Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

Paul Ohodnicki

NETL / DOE Lead PI

Dr. Jesus Delgado, Intelligent Optical Systems PI

Prof. Aydin Babakhani, UCLA PI

Prof. Kevin Chen, U. Pitt. PI

Dr. Scott Frailey, ISGS PI

Prof. David Greve, Carnegie Mellon University PI

U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Presentation Outline

- Problem Statement and Current State of the Art
- Proposed Technology Solutions
- Technical Status
- Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary

Problem Statement

Problem Statement:

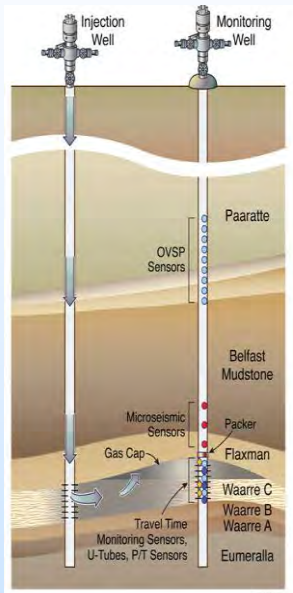
A need exists for embedded sensor technologies capable of ubiquitous, real-time monitoring of wellbore integrity for carbon storage and geothermal applications.

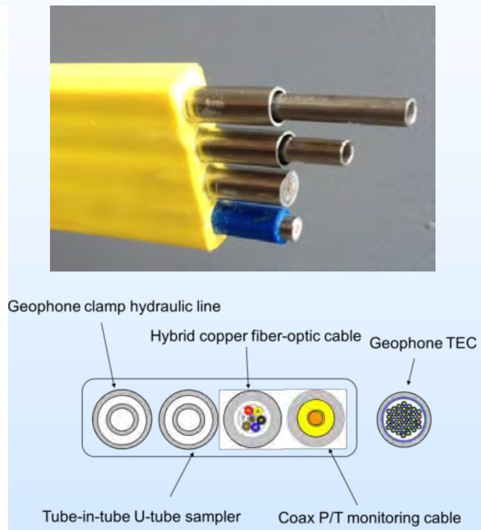
Primary Challenges:

1) Sensor technologies must be robust and capable of operation in carbon storage and geothermal wellbore relevant conditions.
2) Embedded sensor technologies should not create additional potential sources of wellbore failures.
3) Communication with embedded sensors requires advanced telemetry techniques, with electrical wires and contacts being a primary source of failure for conventional sensor instrumentation.

Current State of Art

Physical parameter monitoring → Detect wellbore failures AFTER they have occurred and characterization of the subsurface in terms of physical properties.





T. Daley, B. Freifeld, J. Franklin, LBNL

Fig. 8 SMARTape on the gas pipeline

Long-Range Pipeline Monitoring by Distributed Fiber Optic Sensing

Journal of Pressure Vessel Technology

FEBRUARY 2010, Vol. 132 / 011701-1

1) Distributed fiber optic based sensing technology is having a major impact on the potential for subsurface monitoring.

2) Distributed temperature, stress, and acoustic sensing technology platforms are now commercial and increasingly deployed by industry.

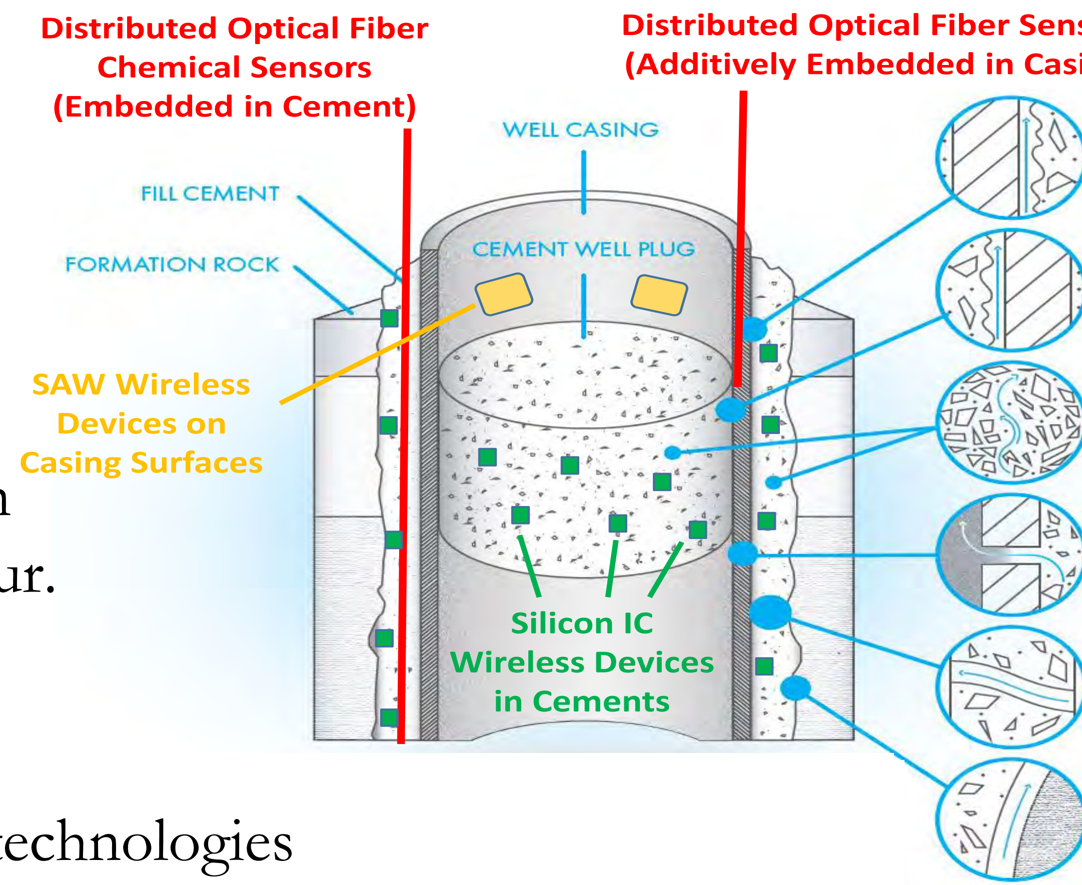
3) Significant needs remain for technical performance improvements, advanced deployment techniques to reduce costs, and data analytics.

Proposed Technology Solutions

Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

Our primary focus…

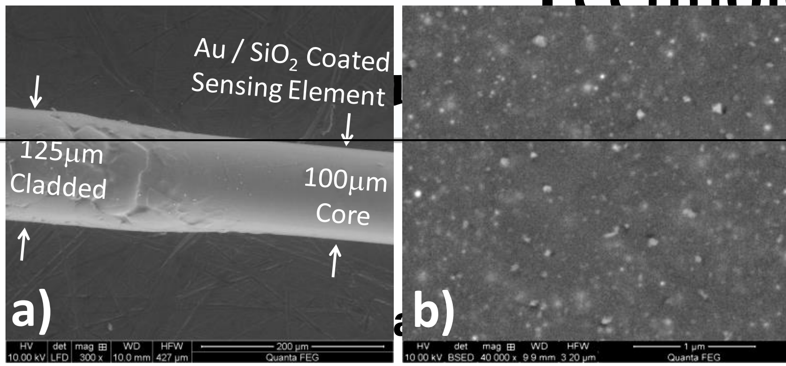
Chemical parameter monitoring → Identify conditions likely to result in failures BEFORE they occur.

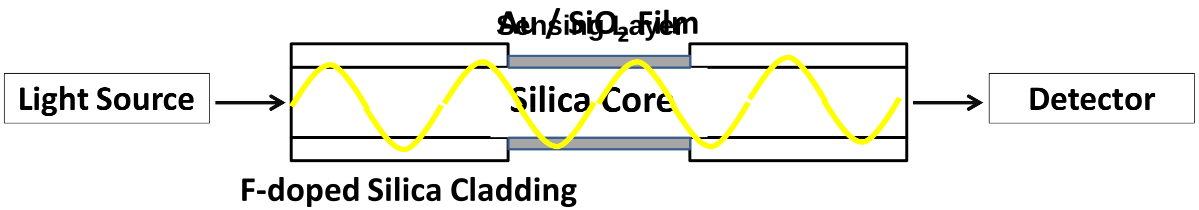


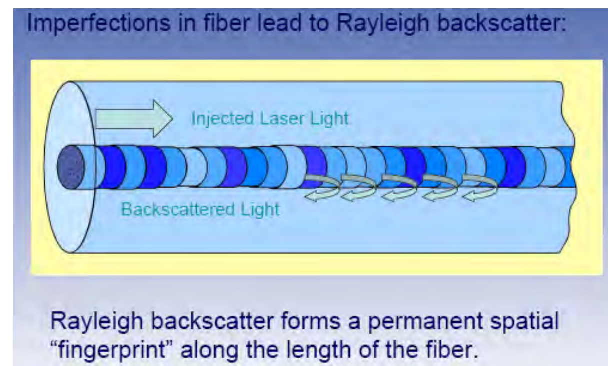
Suite of embedded sensor technologies

The current project targets enabling a suite of technologies functionalized for chemical sensing of high priority parameters (pH, corrosion onset, etc.).

