Annulus Monitoring of CO$_2$ Injection Using Wireless Autonomous Distributed Sensor Networks

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Carbon Storage Virtual Meeting
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Presentation Outline

1. Overview 2 min

2. Technical Accomplishments
   - Autonomous Microsensors: Dr. Axel Scherer 5 min
   - Microsensor Encapsulations: Dr. Jeff Mecham 5 min
   - Smart Casing Collars and Wired Pipe: Andrew Wright 5 min
   - Field Experiment; Dr. Mohsen Ahmadian 5 min

3. Lessons Learned 3 min

4. Synergy Opportunities 2 min

5. Project Summary 3 min

6. Appendix
System Description: A distributed wireless sensor network system, providing near-wellbore reservoir monitoring in the casing annular space

- Millimeter scale autonomous mix of microsensors measuring CO₂, pH, temperature, and CH₄, with surface coatings to facilitate survival, transport, and emplacement
- Smart casing collars and wired pipe, to facilitate real-time communications with surface automation

(Left) Sensor systems that communicate wirelessly with casing collars, (Right) providing real-time distributed sensor measurements in the casing annular space, and the formation
The Opportunity: 10 cent “disposable sensors” to measure T and pH

Millimeter scale mix of autonomous microsensors measuring pH, temperature, CO$_2$, and CH$_4$
Temperature responses of 6 wireless temperature sensors

- poly-Silicon Thermometers

Increasing Si film thickness
In acid solutions, the polymer is doped with $H^+$ ions to create the emeraldine salt (ES) form of PANI, which is highly electrically conductive.

The resulting surface charge decreases the resistance, leading to a voltage change.

When the polymer is exposed to basic solutions, the captured $H^+$ ions are neutralized by $OH^-$, resulting in the opposite effect.
pH meters

- We use the change in conductivity of Polyaniline (emeraldine phase PANI) with hydrogen ion concentration
Technical Status: Dr. Axel Scherer, Caltech

Autonomous Microsensors

![Graphs showing voltage vs pH and time for different sensors.](image1)

- **pH Sensor Lag time**

- **Temperature drift**

![Graphs showing voltage vs temperature for different pH levels.](image2)
RF Tag Reader
Technology basis for SNL Smart Collars

Our RF tag reader powers temperature sensor through near-field inductive coupling at 850MHz.

The sensor uses reflected RF power to communicate back to the reader.
Task 3 Objective: RTI is developing coating formulations for microsensor systems to enable survival and emplacement direct contact with the formation

- Subtask 3.1 Encapsulations and Sensor Coatings
  - Develop coatings materials formulations to provide hermetic encapsulation, abrasion resistance and control buoyancy/specific gravity
  - Apply tunable outer surface coating to provide driving force through injection fluid to proper sensor emplacement destination
  - Timeline: Best performing materials will be down selected and applied to working sensors by the end of Year 1. Coated functioning SoC sensors will be developed at the end of the first year.
Sensor Encapsulation Progress to Date:

- 3 Low Surface Energy Surface Coating Types Developed
  - Small molecule: cheapest and easiest to apply
  - Particle-based: highest contact angle
  - Polymer-based: imparts impact resistance and can be weighted

- Next Steps
  - Investigate coating application design to determine configuration that provides best driving force and vector control. We have some coating design flexibility.
  - Utilize both casing and formation elements in lab test fixture to simulate underground environment and conditions
Multiple wired pipes will be used for communications and power transfer between the surface PC and Smart Collars.

A Smart Collars will be placed in-between two sections of wired pipe as illustrated.

The Smart Collars are placed at various locations along the length of wired pipe to expand the range of communications with the RFID sensor integrated into the cement in the borehole.
Smart Collar Communication

• Communications between computer and Smart Collars
  – Ethernet over coax (EOC) will be used to convert the ethernet signal to a coaxial line, data is then transmitted through the wire pipe
  – Within the Smart Collar the signal is converted back to ethernet to the internal microprocessor, that communicates with the RFID reader via USB

• Powering the Smart Collars
  – A wideband AC signal will be transmitted along with the data signal through the wired pipe where it is filtered out to charge a super capacitor within the smart collar

• RFID Communications
  – An off-the-shelf RFID reader operating at 902-928 MHz will be utilized for communications to the RFID sensors
  – The signal from the reader will be amplified between 5 – 9 watts of RF power to enable communications through the lossy cement medium
Initial Cement Characterization

• Utilized open-ended coaxial probe technique for initial characterization of the cement that will be surrounding the RFID sensor
• Dielectric constant at 920 MHz is 7.5 - 8.2
• Loss tangent at 920 MHz is about 0.12
• Further testing required for evaluating the material at various brine levels
  – This sample set is dry cement
• Next, data will be placed into Ansys High Frequency Structure Simulator (HFSS) to calculate the loss of the medium
Proposed test well allows for positive detection of a low pH fluid at either known cement (zone A blue dots) or gravel-packed sensor points (zone C black dots) with the engineered fluid contact points at 135 or 175 ft deep sections of the borehole.

The rest of the borehole and sensors are isolated from fluids (zone B red dots).

pH adjusted fluids will be introduced through one or more slotted PVC pipe to the zone of interest.

