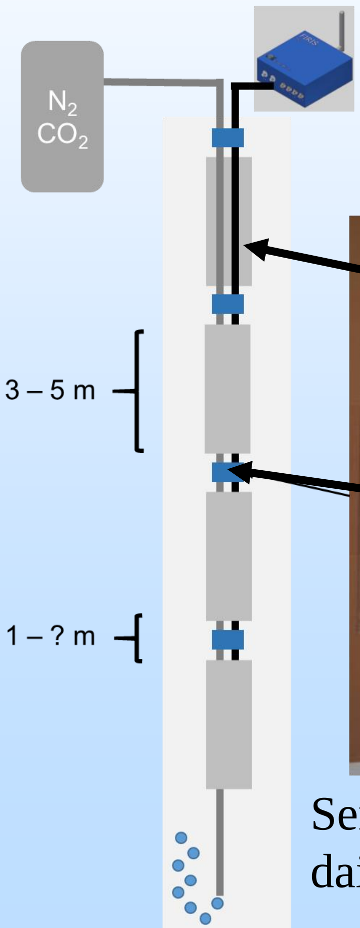
Perforations in support pipe enable liquid permeation



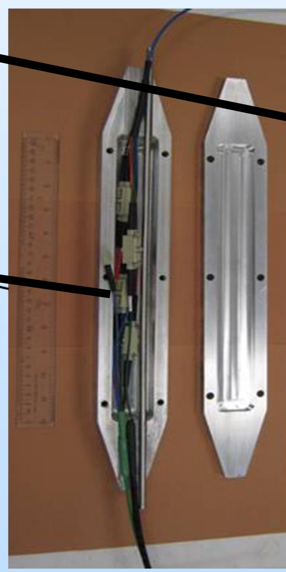
Optical fiber sensors are integrated into cement cores to demonstrate real-time sensing inside cement under well conditions.

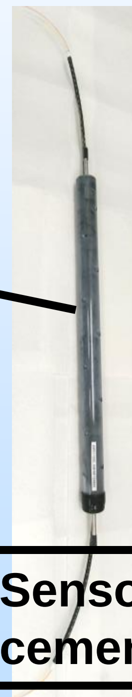
Project Progress: Optical fiber sensor deployment and field validation

PHASE 0: Lab Studies of Sensors in Cement. Status: in progress
PHASE I: Perform Study in a Shallow Water Well (up to 50 feet). Status: TBP
PHASE II: Perform Study in a Deep Water Well (up to 2,000 feet). Status: TBP



Clamp





Sensor integrated cement core

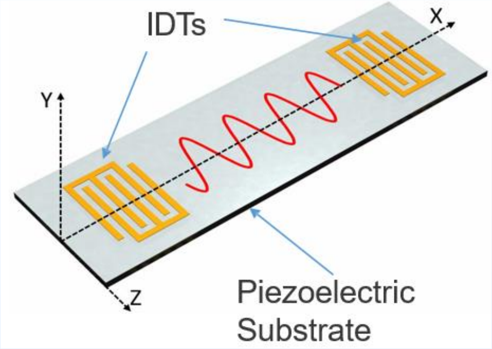
Sensor integrated cement cores will be daisy-chained to enable distributed sensing.

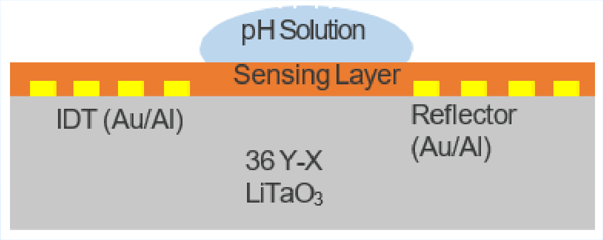
Field optoelectronic hardware

Multi-band optoelectronic light sources and detectors enable signal correction for non-pH environmental effects.