Technology Platform #1:
ptic Based Chemical Sensors







→ **Eliminate Electrical Wiring and Contacts at the Sensing Location**

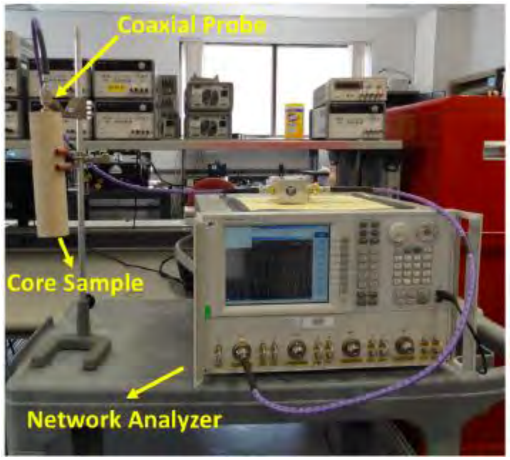
→ **Tailored to Parameters of Interest Through Functional Materials**

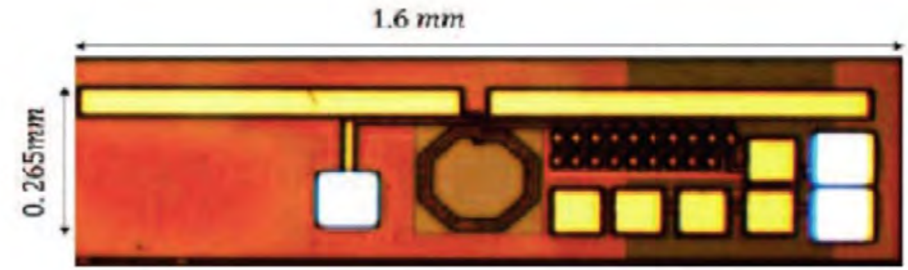
→ **Compatibility with Broadband and Distributed Interrogation**

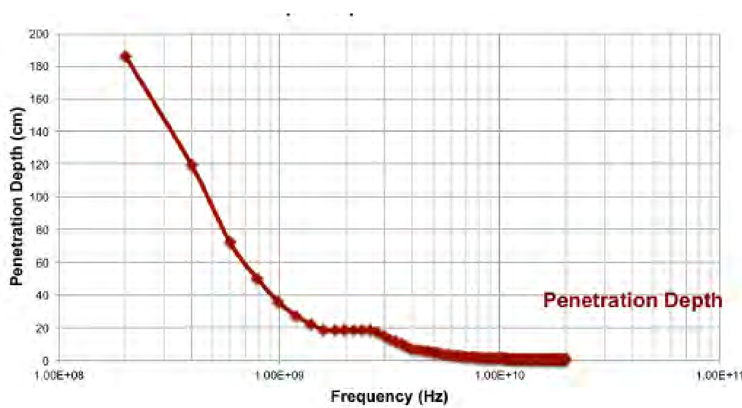
Distributed fiber optic based chemical sensors are being developed through functionalization of the optical fiber platform with chemical sensing layers.

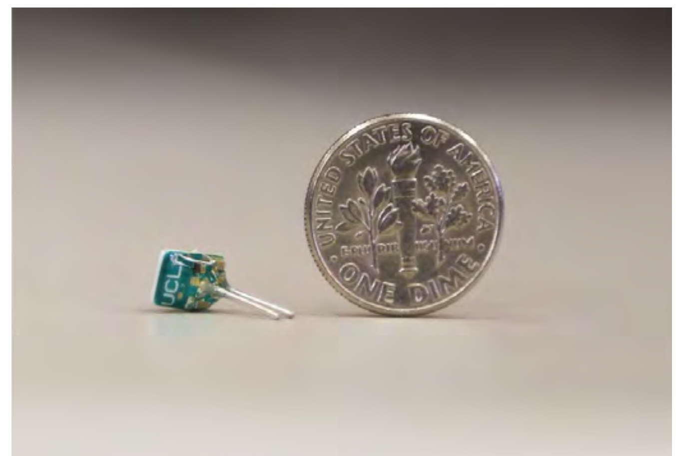
Primary deployment : Embedding within the wellbore cements for pH monitoring

Technology Platform #2: Passive, Wireless Silicon Integrated Circuit Sensors





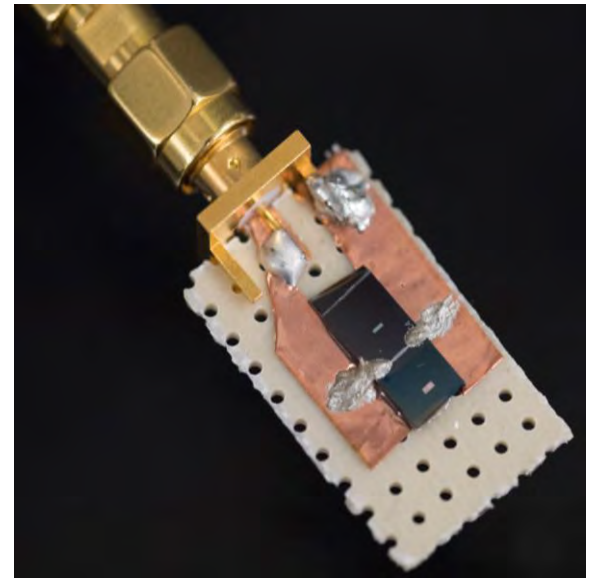




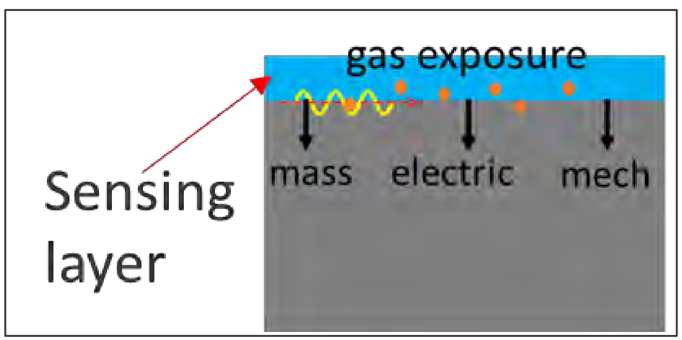
Silicon integrated circuit based devices will be mixed within the cement formulations to be embedded throughout wellbore cements.

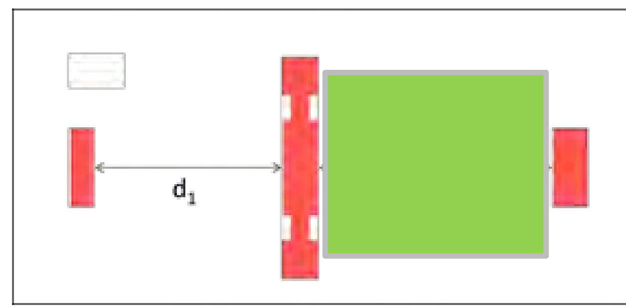
Primary deployment : Wellbore cement interior for pH monitoring

Technology Platform #3:
Passive, Wireless Surface Acoustic Wave Sensors



$$\frac{\Delta v}{v_0} = \frac{\Delta f}{f_0} = \frac{\Delta \phi}{\phi_0}$$

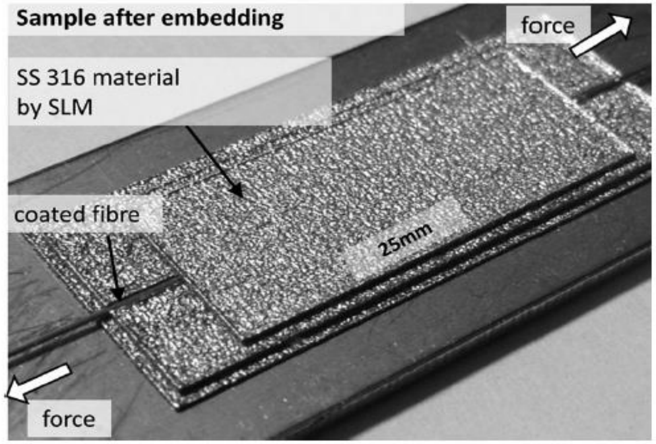


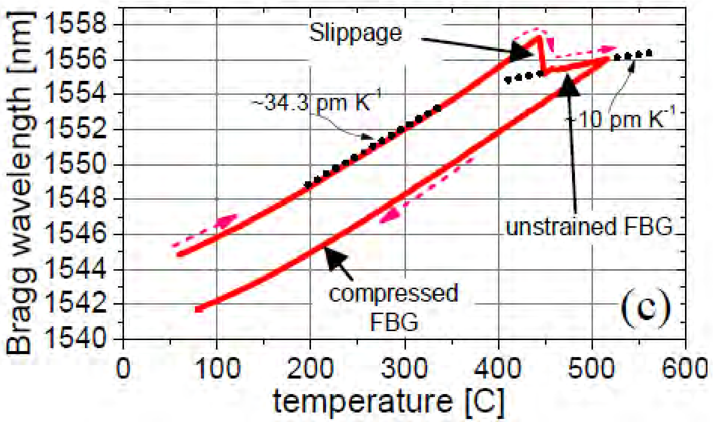


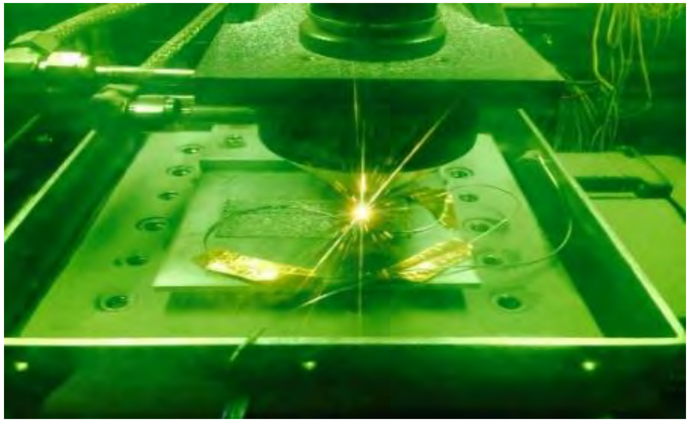
Surface acoustic wave sensor devices will be functionalized for deployment on the interior or exterior of the metallic casing.

