Annulus Monitoring of CO_2 Injection Using Wireless Autonomous Distributed Sensor Networks

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U.S. Department of Energy
National Energy Technology Laboratory
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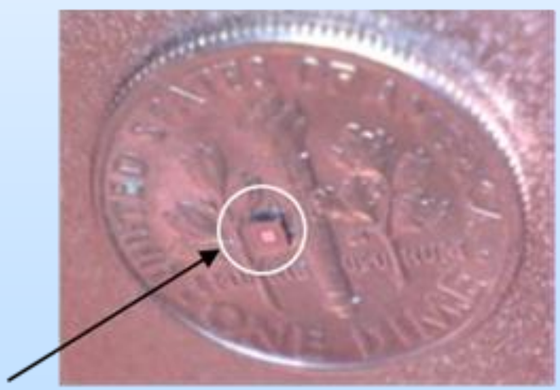
Presentation Outline

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

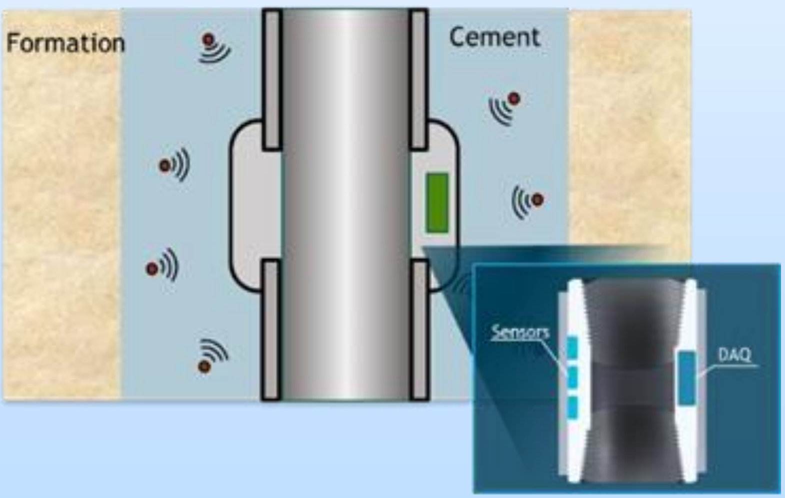
Project Overview

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 CO_2, pH, temperature, and CH_4, with surface coatings to facilitate survival, transport, and emplacement
- Smart casing collars and wired pipe, to facilitate real-time communications with surface automation



1mm System on a chip (SoC)



(Left) Sensor systems that communicate wirelessly with casing collars, (Right) providing real-time distributed sensor measurements in the casing annular space, and the formation