Project Progress: SAW pH sensing

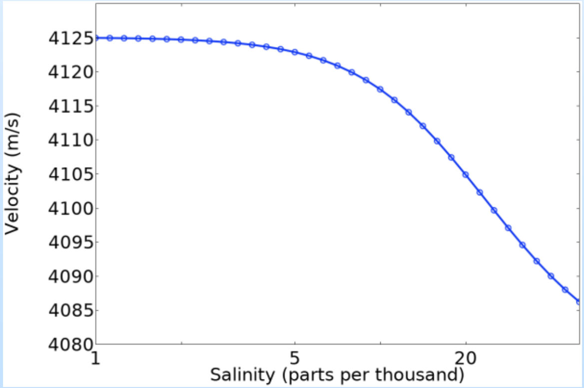
Shear Horizontal Surface Acoustic Waves



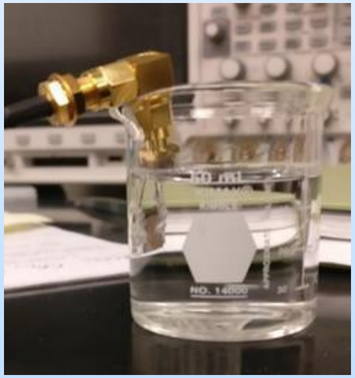


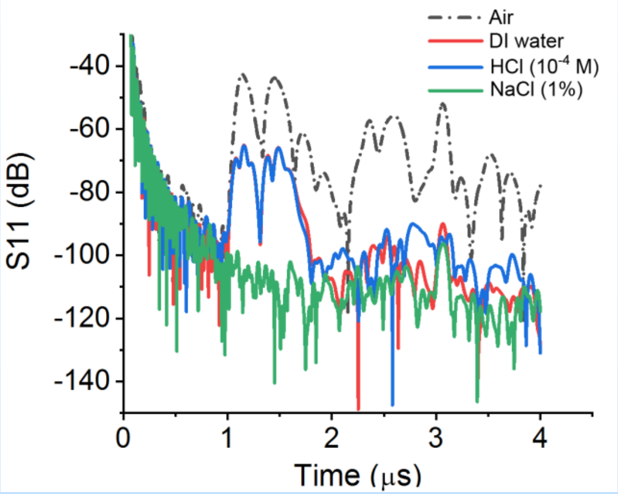
- 36° rot Y-cut X-propagating $LiTaO_3$
- Severe SAW attenuation for NaCl
- Small velocity change for HCl

Modeling



Experiment

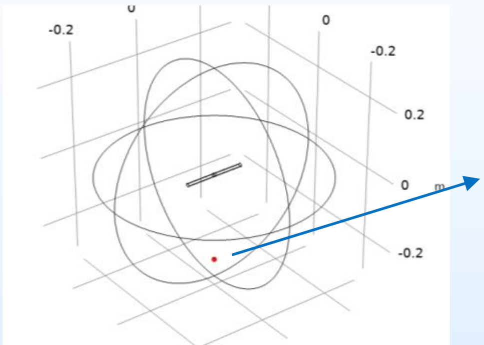


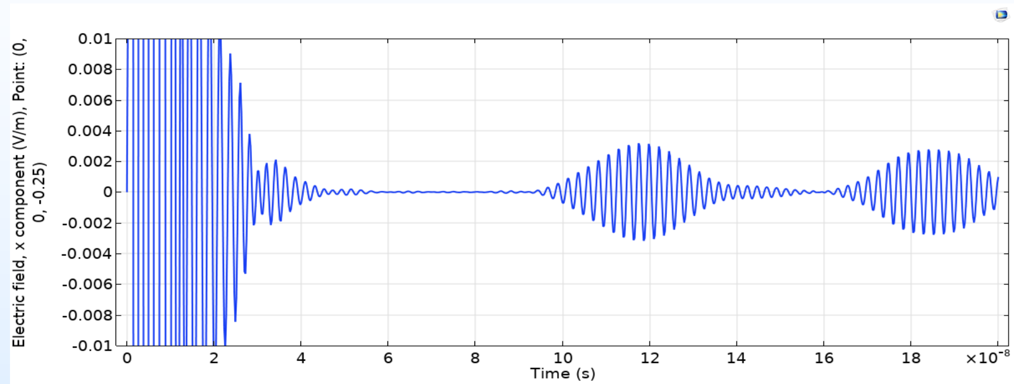


SAW Device Modeling and Experiments as Proof of Concept for Aqueous Phase Operation. Demonstrated the Velocity Change and Attenuation with Various Salinity and pH.