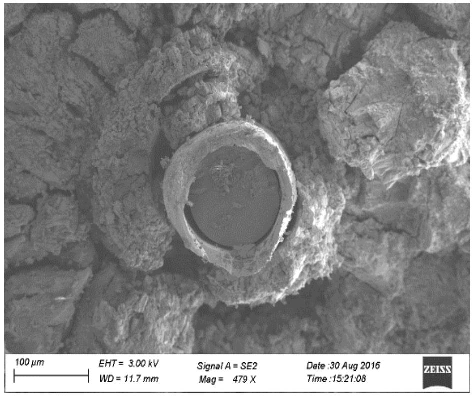
Primary deployment : Wellbore casing surfaces for pH and corrosion onset

Additional Research Effort:
Optical Fiber Sensors Embedded in Casing









Optical fibers will also be embedded within metallic casings for monitoring of internal temperature, strain, and acoustic signals indicative of early failures.

Primary deployment : Internal to metallic casings through additive techniques

Team Structure

The Team:

DOE Laboratory

Industry

Academia

State Research Institute

University of Pittsburgh
Additively Embedded Fiber Optic Sensors
Sensor Infused Wellbore Casings

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

NATIONAL ENERGY TECHNOLOGY LABORATORY

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

ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

Illinois State Geological Survey
Geological and Wellbore Expertise
Industry Partnership Engagement

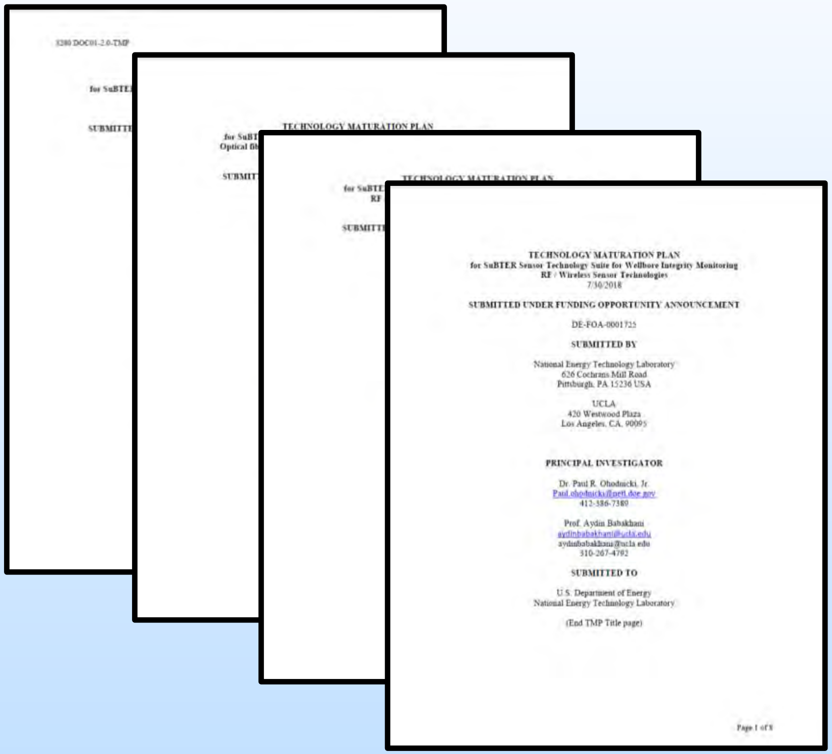
University of California, Los Angeles
Silicon Integrated Circuit Sensors
Wireless Energy Harvesting and Telemetry

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

An interdisciplinary team has been assembled to address the proposed technology development leveraging "best in class" expertise.

Technical Status :
Industry Engagement and Technology Maturation Plans

Technology maturation plans have been developed for each technology. (4 total)


TECHNOLOGY MATURATION PLAN
for SuBTER Sensor Technology Suite for Wellbore Integrity Monitoring
RF / Wireless Sensor Technologies
7/30/2018

SUBMITTED UNDER FUNDING OPPORTUNITY ANNOUNCEMENT

DE-FOA-0001725

SUBMITTED BY

National Energy Technology Laboratory
626 Cochrans Mill Road
Pittsburgh, PA 15236 USA

UCLA
420 Westwood Plaza
Los Angeles, CA 90095

PRINCIPAL INVESTIGATOR

Dr. Paul R. Ohodnicki, Jr.
Paul.ohodnicki@netl.doe.gov
412-386-7380

Prof. Aydin Babakhani
aydinbabakhani@ucla.edu
310-267-4792

SUBMITTED TO

U.S. Department of Energy
National Energy Technology Laboratory

(End TMP Title page)

An industry partnership group has been established to review and provide on-going industry feedback.

Invitees	Title	Expertise	Company
Igor Kosacki	Materials Engineering Manger	Sensor development	WellDiver
John Lovell	Vice President – Technology and Strategy	Temperature and pressure measurement systems, Wellhead asphaltenes sensor	MiscroSilicon Inc.
George Koperna	Vice President	CO_2 EOR and storage, reservoir engineering	Advanced Resources International, Inc.
Charles Gorecki	Directory of Subsurface R&D	EOR, CO_2 storage	Energy & Environmental Research Center
Pierre Ramondenc	Well Intervention Domain Manager	Coiled tubing well interventions, real-time fiber-optics	Schlumberger
Laura Nofziger	Senior Vice President and Managing Director	Geothermal Power Plant operations and maintenance	AltaRock Services, LLC
Tim Ong	Principal Strategy – Technology & Innovation	Strategy planning-technology and innovation	BHP Billiton
Dennis Dria	Petroleum Technology Advisor	Fiber-optic technology development and implementation	Myden Energy Consulting, PLLC
Austin Vonder Hoya	Senior Advisor	Geophysical technology	Pioneer Natural Resources USA

The first 6 months of the project is focused on technology maturation plan development and industry engagement.

Technical Status : Chemical Sensing Layers

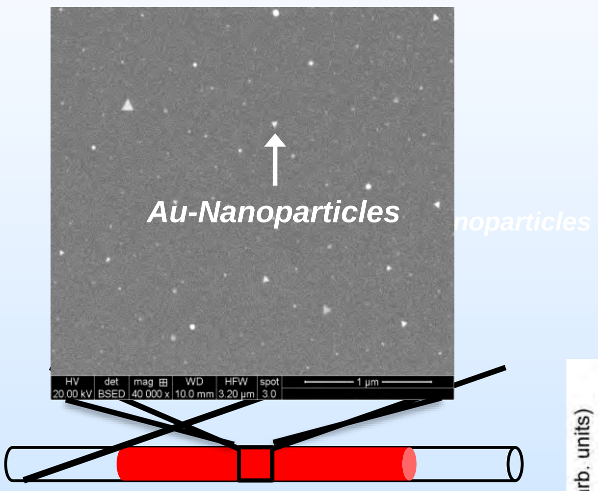
Potential sensing layers to consider

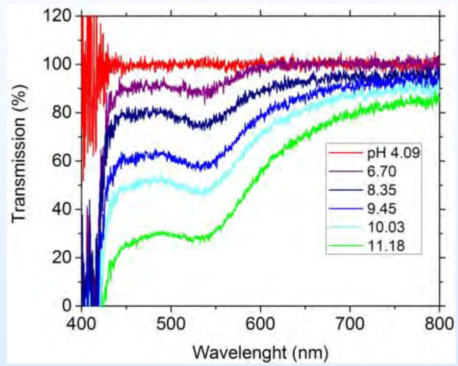
	Examples	Stability Limits in Wellbore Conditions	Notes
Organic Dyes	cresol red, bromophenol blue and chlorophenol red mixture;	Low to moderate	Stability under wellbore conditions will be limited. Embedded within sol-gel or polymer matrices. Leaching of dyes presents challenges for long-term deployment.
Polymers	Polyaniline, polypyrrole	Low to moderate	Stability under wellbore conditions will be limited. Can exhibit long response times due to diffusion limitations.
Inorganic Sensing Layers	Metal oxides, noble metals, nanocomposites	Moderate to High	Potentially extremely stable. Sensing mechanisms are not as well understood, and need further research and development including selectivity.

A literature review is underway along with initial discussions and foundational experiments regarding the primary R&D pathways for chemical sensing layers.

Technical Status :
Chemical Sensing Layers

Approach #1: Silica and Au / Silica based sensing layers

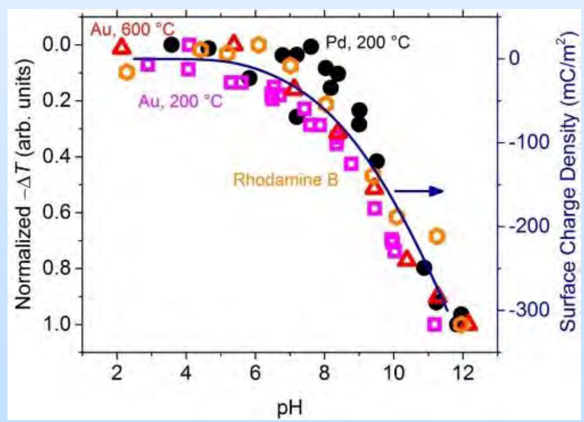




Reversible, sensitive pH responses were demonstrated under prior project activities.

Conversion to the inorganic oxide required a high calcination temperature >~500°C.

pH dependent surface charging at silica surfaces dominated observed responses



Can this class of sensing layers be optimized for reel-to-reel coating and deployment?