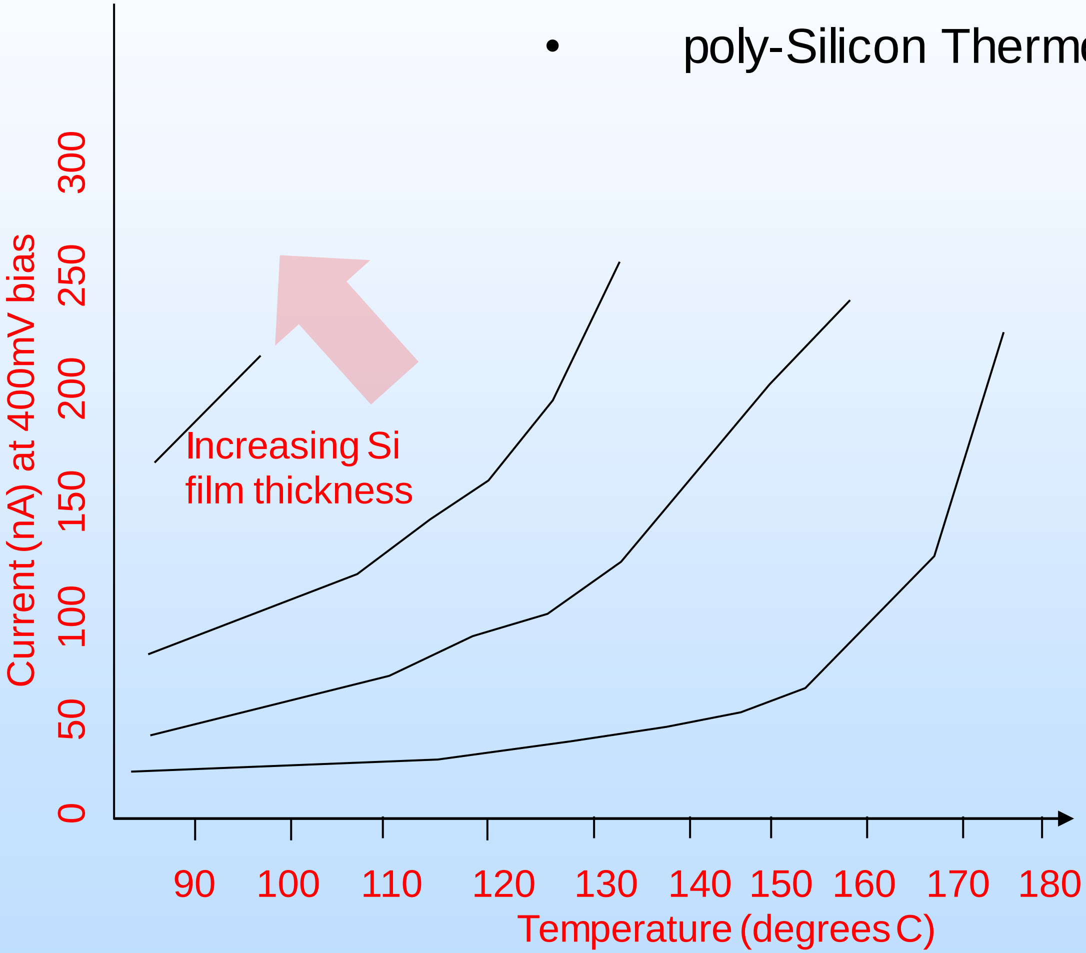
Technical Status: Dr. Axel Scherer
Autonomous Microsensors, Caltech

The Opportunity: 10 cent "disposable sensors" to measure T and pH

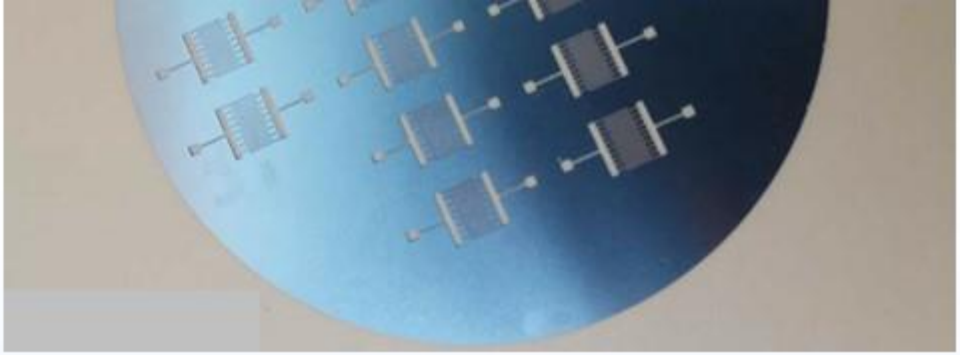
Millimeter scale mix of autonomous microsensors measuring pH, temperature, CO_2, and CH_4

Temperature responses of 6 wireless temperature sensors

- poly-Silicon Thermometers



Concept of PANI pH sensors



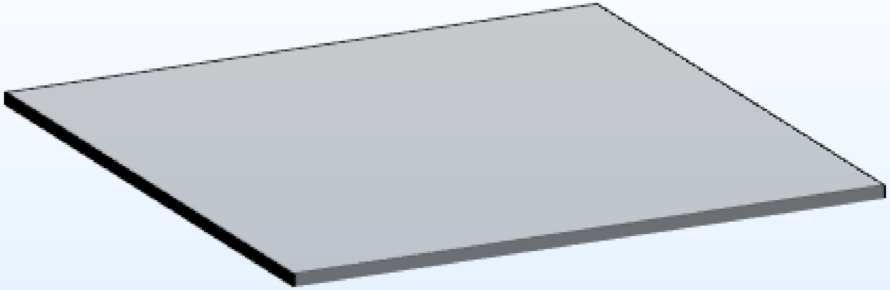
In acid solutions, the polymer is doped with H^+ ions to create the emeraldine salt (ES) form of PANI, which is highly electrically conductive.