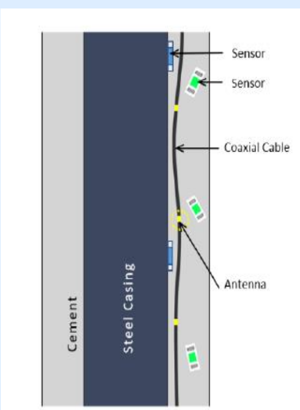
Project Progress: Wireless Telemetry Concepts

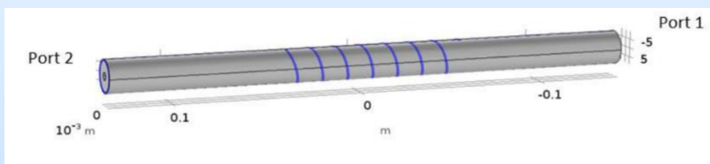
- Simulations of a Dipole Antenna + SAW in cement

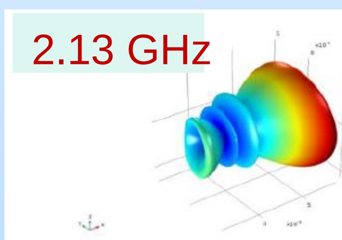


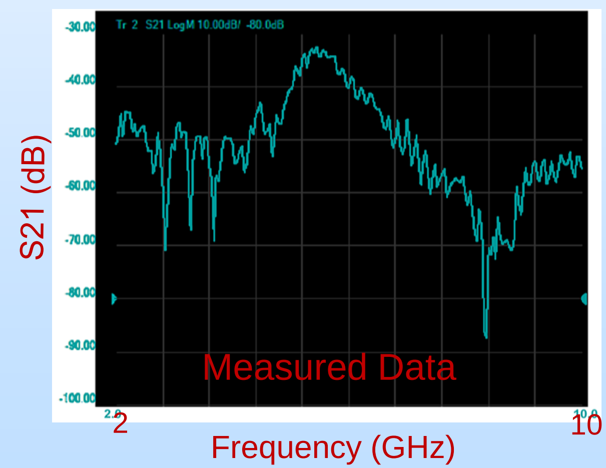


- Simulations and Measurements of Helical Antenna around a Coaxial Cable





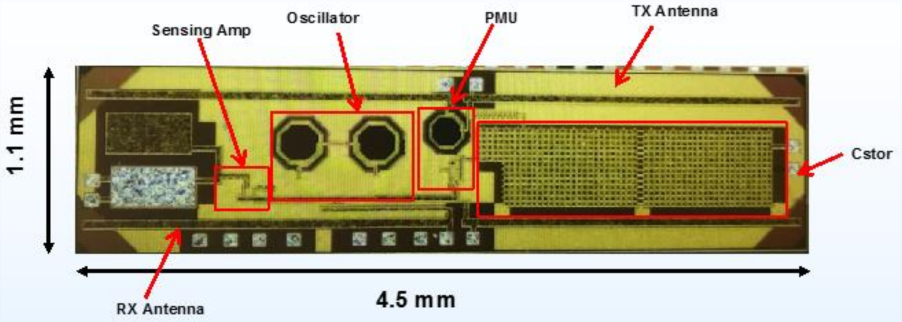


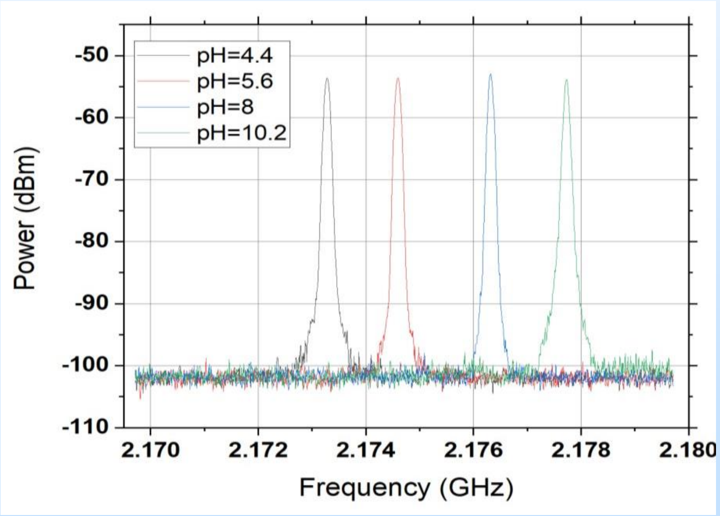


Wireless Telemetry Methods are Being Explored for Compatibility with Applications in Subsurface Media Including Novel Antenna Designs.