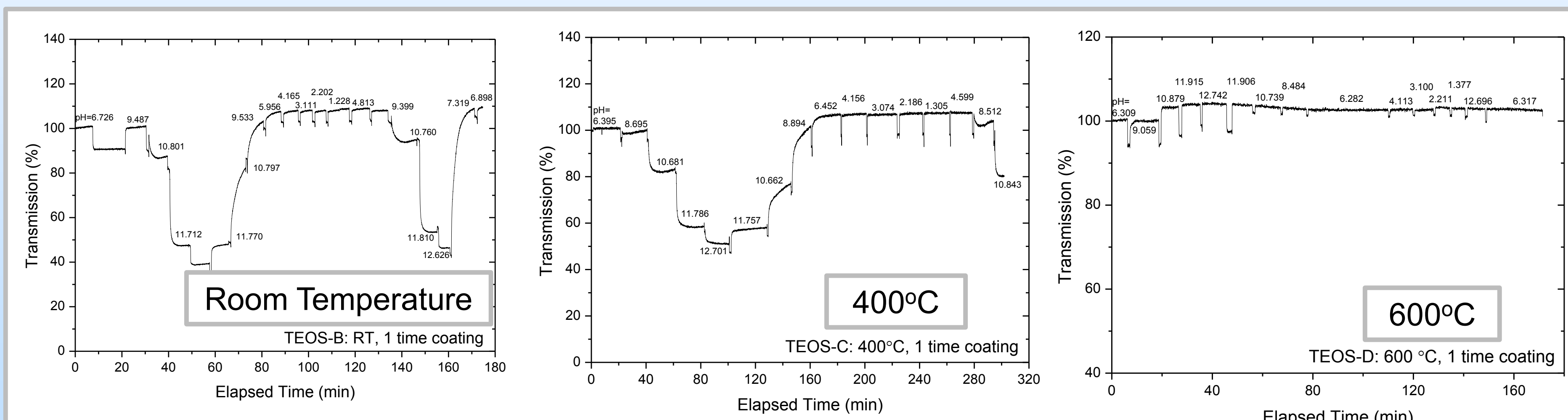
One early focus is adopting previously investigated Au / silica based sensing layers for the optical sensing platform to be compatible with reel-to-reel coating processes.

Technical Status : Chemical Sensing Layers

Approach #1: TEOS (Tetraethyl orthosylicate) $Si(OC_2H_5)_4$

TEOS (Tetraethyl orthosylicate) $Si(OC_2H_5)_4$

Hydrolysis and condensation catalyzed by acids / bases



Preliminary results suggest that calcination temperature plays a key role in reversibility, response magnitude, and wavelength dependence.

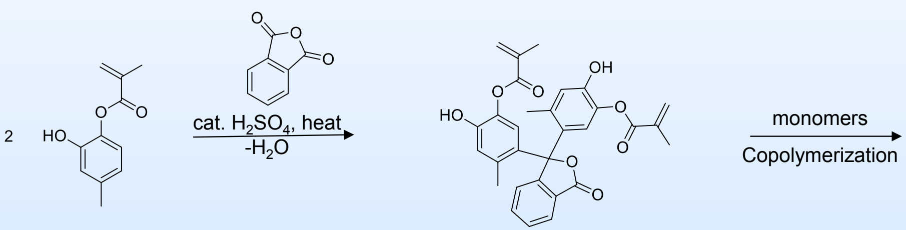
Technical Status :
Chemical Sensing Layers

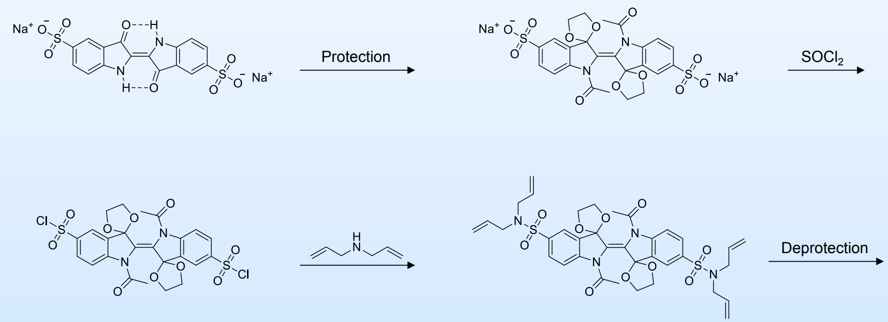
Approach #2: Polymers and organic dyes

→ Explore and improve temperature stability

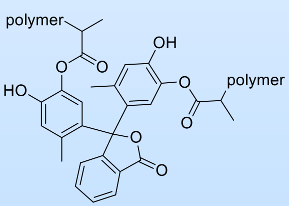
→ Identify dyes relevant for basic conditions

Leveraging prior work exploring organic dyes in vinyl-based and methacrylate-based polymers

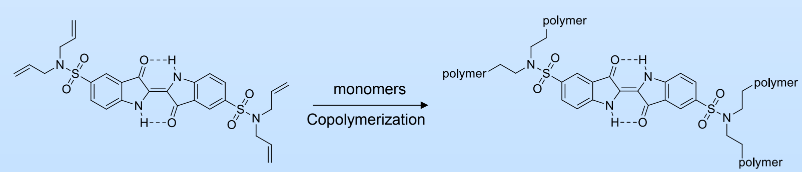




Absorption change at pH ~ 11



pKa ~ 10
Absorption peak ~595nm



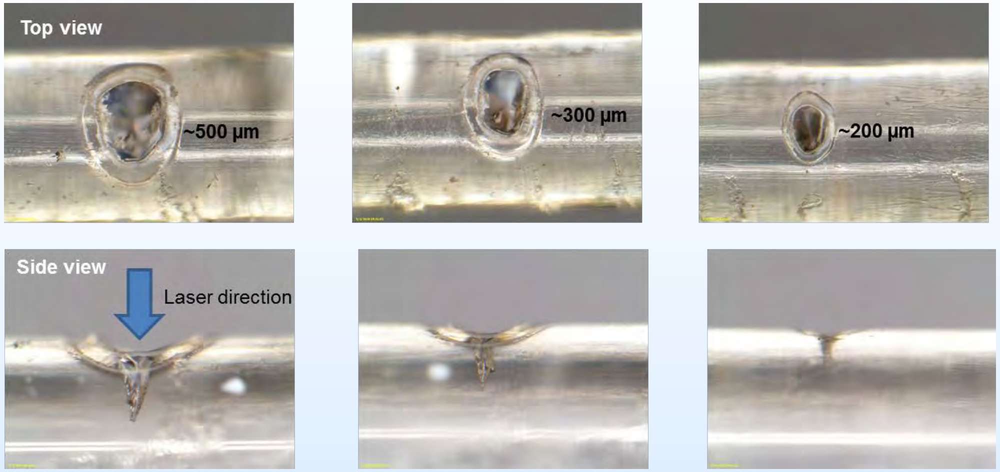
Thymolphthalein Derivatives

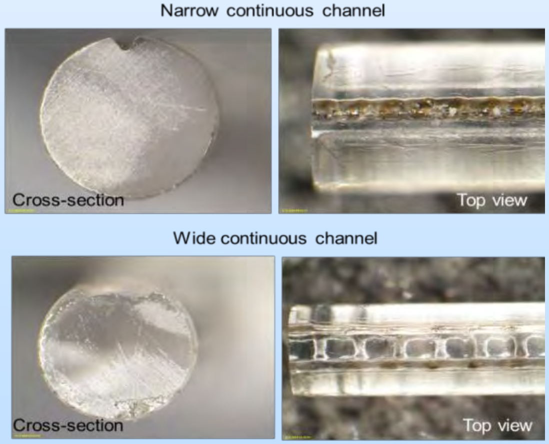
Indigo Carmine Derivatives

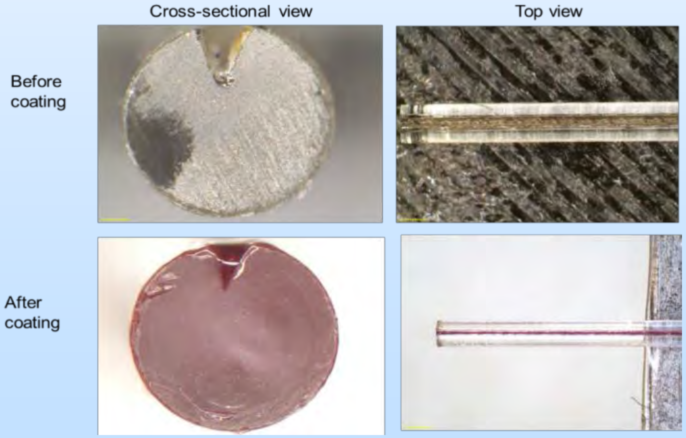
Polymers and indicator molecules explored under previous project activities are being modified for internal cement monitoring (high pH) and improved temperature stability.

Technical Status :
Optical Fiber Sensor Fabrication / Deployment

Early efforts are underway to identify preferred sensor fabrication strategies to enable field deployment efforts in future fiscal years.



