Embedded Sensor Technology Suite for Wellbore Integrity Monitoring

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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**: 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

- Sensing Layer
- Silica Core
- F-doped Silica Cladding

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 Cement and Casing Steel
Oxide based sensing layers have been demonstrated for pH sensing with stability in elevated temperature and high alkalinity environments.
Silica coated optical fiber sensors have been used to demonstrate multi-point distributed pH sensing at the high pH conditions.
Polymers with pH indicators are also developed for high temperature and high alkalinity environments.
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.

Established fiber recoating facilities are being leveraged to scale promising inorganic and organic sensing layers to m- and eventually km-scale lengths.
Optical Fiber Sensor Deployment and Field Validation

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

- **Fiber sensor protection**
- **Fiber sensor cement integration**

- 4 optical fiber channels
- 6 mm diameter
- 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
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
SAW pH Sensing in Aqueous Solutions

Shear Horizontal Surface Acoustic Waves

SAW device modeling and experiments as proof of concept for aqueous phase operation. Demonstrated the velocity change and attenuation with various salinities and pH.

- 36° rotated Y-cut X-propagating LiTaO$_3$
- Severe SAW attenuation for NaCl
- Small velocity change for HCl
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.
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 Cement

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.
Wirelessly-Powered SiIC Device

Status of the New MHz Radios To Push the Operating Range

- 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).
Sensor Embedding in Cement

- 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.
Additive manufacturing methods were used for integration of optical fibers into steel parts with capability of high-resolution temperature and strain sensing.
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.
Summary

- 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