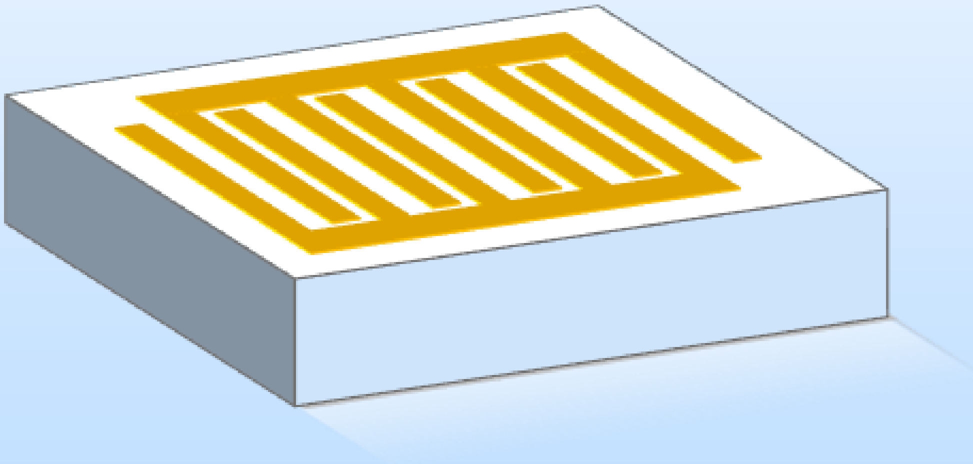
The resulting surface charge decreases the resistance, leading to a voltage change.

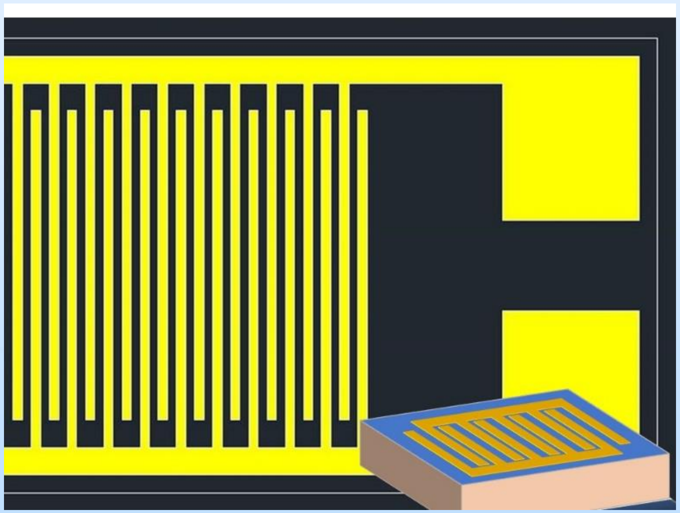
When the polymer is exposed to basic solutions, the captured H^+ ions are neutralized by OH^-, resulting in the opposite effect.