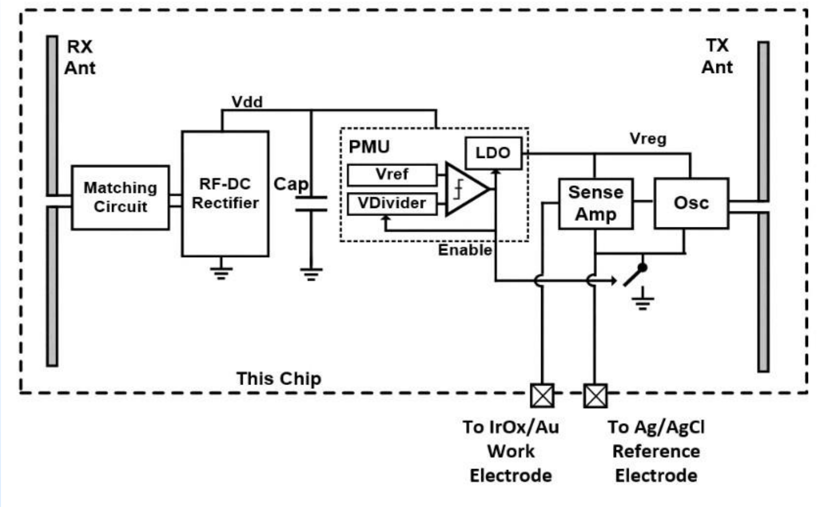
Project Progress: SiIC Device Design / Fabrication

Device Micrograph





Circuit Architecture of Latest pH Sensor Designs



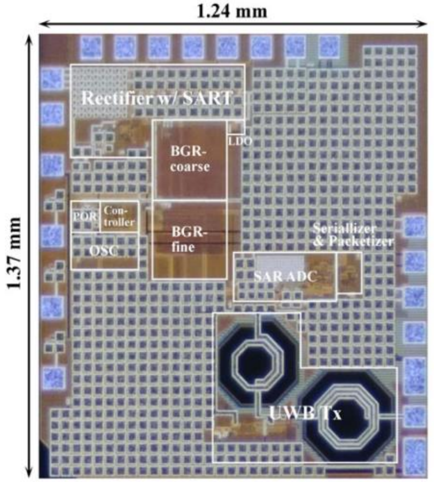
- The chip successfully transmitted wireless signals at 2.173~2.178GHz when exposed to different pH values.
- Chip Radiation Frequency Changed as a Function of pH Value.

SiIC Design / Fabrication Enabled Successful Device Operation Including the Integration of Sensing Layer Electrodes for pH Functionalization

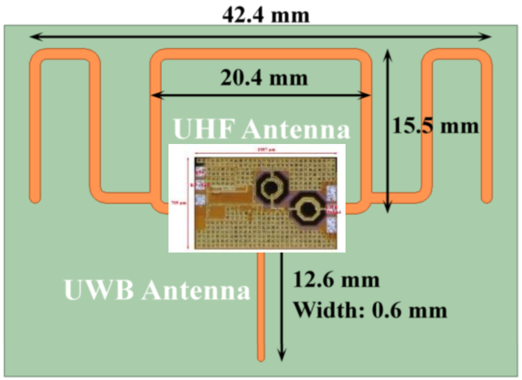
Project Progress: Wirelessly-Powered SiIC Device

Status of the New MHz Radios To Push the Operating Range

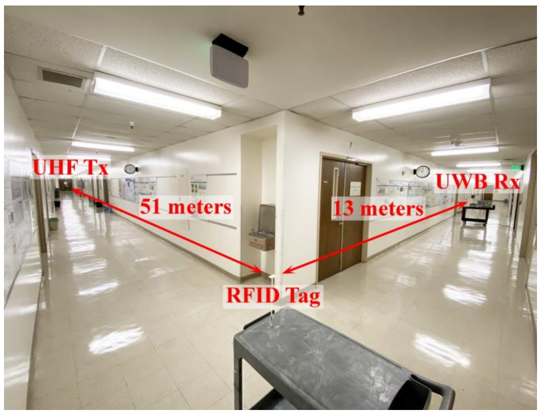
Radio 1: Power Harvester, PMU, ADC, ASIC, UWB Radio



