Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

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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:

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.

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.).
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.

Key features:

- Eliminate Electrical Wiring and Contacts at the Sensing Location
- Tailored to Parameters of Interest Through Functional Materials
- Compatibility with Broadband and Distributed Interrogation

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

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
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.
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)

An industry partnership group has been established to review and provide ongoing industry feedback.

<table>
<thead>
<tr>
<th>Invites</th>
<th>Title</th>
<th>Expertise</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Sensor development</td>
<td>WellDiver</td>
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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

<table>
<thead>
<tr>
<th></th>
<th>Examples</th>
<th>Stability Limits in Wellbore Conditions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organic Dyes</strong></td>
<td>cresol red, bromophenol blue and chlorophenol red mixture;</td>
<td>Low to moderate</td>
<td>Stability under wellbore conditions will be limited. Embedded within sol-gel or polymer matrices. Leaching of dyes presents challenges for long-term deployment.</td>
</tr>
<tr>
<td><strong>Polymers</strong></td>
<td>Polyaniline, polypyrrole</td>
<td>Low to moderate</td>
<td>Stability under wellbore conditions will be limited. Can exhibit long response times due to diffusion limitations.</td>
</tr>
<tr>
<td><strong>Inorganic Sensing Layers</strong></td>
<td>Metal oxides, noble metals, nanocomposites</td>
<td>Moderate to High</td>
<td>Potentially extremely stable. Sensing mechanisms are not as well understood, and need further research and development including selectivity.</td>
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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 $>\sim 500{^\circ}C$.

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$_2$H$_5$)$_4$

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

Hydrolysis and condensation catalyzed by acids / bases

Transmission (%)

Elapsed Time (min)

pH=

Room Temperature

400°C

600°C
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

Thymolphthalein Derivatives

- pKa ~ 10
- Absorption peak ~595nm

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" 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

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

Potential shift expected for varying solution phase pH

First iteration device layout and designs completed

Technology node: TSMC 180nm CMOS

Size: 5mm by 1mm
Technical Status:
Wireless Telemetry for Embedded Sensors

Experiments / simulations of RF propagation through subsurface media

Simulations of RF signal launching and propagation in metallic tubular structures

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 CO₂ 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
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.
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.
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.

- **T=20°C, p=1atm**
  - pH Sensor Layer, pH 5-10
  - Corrosion Proxy

- **T=80°C, p=1atm**
  - pH Sensor Layer, pH 5-10
  - Corrosion Proxy

- **T=150°C, p=3000psi**
  - pH Sensor Layer, pH 5-10
  - Corrosion Proxy

**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 onset or incipient structural failures.
Two-stage wellbore field deployment of fiber optic pH sensor technology.
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.

Simulation of SAW and SiIC Operation in Fluid Phases
Corrosion Proxy Functionalized SAW Sensor
pH Functionalized SiIC Sensor
Cement Embedded SiIC Sensor
Wireless Telemetry with SiIC Sensors Embedded in Cement

Ambient Conditions

Budget Period 1
Budget Period 2
Budget Period 3
Task 6: Sensor-Infused Wellbore Material Characterization

Approach:
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.


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 SilC 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 SilC 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 SilC Integrated cements and casings

Impact

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<tr>
<th>Key Accomplishments/Deliverables</th>
<th>Value Delivered</th>
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<tr>
<td><strong>2018:</strong> Project initiated 4/2018.</td>
<td>• New sensing layers integrated with fiber optic, surface acoustic wave, and silicon integrated circuit devices for pH sensing</td>
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<td><strong>2019:</strong></td>
<td>• Field deployed fiber optic based pH sensor technology</td>
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<tr>
<td><strong>2020:</strong></td>
<td>• Laboratory tested wireless surface acoustic wave and silicon IC pH sensors</td>
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Go / No-Go

1. Successful field deployment of the optical fiber based pH sensor for ambient pressure/temperature
Bibliography:
Project Publications & Presentations


Bibliography:

Past Publications & Presentations


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


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;