pH meters

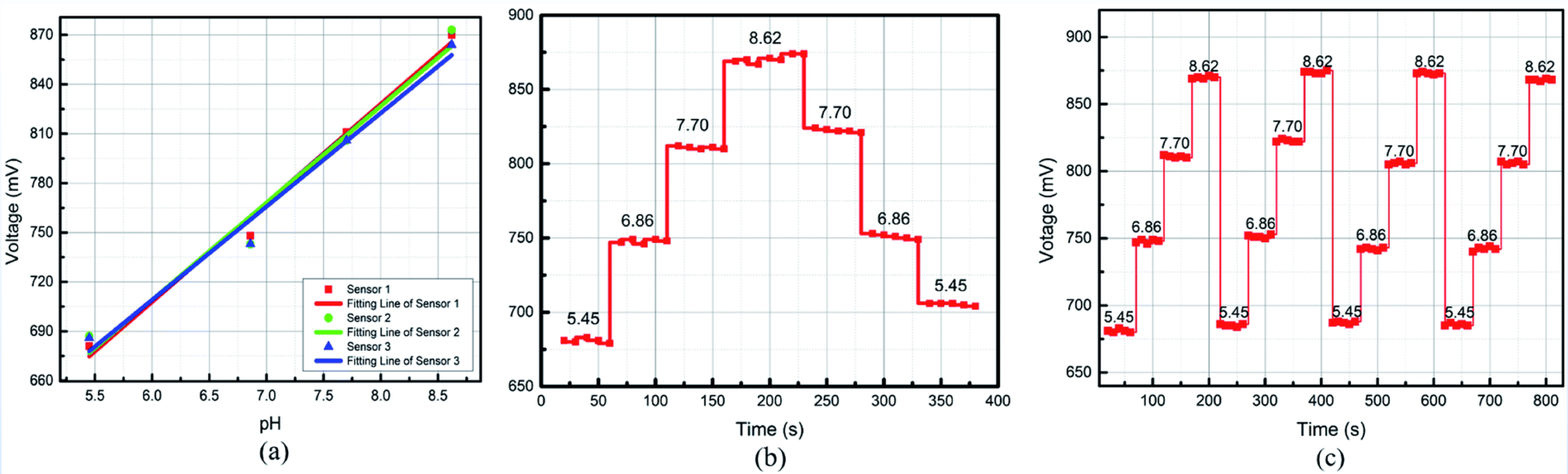
- We use the change in conductivity of Polyaniline (emeraldine phase PANI) with hydrogen ion concentration



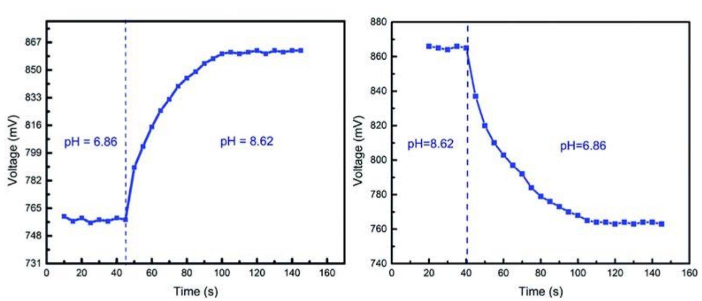




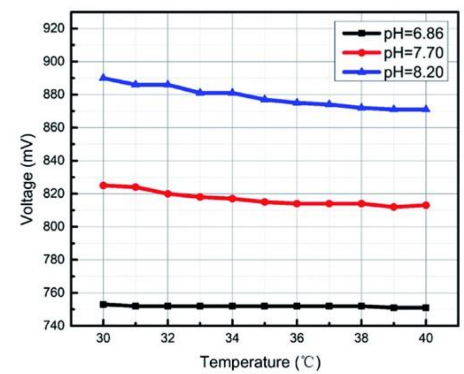
Technical Status: Dr. Axel Scherer, Caltech
Autonomous Microsensors



pH Sensor Lag time



Temperature drift



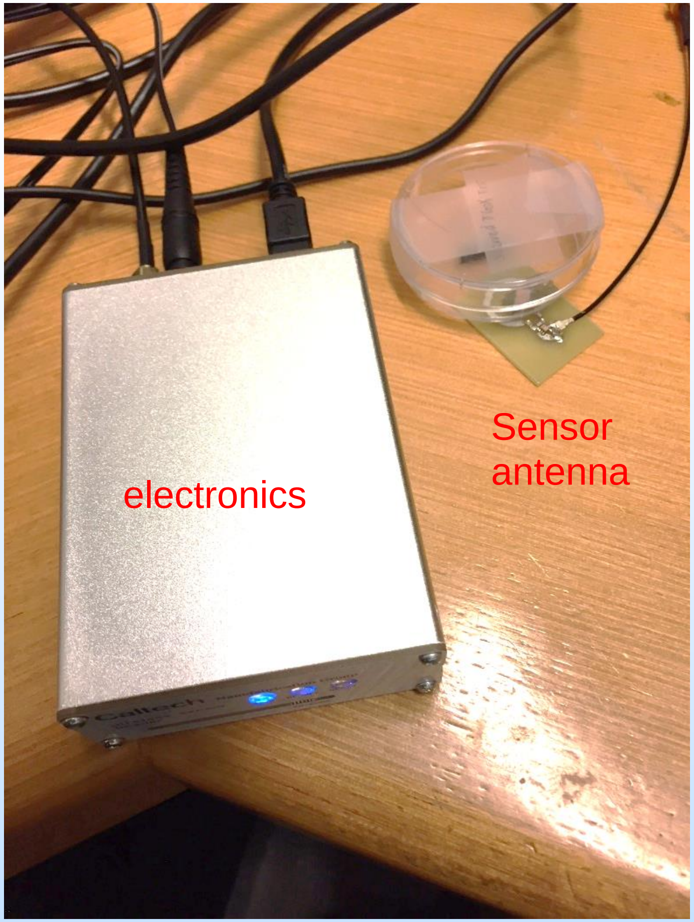
(a)