Radio 2: PCB Antenna, Power Harvester, PMU, and UWB Radio used to demonstrate 50m operation range



Successfully Demonstrated **50m** Operating Range (**Radio 2**)

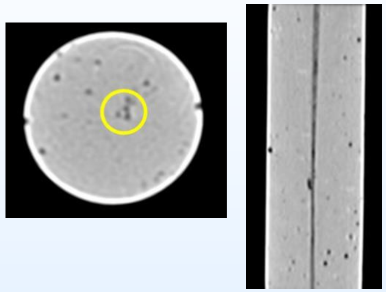


- Successfully demonstrated harvesting electromagnetic energy at 10s of MHz and used it to power the SiIC sensor.
- Demonstrated a range of 50m with a wirelessly-powered radio operating at 10s of MHz while maintaining a small antenna size (~4cm).

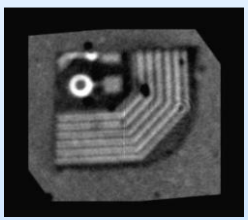
Project Progress: Sensor Embedding in Cements

Cement Cores

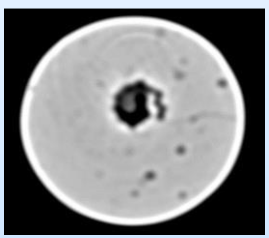