Sensors will be adhered onto the PVC pipe to ensure correct positioning and ensures fluid contact.

Alternative test plan:

Use the proposed test well in conjunction with the other observation wells available at the DFPS (as described on next slide).
Field Test Plan and Timing, BEG

BP1:
1. Get sign off on DFPS as the field test location from the DOE
2. Design a hydrogeological model in CMG based on the existing infrastructure to simulate various injection scenarios. The model outputs are the spatiotemporal solutions for pressure, temperature, salinity, and pH.
3. Order transducers, straddle packers, and an electric submersible pump for deployment to the DFPS.

BP2:
1. Deploy to the DFPS and evaluate/calibrate the simulation results by injecting at 135 and 175 ft depth
2. Test survivability and functionality of the highest TRL (currently temperature and pH microsensors) and reference transducers at the DFPS observation wells (i.e., an unthreaded unembedded case)

BP3:
1. Drill the new instrumented well between the existing observation wells
2. Field deployment round 2 with sensors embedded in cement and gravel pack
3. Conduct field work, including pH adjusted fluid injection and history matching.

Technical Status: Dr. Mohsen Ahmadian
Accomplishments to Date

- COVID Project Plan Revisions and Contract Extensions Complete
- Y1 Go/No Go Criteria Passed, Devine Field Site Approved
- Sensors Being Characterized with Materials and Fluids in the Lab
- Instrumented Wellbore Test Bed established at Sandia
- Temp Sensors, pH sensors & RF readers fabricated & measured in the lab
- Low Surface Energy Surface Coating Types Developed to Coat Microsensors
  - Small molecule: cheapest and easiest to apply
  - Particle-based: highest contact angle
  - Polymer-based: imparts impact resistance and can be weighted
- Characterized wired pipe; Designed and selected components for communications though wired pipe, power to collars, RFID signal amplification and reader.
- Characterizing cement around RFID sensors in anechoic chamber
- Devine Field Modeling and Test Plan Created
Lessons Learned

– Hysteresis and drift are potential challenges for long-term pH
– Potential high signal loss in cement if highly saturated with brine. Higher amp. could compensate
– More than one smart casing collar would be useful in the field experiment (estimating cost)
– COVID extended our schedule 2 Quarters, NCE approved
Synergy Opportunities

– This project creates the possibility of real time autonomous sensors communicating with surface/subsurface infrastructure

– Sensors can provide real time streaming data to automated systems (drilling, pumping, resource storage, geothermal, EOR)

– Opportunity to characterize and optimize subsurface operations using artificial intelligence and machine learning

– Instrumented wellbores, capable of remote decadal monitoring of environmental, induced and natural seismicity and containment; including in natural disasters

– Earth monitoring increases the reliability and security of our nation’s energy supply
Project Summary

Key Findings:
- System integration underway with good team collaboration
- Smart collars create a reliable and feasible signal pathway
- Calibration will be needed for long term pH measurements
- Lab test beds set up and characterization underway

Next Steps:
- Caltech sensor testing in increasingly realistic conditions
- SNL measurements in cement to establish the needed power
- Field test site permitting and contracting
- We have a feasible and exciting field experiment planned in BP3
Appendix
Benefit to the Program

Program goals of monitoring at carbon storage sites

– Monitor the movement of CO$_2$ at carbon storage sites and assure permanence for geologic storage
– Decrease the cost and uncertainty in CO$_2$ measurements and satisfy regulations for tracking
– Confirm that CO$_2$ is stored in the target reservoir
– Assist in optimizing storage and injection operations

Project benefits by placing sensors in the casing annulus

– Measure critical subsurface parameters for injected CO$_2$
– Provide measurements of downhole and reservoir conditions for real-time process optimization
– Provide long-term post-injection monitoring of CO$_2$
Project Overview

Goals and Objectives

The **objective of this project** is to:

- Develop a fully integrated wireless autonomous distributed sensor network to measure CO$_2$, pH, temperature, and CH$_4$ in carbon capture and storage

The **goals of this project** are to:

- Develop and integrate wireless autonomous microsensor technology from California Institute of Technology (CIT), sensor packaging and emplacement technology from Research Triangle Institute (RTI), and smart well completions (wireless active casing collars and wired pipe) from Sandia National Laboratories (SNL)

- Design and test a wireless sensing system with sensors deployed within the casing annulus to improve reservoir and above zone monitoring for the expected life of the wellbore; (assuring permanence, reducing cost/uncertainty, confirming and optimize injection/storage)
Communications Plan:
- Monthly calls with researchers
- Quarterly Written Reports to DOE
### Gantt Chart

#### Project Period of Performance: 4/1/20-9/30/23

**BP 1: 4/1/2020--9/30/21**

**BP 2: 10/1/21--9/30/22**

**BP 3: 10/1/22--9/30/23**

<table>
<thead>
<tr>
<th>Tasks/Subtasks/Milestones</th>
<th>Leaders</th>
<th>Q1</th>
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<td>Chapman &amp; Ahmadian, UT</td>
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<td>Task 2.0 – Autonomous Microsensor Development</td>
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