RF Tag Reader

Technology basis for SNL Smart Collars

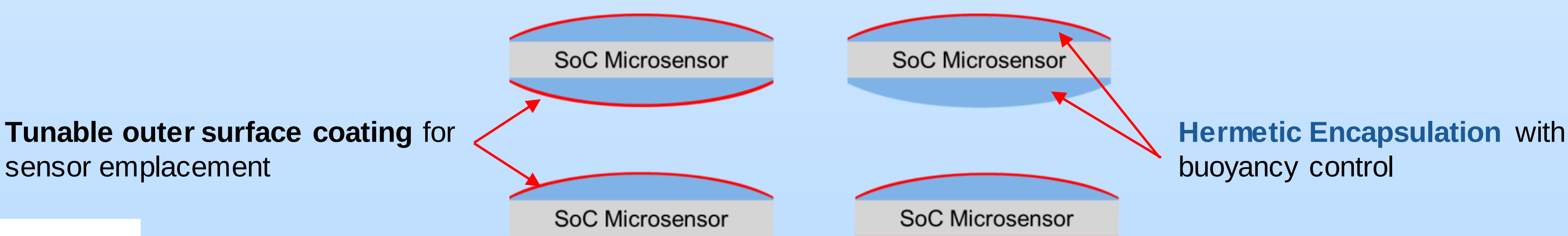
Our RF tag reader powers temperature sensor through near-field inductive coupling at 850MHz.

The sensor uses reflected RF power to communicate back to the reader



Technical Status: Dr. Jeff Mecham
Microsensor Encapsulations, RTI

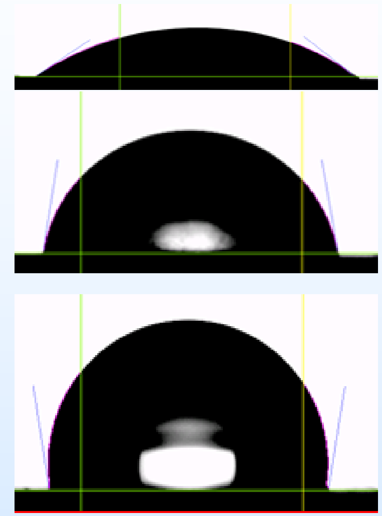
- Task 3 Objective: RTI is developing coating formulations for microsensor systems to enable survival and emplacement direct contact with the formation
  - Subtask 3.1 Encapsulations and Sensor Coatings
    - Develop coatings materials formulations to provide hermetic encapsulation, abrasion resistance 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.