Optical Fibers



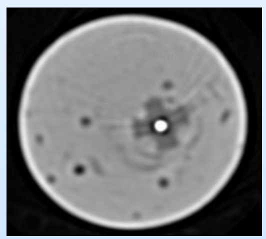
SiIC Chip

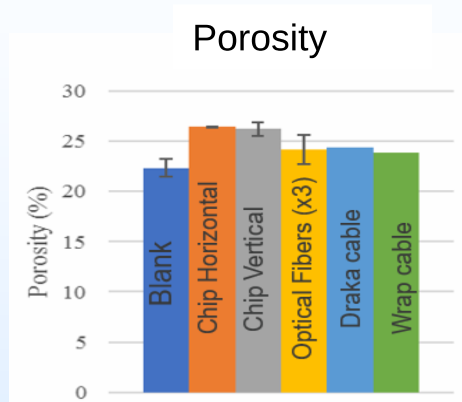


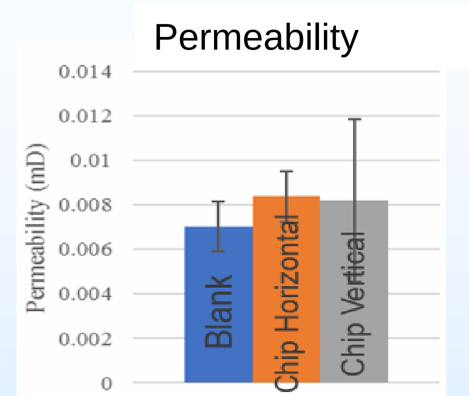
Wrap

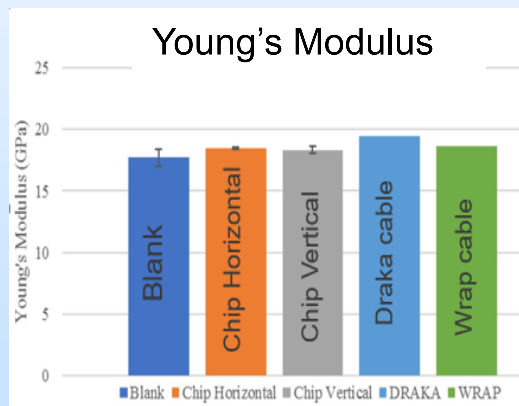


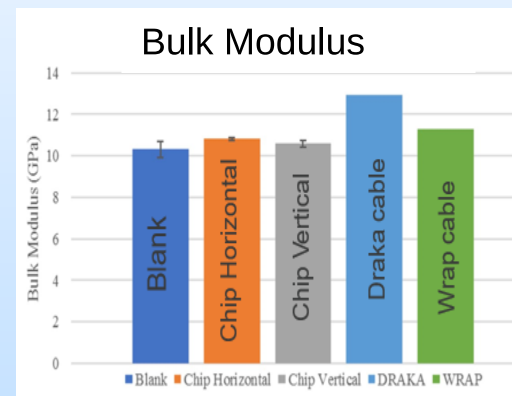
Draka









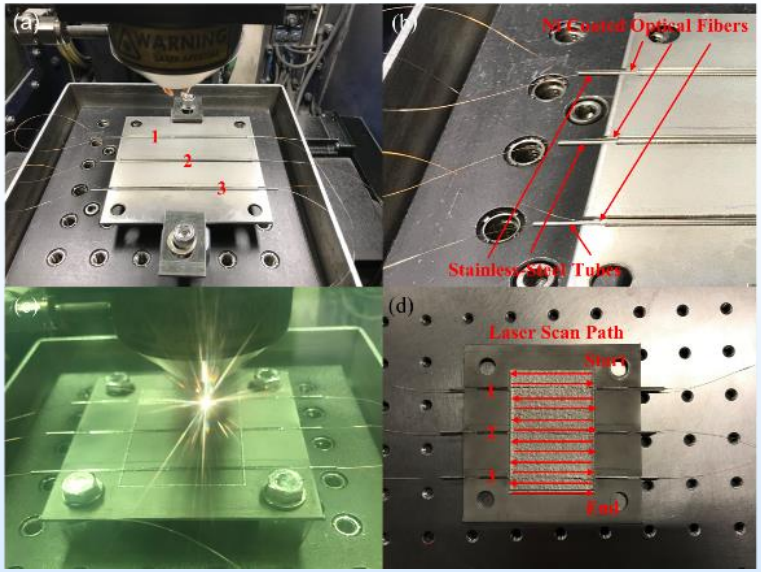


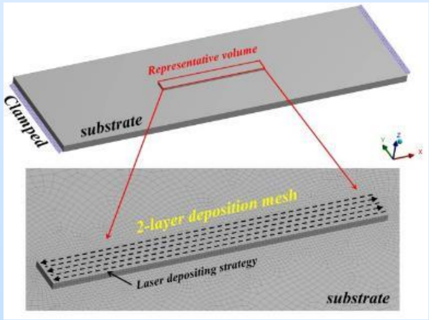
- CT scans confirmed good bonding with cement;
- Optical fiber Draka cables enhanced the Young's and Bulk Moduli.

3D CT Scans and Cement Property Measurements were Performed to Understand Structural Impacts of Embedded Sensors on Cement.

