Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

Presenter: Dr. Paul R. Ohodnicki, Jr.
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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:
- Enable identification of wellbore integrity risks BEFORE they result in failures
Technology #1: Distributed Optical Fiber Sensors

Sensing Principle: Evanescent Wave Sensors

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

Deployment Scenario: Embedded Within Wellbore Cements and Casing Metals
Technology #2: Passive and Wireless SAW Devices

Deployment Scenario: Embedded on Interior and Exterior Casing Surfaces

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
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

CT Scans of Embedding

Optical Fibers

Casing Alloys

Mechanical Testing

SiIC Sensors

Inductor rings

Antenna

Proof-of-Concept Sensor Embedding Efforts Combined with Structural (CT-Scans) and Performance (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 Deliverable and Outcomes

#2: Maturation of New Wireless / RF Sensing Technology for Subsurface
#3: Field Validation of New Fiber Optic pH Sensing Technology
**Project Structure: Project Timing and Status**

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

<table>
<thead>
<tr>
<th>Key Accomplishments/Deliverables</th>
<th>Value Delivered</th>
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<tbody>
<tr>
<td>2018: 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>
</tr>
<tr>
<td>2019:</td>
<td>• Field deployed fiber optic based pH sensor technology</td>
</tr>
<tr>
<td>2020:</td>
<td>• Laboratory tested wireless surface acoustic wave and silicon IC pH sensors</td>
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</table>
Regular Meetings Have Occurred with the Industry Advisory Group to Provide Feedback and Guide Technology Maturation Plans for the Overall Project.

### Key Practical Challenges Discussed

1) Potential Deployment Strategies for Fibers in Wellbore Cements

2) Wireless Telemetry Methods in Subsurface Environments

3) Elevated Temperatures / Pressures During Cement Hydration

4) Fiber Darkening in Subsurface

5) Vibration and Shock Tests of Sensors

### Advisory Group Members

<table>
<thead>
<tr>
<th>Invites</th>
<th>Title</th>
<th>Expertise</th>
<th>Company</th>
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<tbody>
<tr>
<td>Igor Kesacki</td>
<td>Materials Engineering Manager</td>
<td>Sensor development</td>
<td>WellDiver</td>
</tr>
<tr>
<td>John Lovell</td>
<td>Vice President – Technology and Strategy</td>
<td>Temperature and pressure measurement systems, Wellhead asphaltines sensor</td>
<td>MicroSilicon Inc.</td>
</tr>
<tr>
<td>George Koperna</td>
<td>Vice President</td>
<td>CO₂, EOR and storage, reservoir engineering</td>
<td>Advanced Resources International, Inc.</td>
</tr>
<tr>
<td>Charles Corecki</td>
<td>Directory of Subsurface R&amp;D</td>
<td>EOR, CO₂, storage</td>
<td>Energy &amp; Environmental Research Center</td>
</tr>
<tr>
<td>Pierre Raucontenc</td>
<td>Well Intervention Domain Manager</td>
<td>Coiled tubing well interventions, real-time fiber-optics</td>
<td>Schlumberger</td>
</tr>
<tr>
<td>Laura Notziger</td>
<td>Senior Vice President and Managing Director</td>
<td>Geothermal Power Plant operations and maintenance</td>
<td>AltanaRock Services, LLC</td>
</tr>
<tr>
<td>Tim Onig</td>
<td>Principal Strategy - Technology &amp; Innovation</td>
<td>Strategy planning, technology and innovation</td>
<td>BHP Billiton</td>
</tr>
<tr>
<td>Dennis Dria</td>
<td>Petroleum Technology Advisor</td>
<td>Fiber-optic technology development and implementation</td>
<td>Myles Energy Consulting, PLLC</td>
</tr>
<tr>
<td>Austin Vonder Hoja</td>
<td>Senior Advisor</td>
<td>Geophysical technology</td>
<td>Pioneer Natural Resources USA</td>
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### Ranking of Geochemical Parameters to Be Monitored

<table>
<thead>
<tr>
<th>Rank</th>
<th>Geochemical parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>pH</td>
</tr>
<tr>
<td>2</td>
<td>H₂S, HS⁻</td>
</tr>
<tr>
<td>3</td>
<td>Dissolved CH₄ and CO₂</td>
</tr>
<tr>
<td>4</td>
<td>Corrosion ions (Mn²⁺, Fe²⁺, etc.)</td>
</tr>
<tr>
<td>5</td>
<td>Ionic strength, Solution conductivity</td>
</tr>
<tr>
<td>6</td>
<td>TDS</td>
</tr>
<tr>
<td>7</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>8</td>
<td>Cl⁻</td>
</tr>
<tr>
<td>9</td>
<td>Na⁺</td>
</tr>
<tr>
<td>10</td>
<td>Ca²⁺</td>
</tr>
</tbody>
</table>
Silica and Au / SiO₂ Films Have Been Developed and Demonstrated for pH Sensing Under High Alkalinity Environments.
Silica and Au / Silica Films Films Have Been Used to Demonstrate Multi-Point Distributed pH Sensing.
Project Progress: Sensing Layer Scale-Up

- **Challenge:**
  - Rapidly cure a coating in time for fiber to travel from top to bottom of rig
  - TEOS-based pH coating curing time NOT compatible with reel-to-reel coating

- **Strategy:** Fast Photocuring
  - Photocured hydrogels is well developed
  - Photocuring of TEOS sol-gels is being developed

- **We have demonstrated production of films in the range of tens of seconds**
- **Calcination can be performed as a second step**
- **We are evaluating fiber coating protocols**

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

Alternative Oxide Based Sensing Layers are Being Explored for Maximum Stability in Elevated Temperature and High Alkalinity Environments.