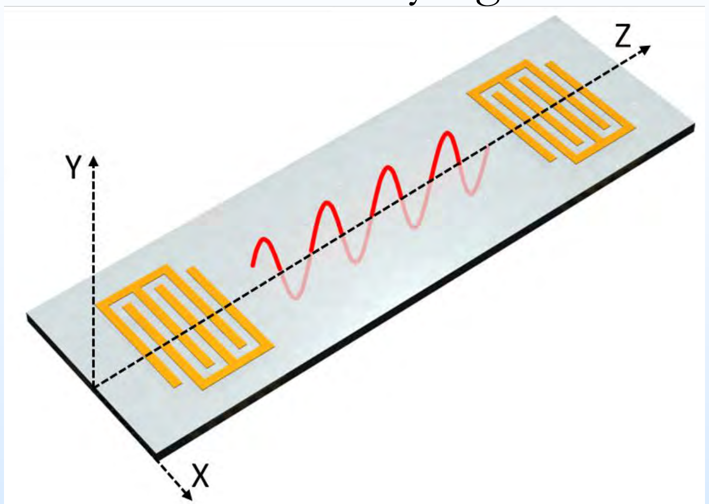




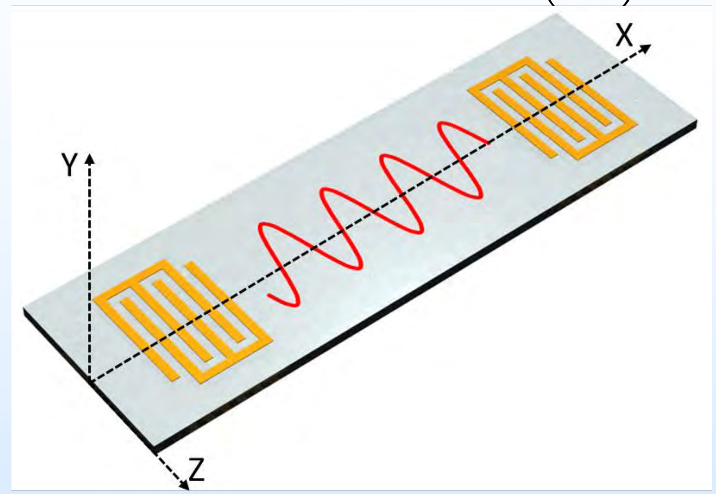
Example approach : protective coating of silica based fibers combined with laser drilled holes to enable sensing materials to be directly integrated within the fiber core.

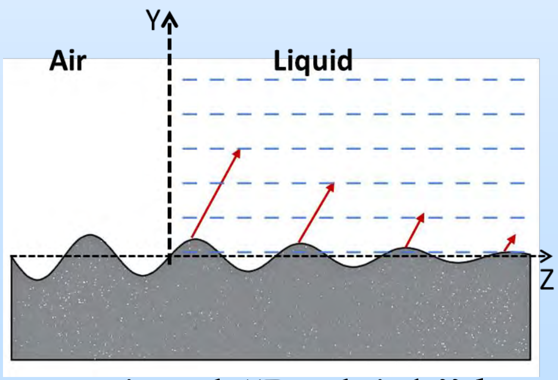
Technical Status :
Surface Acoustic Wave Device Modeling & Design

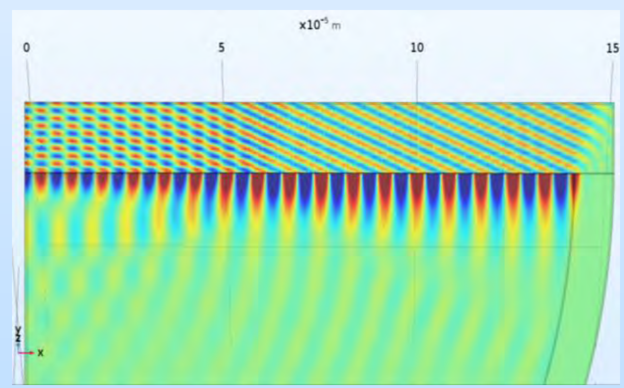
Conventional Rayleigh SAW



Modified Surface Horizontal (SH) SAW



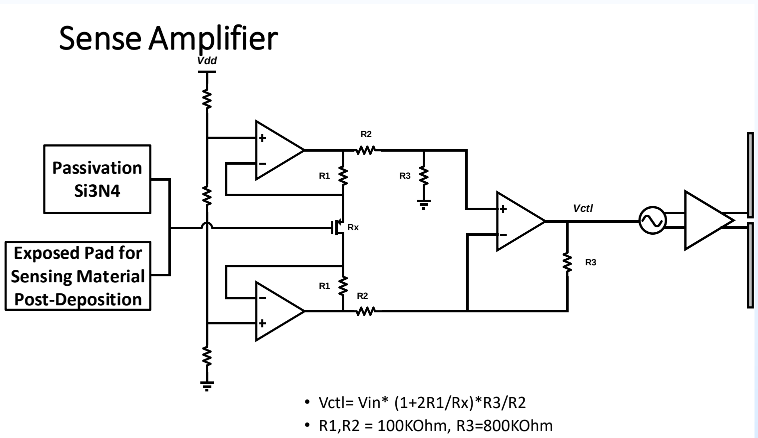




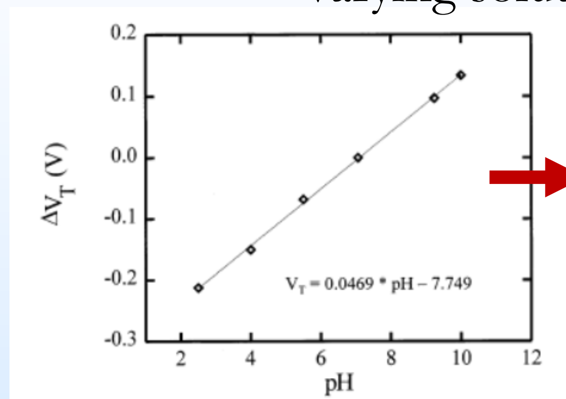
Conventional "Rayleigh" based surface acoustic waves attenuate rapidly in aqueous or liquid phase media, alternative devices are being modeled and designed.

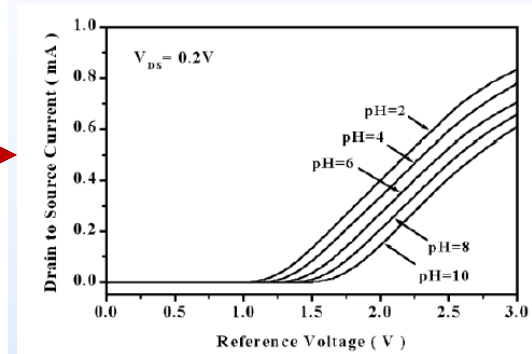
Technical Status :
Silicon Integrated Circuit Device Modeling & Design

Schematic of sensing amplifier

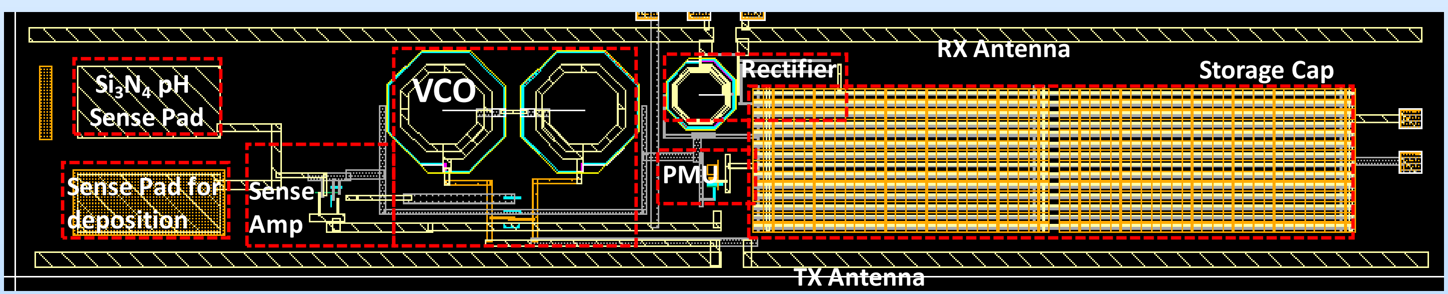


Potential shift expected for varying solution phase pH





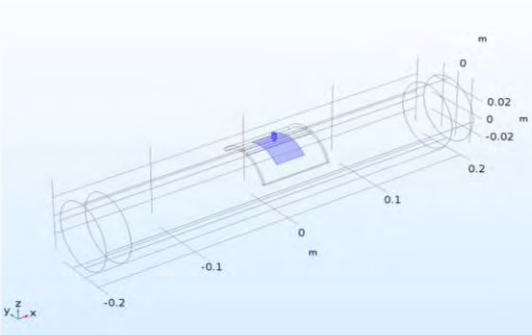
First iteration device layout and designs completed

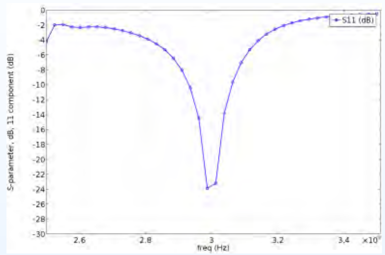


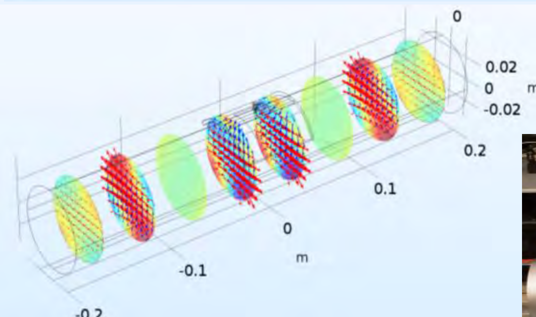
Technology node:
TSMC 180nm CMOS
Size: 5mm by 1mm

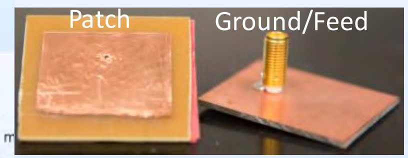
Silicon integrated circuit based sensors are being designed for wireless pH sensing applications using field effect mechanisms based on sensing layer surface electrochemistry.