Project Progress: Sensor Embedding in Casing

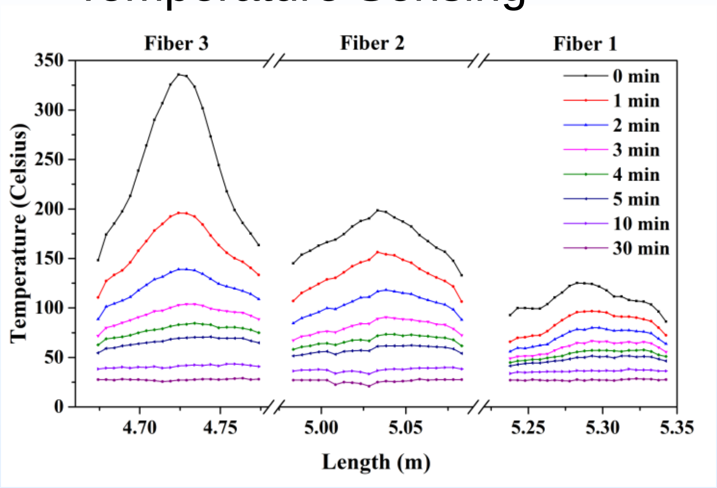
Embedded Fibers in Steel



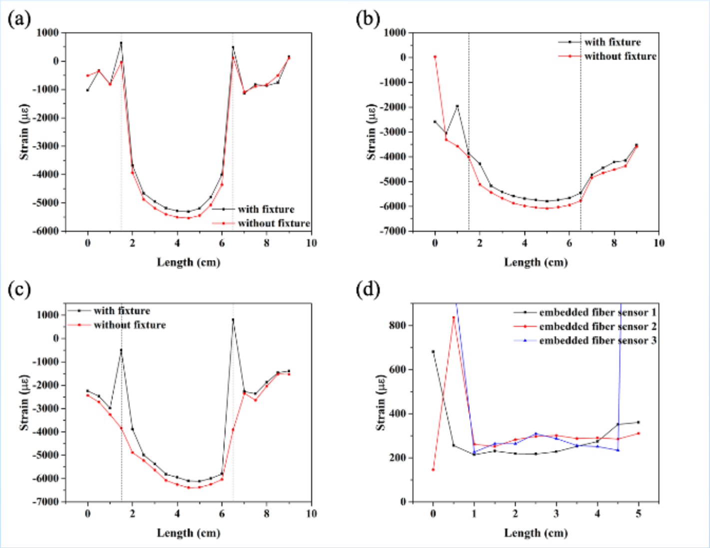


FEA simulation of 3D printing

Temperature Sensing



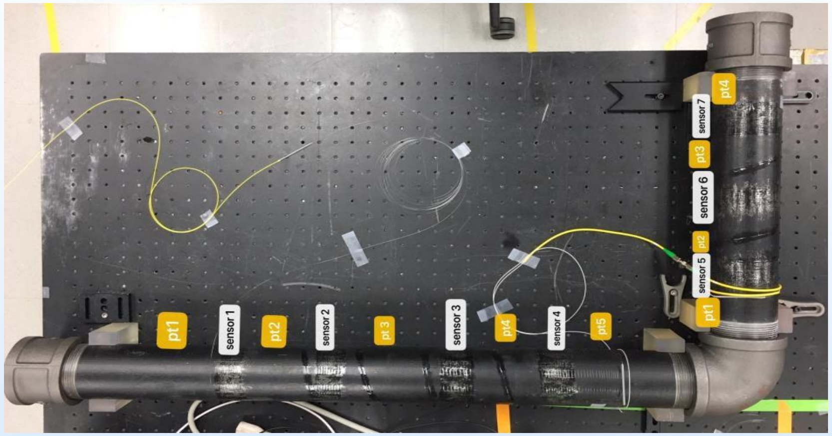
Strain Sensing



Additive Manufacturing Methods were used for Integration of Optical Fibers Into Steel Parts with Capability of high-resolution Temperature and Strain Sensing.

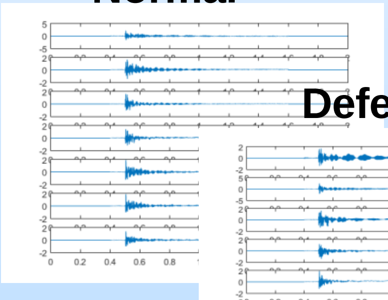
Project Progress: AI-Enhanced Optical Fiber Sensing

Defect Distribution in Metallic Structures

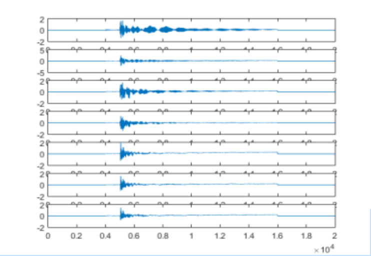


Various Types of Defects to Classify

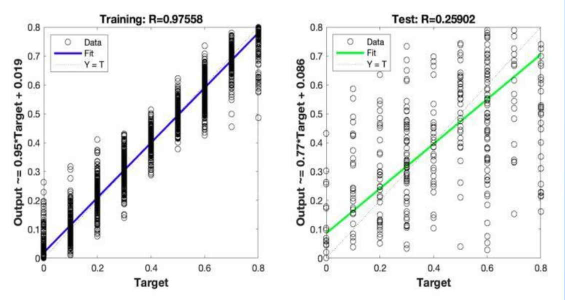
Normal



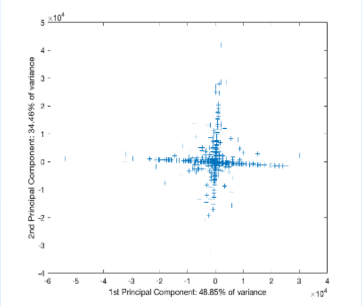
Defective



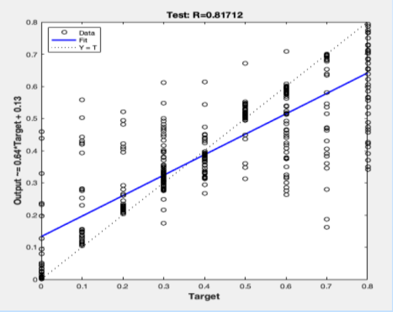
Linear Regression



Principal Components



Shallow Neural Network



AI-Enhanced Methods to Analyze the Optical Fiber Sensing Data for Defect Identification of a Steel Pipe