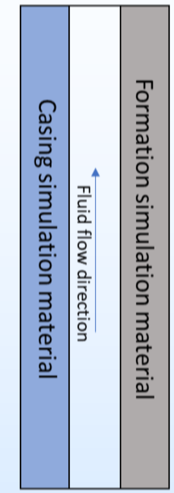


Technical Status: Dr. Jeff Mecham, RTI
Microsensor Encapsulations

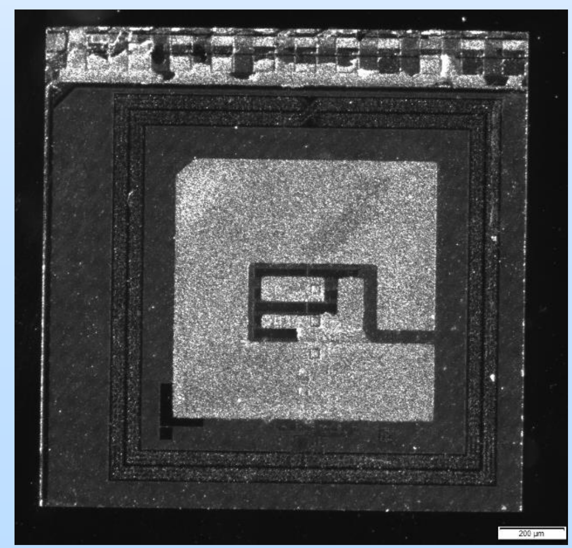
Sensor Encapsulation Progress to Date:

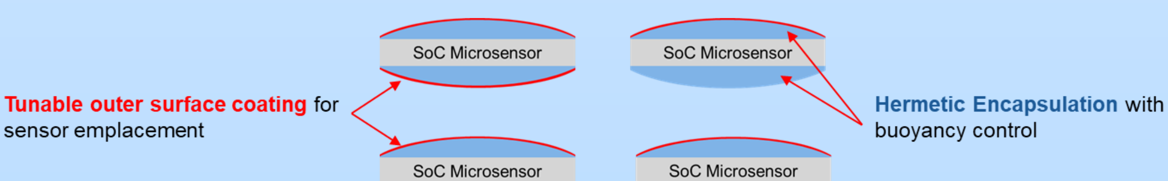
- 3 Low Surface Energy Surface Coating Types Developed
  - Small molecule: cheapest and easiest to apply
  - Particle-based: highest contact angle
  - Polymer-based: imparts impact resistance and can be weighted
- Next Steps
  - Investigate coating application design to determine configuration that provides 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