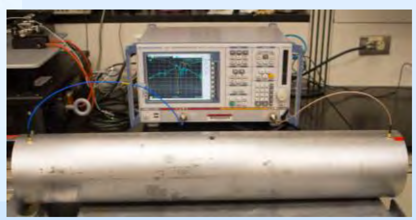
Technical Status :
Wireless Telemetry for Embedded Sensors





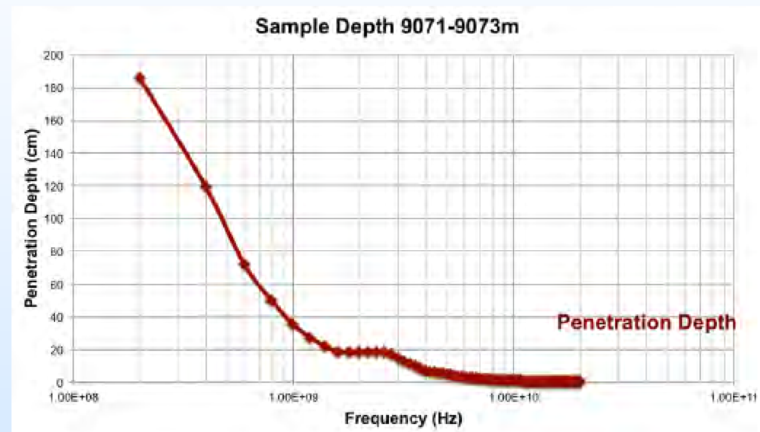






Simulations of RF signal launching and propagation in metallic tubular structures

Experiments / simulations of RF propagation through subsurface media

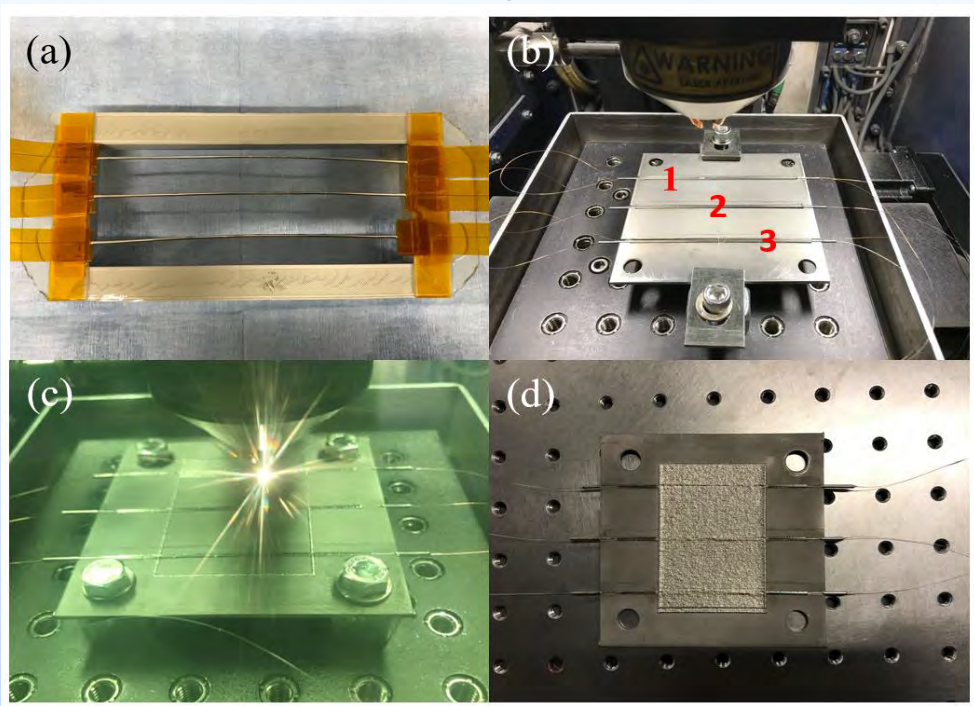


Wireless telemetry is being explored for subsurface application environments, including simulations of propagation within tubular structures and through subsurface media.

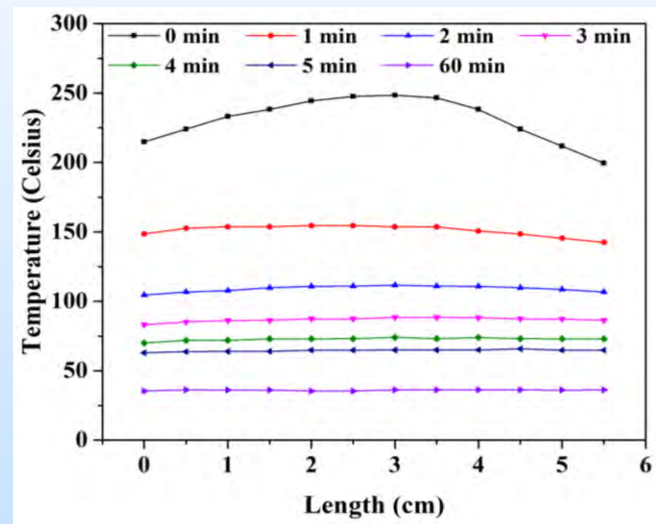
Technical Status :
Embedding of Sensors in Cement and Casing Materials

Laser Engineered Net Shaping (LENS)

Embedding of fibers in high temperature metals, including curved parts.



Example: Internal temperature distribution across the plate following the embedding process.



Thick film metal coatings on optical fibers are used to protect them during subsequent embedding which includes additive manufacturing based techniques such as LENS.

Accomplishments to Date

- An industry partnership group has been established and will meet on August 24th to provide input to the Technology Maturation Plans
- A survey of potential pH sensing layers has been performed and is under development as a review article
- Chemical sensing layer development has focused on layers with pH ranges, stability, and scalability relevant for field deployment
- Initial designs have been developed for both surface acoustic wave and silicon integrated circuit based sensors
- RF propagation through wellbore environments and materials has been performed with experiments and simulations
- Optical fiber embedding has initiated for casing and cement materials

Lessons Learned & Synergy Opportunities

Lessons Learned

– Stability of optical fibers within cements will be a challenge

– Field deployments require significant advances for chemical sensing

– Sensing layers developed must be compatible with limitations imposed by scale-up technology for field deployment

Synergy Opportunities

– Opportunities exist to leverage on-going work in CO_2 sensing under the Carbon Storage program research efforts within NETL R&IC

– Geochemistry efforts under the Carbon Storage program can provide insights to key parameters to measure and relevant environments

– Wellbore cement materials and integrity expertise is critical to inform key parameters, ranges, and deployment requirements

Project Summary

- Four Complementary Technologies are Being Developed with Synergies in Enabling Sensing Materials for pH and Corrosion
- Optical and Microwave Platforms are Being Leveraged to Address Needs for High Temperature, Harsh Environment Operating Conditions
- Objective = A Suite of Complementary Sensing Technologies to Enable an Integrated Sensing Network for Wellbore Integrity Monitoring
- Technology Maturation Plans and Industry Partnership Group Establishment are Primary Activities Early in the Program
- The Team is Ramping up Technical Development Efforts in Parallel
- The Project is On Track Administratively and Technically to Date

Appendix

Benefit to the Program

- Program Goals:
  - Validate/ensure 99% storage permanence.

- Project benefits:
  - *Development and demonstration of new real-time sensing technologies for wellbore integrity monitoring.*
  - *Characterization of sensor embedding impacts on mechanical properties, corrosion resistance, and permeation of wellbore materials.*

Project Overview
Goals and Objectives

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

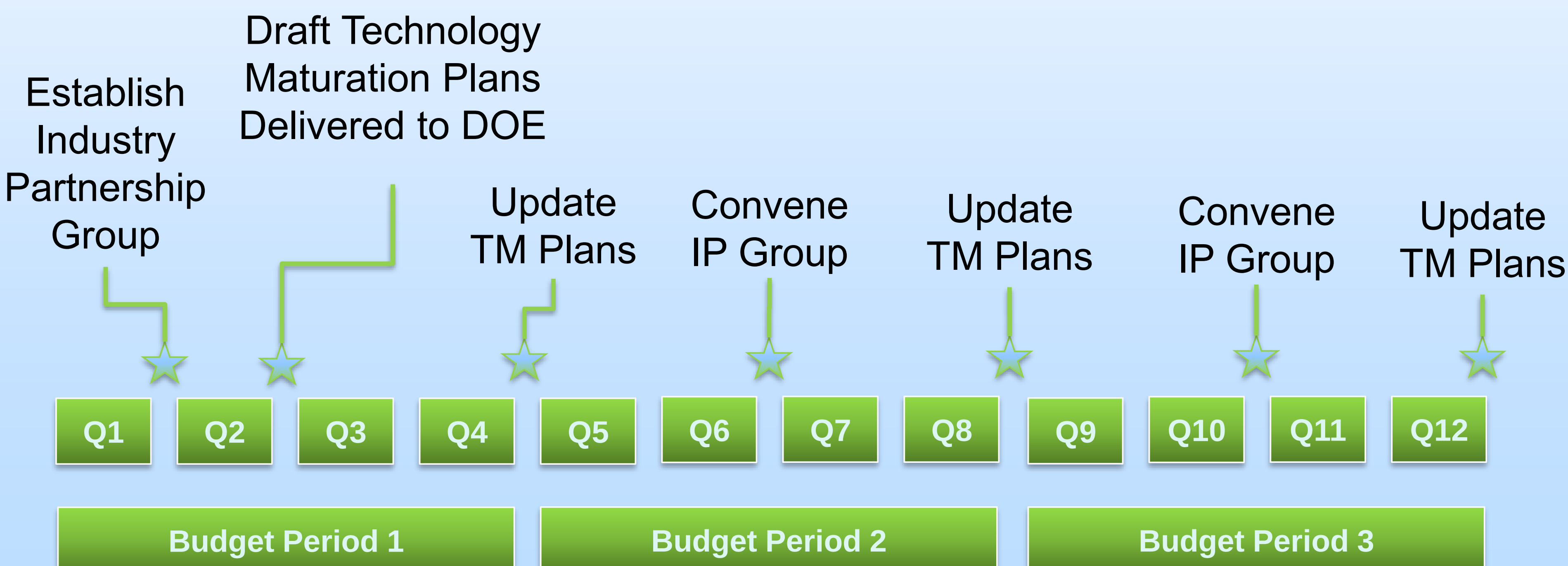
The task structure includes industry engagement and feedback, new sensor and enabling technology development and deployment, and sensor-infused wellbore materials performance characterization and benchmarking.