Project Summary: Success and Next Steps

Project Success to Date

- Fiber optic sensor technology for pH and corrosion sensing at 80°C and high pH
- Aqueous phase sensing of novel SAW devices through simulation and experiments
- Wirelessly-powered SiIC sensors for successful pH sensing in a liquid phase
- Matured the technology through embedding sensors in cement to prepare for field validation
- Novel concepts in wireless subsurface telemetry methods and early lab testing
- AI-enhanced distributed optical fiber sensing for defect identification
- Evaluated the properties and performance of sensor-infused cement

Next Steps

- Multi-segment distributed pH sensing at 80 ^{o}C using optical fiber sensors
- Integration of pH sensing layers with wireless SAW sensors
- Field validation of embedded fiber optic pH sensors in cement
- Demonstration of wireless interrogation of SiIC devices embedded in cement

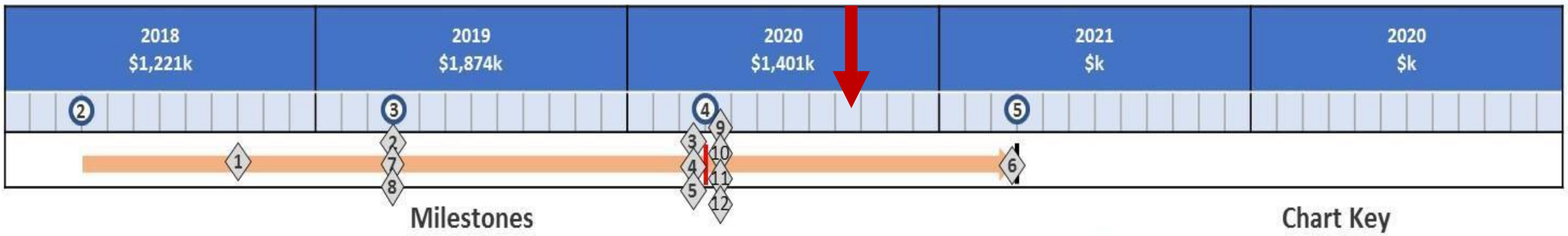
Acknowledgement and Disclaimer

Acknowledgement: This work was performed in support of DOE's Carbon Storage Program. The Research was executed through the NETL Research and Innovation Center's Embedded Sensor Technology Suite for Wellbore Integrity Monitoring FWP. Research performed by Leidos Research Support Team staff was conducted under the RSS contract 89243318CFE000003.

Appendix

Project Structure: Project Timing and Status

Today



Milestones

1. Delivery of Technology Maturation Plan to FPM
2. Industry Feedback Regarding Chemical Species and Use Cases Identified as Primary Targets of R&D
3. Demonstration of Fiber Optic Sensor Coating for pH at 80C, 1atm, for 1 day with stability within 25% using self-referencing
4. Demonstration of corrosion proxy capable of early on-set detection at 80C, P=1atm
5. Demonstration of fiber optic sensor prototype with up to 4 sensing segments at ambient temperature
6. Demonstration of fiber optic sensing prototype with up to 4 sensing segments at T=80C
7. Simulation demonstrating potential for successful SAW operation in wellbore fluids
8. First Proposed SiIC Device Design Compatible with Fluid and Cement Wellbore Media Applications
9. Successful Wired SAW Device Response in Fluid Phase at ambient conditions
10. Successful Wired SiIC Device Response in Fluid Phase at ambient conditions
11. Demonstration of adequate technical performance properties of optical fiber integrated cements and casings
12. Demonstration of adequate technical performance properties of SiIC Integrated cements and casings

Chart Key

\# TRL Score | Go / No-Go Timeframe | Project Completion | Milestone

Go / No-Go

1. Successful field deployment of the optical fiber based pH sensor for ambient pressure / temperature

Project on Track to Date

Impact

Key Accomplishments/Deliverables	Value Delivered
2018: Project initiated 4/2018. **2019**: Milestones completed **2020**: Milestones on track, field validation is affected by COVID-19	• New sensing layers integrated with fiber optic, surface acoustic wave, and silicon integrated circuit devices for pH sensing • Field deployed fiber optic based pH sensor technology • Laboratory tested wireless surface acoustic wave and silicon IC pH sensors