<table>
<thead>
<tr>
<th>Oxides</th>
<th>pH&lt;sub&gt;pzc&lt;/sub&gt;</th>
<th>Refractive index (550nm)</th>
<th>Refractive index (1530nm)</th>
<th>pH range of passivity</th>
<th>Melting point</th>
</tr>
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<tbody>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>3.9-8.2</td>
<td>2.6479</td>
<td>2.4538</td>
<td>0- to 14+</td>
<td>~2000 °C</td>
</tr>
<tr>
<td>ZrO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>4-11</td>
<td>2.1661</td>
<td>2.1107</td>
<td>4 to 13</td>
<td>~2700 °C</td>
</tr>
<tr>
<td>α-Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>8-9</td>
<td>1.7704</td>
<td>1.7465</td>
<td>~2000 °C</td>
<td></td>
</tr>
<tr>
<td>Ta&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>2.7-3.0</td>
<td>2.1411</td>
<td>2.0580</td>
<td>0- to 14+</td>
<td>~1500 °C</td>
</tr>
<tr>
<td>NiO</td>
<td>9.9-11.3</td>
<td>2.1818</td>
<td></td>
<td>5-14+</td>
<td>~1950 °C</td>
</tr>
<tr>
<td>MgO</td>
<td>9.8-12.7</td>
<td>1.7405</td>
<td>1.7149</td>
<td>9-14+</td>
<td>~2800°C</td>
</tr>
</tbody>
</table>

* Incorporation with Au nanoparticles are also investigated
Project Progress: Chemical Sensing Layers

**Phenol Red:** Indicator functionalization follow by copolymerization with hydrogel matrix

- Phenol red has moderate pKa but synthetic strategy similar to our desired approach has been published for this indicator, and it exhibits a structure similar to that of indicator dyes successfully synthesized in our lab.

Polymers with pH Indicators are Also Being Explored and Developed for High Temperature and High Alkalinity Environments Relevant for Wellbore Cements.
Various Techniques are Being Explored for Development of Packaging That is Compatible with Installation within Wellbore Cements for Chemical Monitoring.

**Challenge:**
- Sensorized fibers must be robust and not break when spooled, unspooled, or embedded in cement
- Sensors must be exposed to environment

**Perforated Fiber Jacket:** Protection of the fiber optic sensor with a standard polymer jacket perforated with microholes for water permeation

**Status:**
- Optimized fabrication process
- Evaluated mechanical properties
- Investigated fiber integration into cement
- Evaluating coating protocols after jacket perforation

**Permeable Fiber Jacket:** Protection of the fiber optic sensor with a polymer that allows water and ion permeation

**Status:**
- Polymer selected
Project Progress: SAW Device Modeling

Shear Horizontal Surface Acoustic Waves

Early Efforts on SAW Device Modeling Demonstrated Proof of Concept for Aqueous Phase Operation and Identified Value in Metallization of Delay Path.

Reflector (IDT type) Reflectivity for air and water above the SH-SAW.
Project Progress: SAW Device Fabrication / Test

SAW Devices Have Been Successfully Fabricated and Show Stable Operation in the Context of Aqueous Phase Environments with Initial pH Sensing Underway.

Substrate: 36 Y-X LiTaO3
\( f_0 = 520 \text{ MHz}; \) IDT: Al, 120 nm thick

Bare device responds to pH to some extent. Sensing layers will be applied to improve sensitivity.
Several Rounds of Design / Fabrication Enabled Successful Device Operation Including the Integration of Sensing Layer Electrodes for pH Functionalization.
Project Progress: SiIC Device Early pH Sensing

Control Voltage and Oscillator Frequency vs. Sense Voltage

Initial Proof of Concept pH Wireless Device Sensing Responses Have Been Demonstrated with Standard Reference Electrodes, Miniaturization in Progress.
Project Progress: Wireless Telemetry Concepts

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

RF signal launching and propagation in metallic tubular structures with waveguiding.
Project Progress: Sensor Embedding in Cements

CT Scanning and Property Performance Measurements are Being Performed to Understand Structural / Chemical Impacts of Cements After Sensor Embedding.
Additive Manufacturing Methods are Being Explored for Integration of Optical Fibers Into Curved Parts with Minimized Residual Strains Such as Casings.
Efforts are Underway to Prepare for 2\textsuperscript{nd} Year Field Testing Which Serves to Help Prepare for More Extensive Field Testing in the 3\textsuperscript{rd} Year of the Project.
Project Summary: Successes and Next Steps

Project Successes to Date
- Successful design, fabrication, and testing of SiIC wireless pH sensors
- Demonstrated aqueous phase sensing of novel SAW devices
- First demonstration of distributed pH sensing using optical fiber platform
- Novel concepts in wireless subsurface telemetry methods
- AI-enhanced distributed optical fiber sensing for defect identification

Next Steps
- Miniaturization of pH sensor electrodes for wireless SiIC sensing
- Integration of pH sensing layers with wireless SAW sensors
- First field deployment for cement embedded fiber optic pH sensors
- Demonstrated wireless interrogation of SiIC devices embedded in cement