Project Overview
Goals and Objectives

Task 2: Technology Maturation Plan & Industry Engagement

Approach:

An industry partnership group will be established at the beginning of the program to review the proposed technology development and to provide industrial perspective and insight into the proposed metrics and objectives.



Project Overview

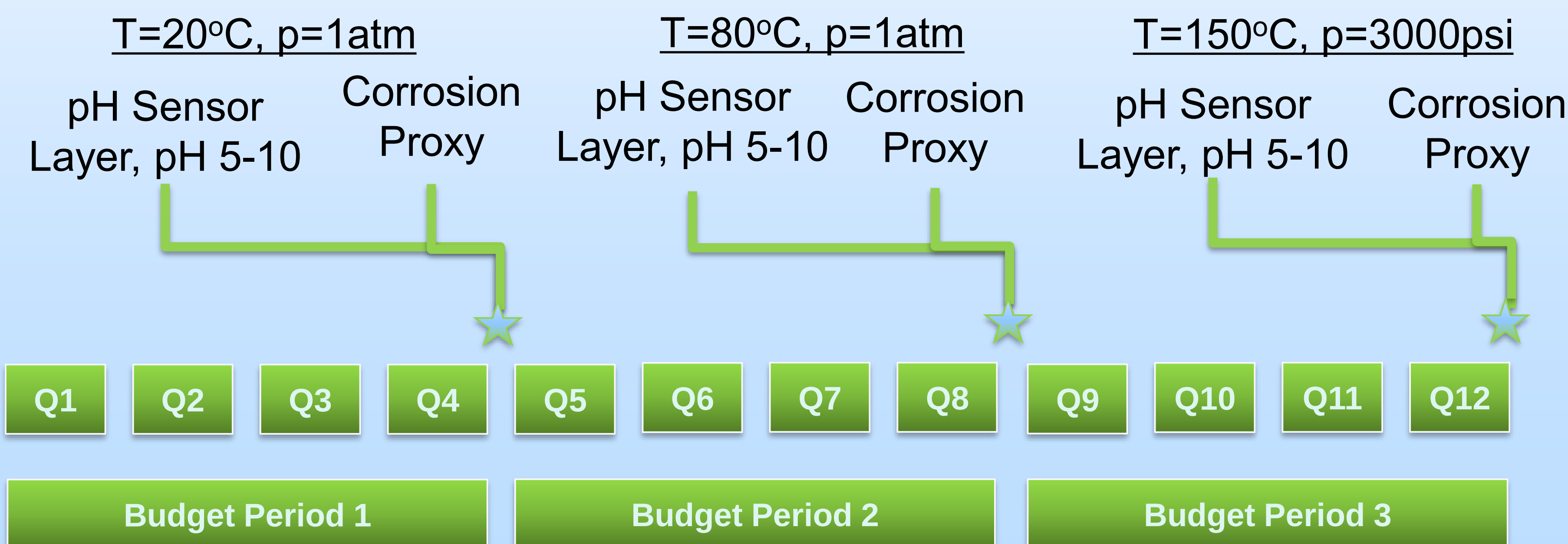
Goals and Objectives

Task 3: Chemical Sensing Layer Research & Development

Approach:

High temperature stable pH sensitive layers and corrosion proxy materials will be developed and integrated with the various device platforms.

Other parameters may also be explored (CO_2, hydrocarbons, water/humidity, etc.) based on inputs from the industry partnership group.



Project Overview

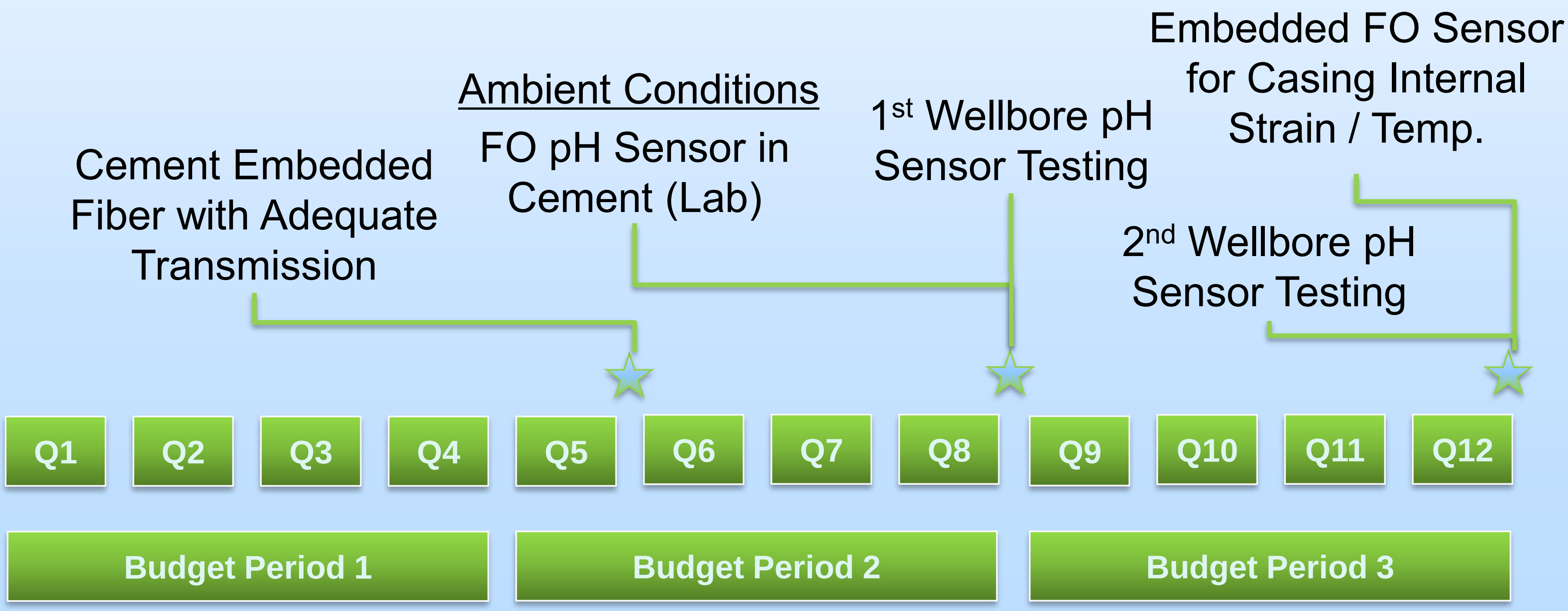
Goals and Objectives

Task 4: Multi-Functional Optical Fiber Sensor Development

Approach:

Embedding of optical fiber sensors within cements and casings for monitoring evidence of corrosion on-set or incipient structural failures.

Two stage wellbore field deployment of fiber optic pH sensor technology.



Project Overview

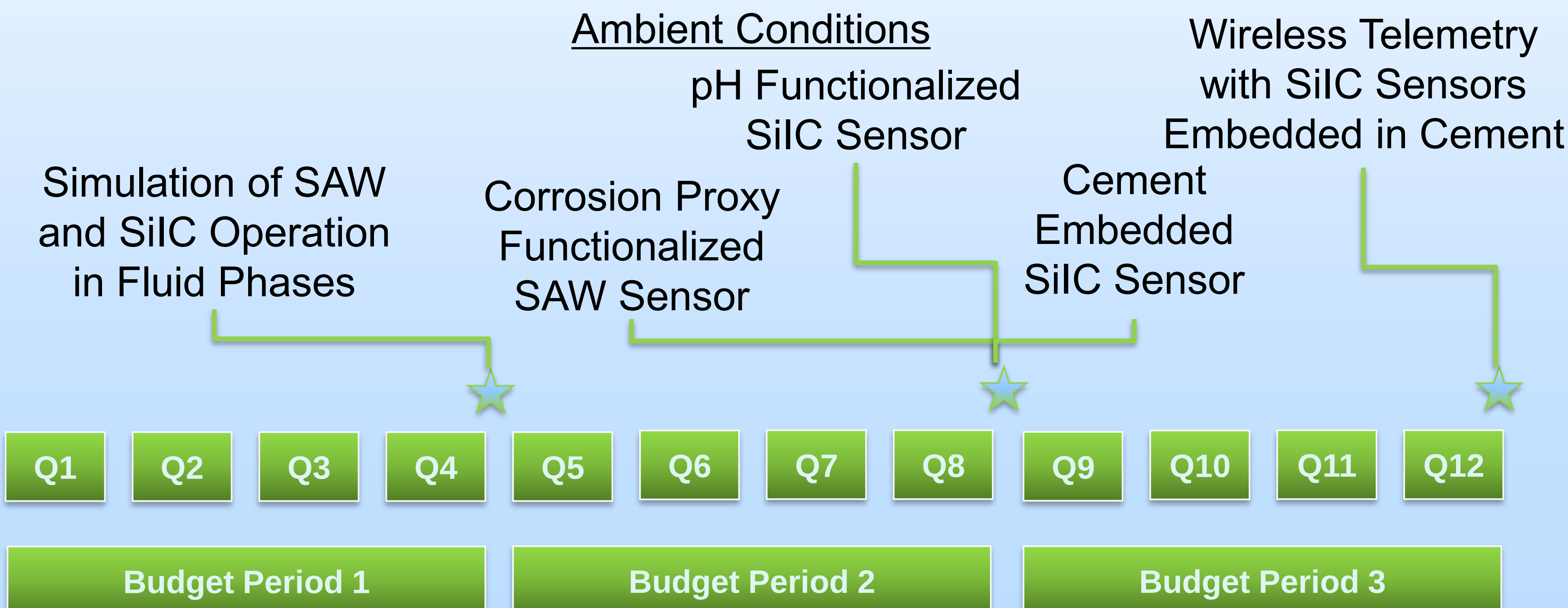
Goals and Objectives

Task 5: Multi-Functional Wireless Sensor Development

Approach:

Development, functionalization, and embedding of Surface Acoustic Wave (SAW) and Silicon Integrated Circuit (SiIC) based sensor devices.

Theoretical and experimental demonstrations of wireless telemetry.



Project Overview

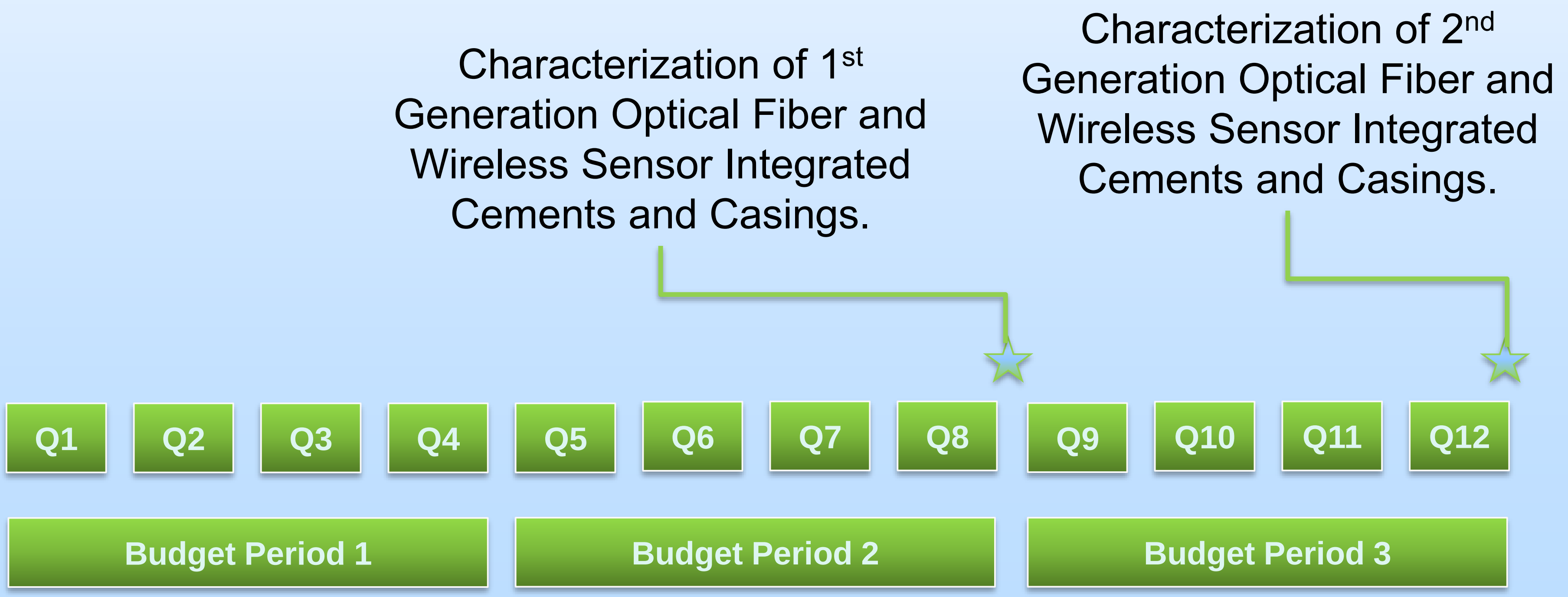
Goals and Objectives

Task 6: Sensor-Infused Wellbore Material Characterization

<u>Approach:</u>

Mechanical property, corrosion, and fluid permeation testing of baseline and sensor integrated cements and casings under relevant conditions.

CT scanner based imaging of sensor embedded cements and casings.



Organization Chart

Jerry Carr,
DOE Project Manager

Dr. Paul Richard Ohodnicki, Jr.
NETL, Lead PI

Dr. Jesus Delgado
IOS PI

Optical Fiber Sensor
Field Deployment

Prof. Aydin Babakhani
UCLA PI

Silicon IC Sensors
Wireless Telemetry

Dr. Barbara Kutchko
Dr. Margaret Ziomek-Moroz
Dr. Nicolas Huerta
Dr. Dustin Crandall
Dr. Ruishu Feng
Dr. Jagan Devkota
Dr. Ping Lu
NETL Co-PIs

Wellbore Sensor Materials
Chemical Sensing Layers
SAW Devices
Wireless Telemetry
Optical Fiber Sensors

Prof. Kevin Chen
U. Pitt. PI

Optical Fiber Sensor
Embedding

Prof. David Greve
CMU PI

SAW Devices
Wireless Telemetry

Dr. Scott Frailey
ISGS PI

Industry Partnership Group

Gantt Chart

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

Impact

Key Accomplishments/Deliverables	Value Delivered
2018: Project initiated 4/2018. **2019**: **2020**:	• 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

Bibliography : Project Publications & Presentations

- Devkota, J., Greve, D.W., and Ohodnicki, P.R., "Design and Integration of Antennas for Launching RF Signals in Metallic Tubular Structures," conference presentation, 2018 Institute of Electrical and Electronics Engineers (IEEE) International Symposium on Antennas and Propagation and the U.S. National Committee (USNC)-International Union of Radio Science (URSI) Radio Science.

- Greve, D., Devkota, J., and Ohodnicki, P., "Wireless CO SAW Sensors with a Nanoporous ZIF-8 Sensing Layer," conference abstract, accepted for presentation at the 2018 International Ultrasonics Symposium (IUS), Kobe, Japan, October 22-25, 2018.

Bibliography :
Past Publications & Presentations

J. Delgado, R.A. Lieberman, "Extended-length fiber optic carbon dioxide monitoring," Proc. SPIE Vol. 8718, *Advanced Environmental, Chemical, and Biological Sensing Technologies X*, T. Vo-Dinh, R.A. Lieberman, G. Gauglitz (Eds.), 2013;

F. Hingerl, S. Marpu, N. Guzman, S. M. Benson,J. Delgado-Alonso "Development and Testing of a New Fiber Optic System for Monitoring CO2 Solubility in Aqueous High-Pressure Geological Systems", *Energy Procedia*, 63, 4134 – 4144, 2014.;

Yang, J. Delgado-Alonso, R. Trevino and S. Hovorka, "Semi-analytical approach to reactive transport of CO2 leakage into aquifers at carbon sequestration sites", *Green Gas Sci. Technol.* 5:1-16, 2015;

Plasmonics-enhanced metal-organic framework nanoporous films for highly sensitive near-infrared absorption", K. J. Kim, X. Chong, P. B. Kreider, G. Ma, P. R. Ohodnicki, J. P. Baltrus, A. X. Wang, Chih-Hung Chang, Journal of Materials Chemistry C (2015) Advance Article, **DOI:** 10.1039/C4TC02846E.

Ultra-sensitive CO2 Fiber Optic Sensors Enhanced by Metal-Organic Framework Film", X. Chong, K. Kim, E. Li, Y. Zhang, P. Ohodnicki, C. Chang, and A. X. Wang, CLEO: Applications and Technology, JTu5A 138 (2016).

"Novel Silica Surface Charge Density Mediated Control of the Optical Properties of Embedded Optically Active Materials and Its Application for Fiber Optic pH Sensing at Elevated Temperatures", C. Wang, P. R. Ohodnicki, X. Su, M. Keller, T. D. Brown, and J. Baltrus, Nanoscale 7, 2527-2535 (2015).

"The effect of ionic species on pH dependent response of silica coated optical fibers", J. Elwood, P. R. Ohodnicki, SPIE Defense + Security, 98360I-98360I-8 (2016).

J. Devkota, P. R. Ohodnicki, and D. W. Greve, "SAW Sensors for Chemical Vapors and Gases", Sensors 17 (4) 801 (2017);

D. W. Greve, T. L. Chin, P. Zheng, P. Ohodnicki, J. Baltrus, and I. J. Oppenheim, "Surface Acoustic Wave Devices for Harsh Environment Wireless Sensing", Sensors 13 (6), 6910-6935 (2013).

Y. Sun, A. Babakhani, "A Wirelessly Powered Injection-Locked Oscillator with On-Chip Antennas in 180nm SOI CMOS", in IEEE MTT-S International Microwave Symposium, May 2016;

H. Rahmani, A. Babakhani, "3GHz Wireless Power Receiver with an On-Chip Antenna for Millimeter-Size Biomedical Implants in 180nm SOI CMOS", in IEEE MTTT-S Int. Microwave Symposium, June 2017;

Y. Sun, A. Babakhani, "Wirelessly Powered Implantable Pacemaker with On-Chip Antenna", in IEEE MTT-S International Microwave Symposium, June 2017