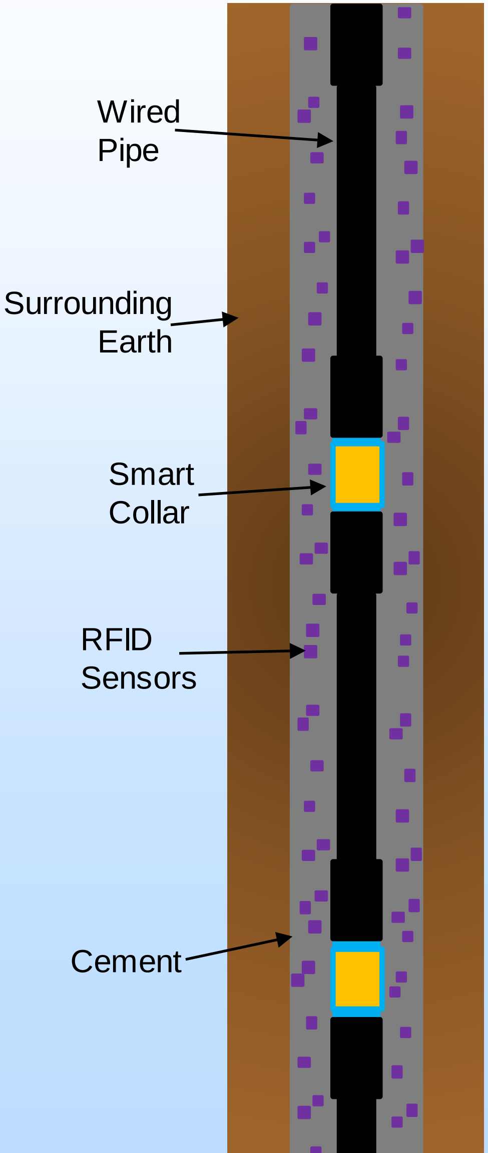
Side view





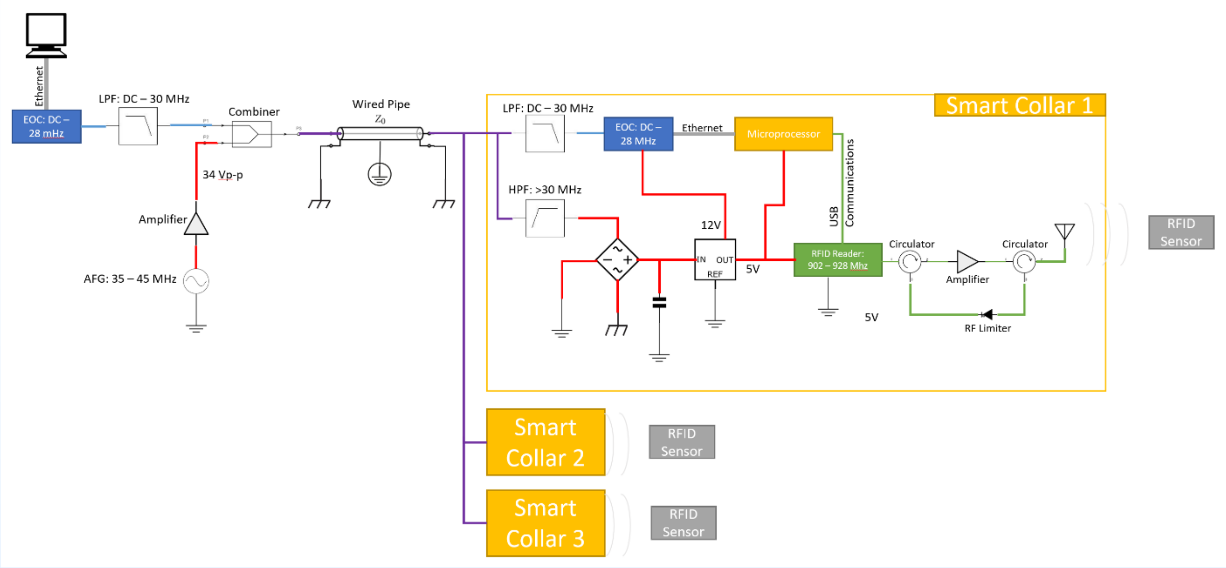
Technical Status: Andrew Wright & Dr. Avery Cashion
Smart Casing Collars and Wired Pipe, Sandia

- 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



Sandia National Laboratories

Smart Collar Communication

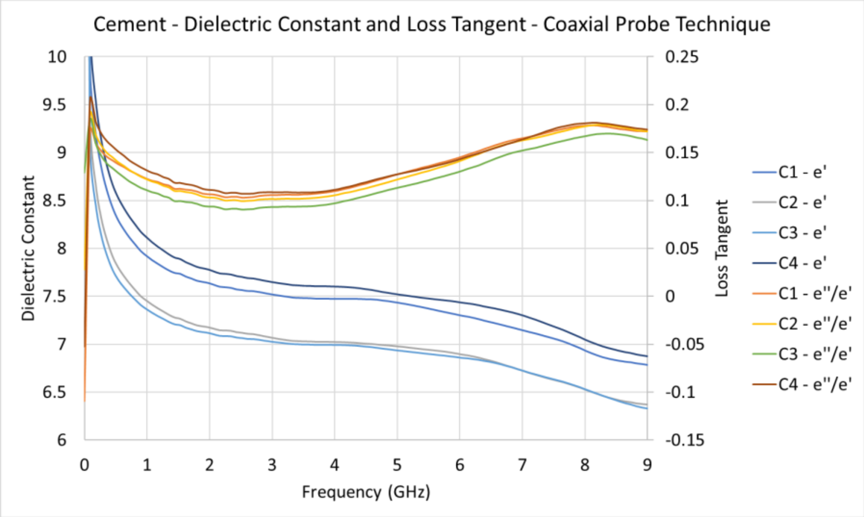


- Communications between computer and Smart Collars
  - Ethernet over coax (EOC) will be used to convert the ethernet signal to a coaxial line, data is then transmitted through the wire pipe
  - Within the Smart Collar the signal is converted back to ethernet to the internal microprocessor, that communicates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

Open-ended Coaxial Probe Technique



Technical Status: Dr. Mohsen Ahmadian
Field Experiment, Bureau of Economic Geology

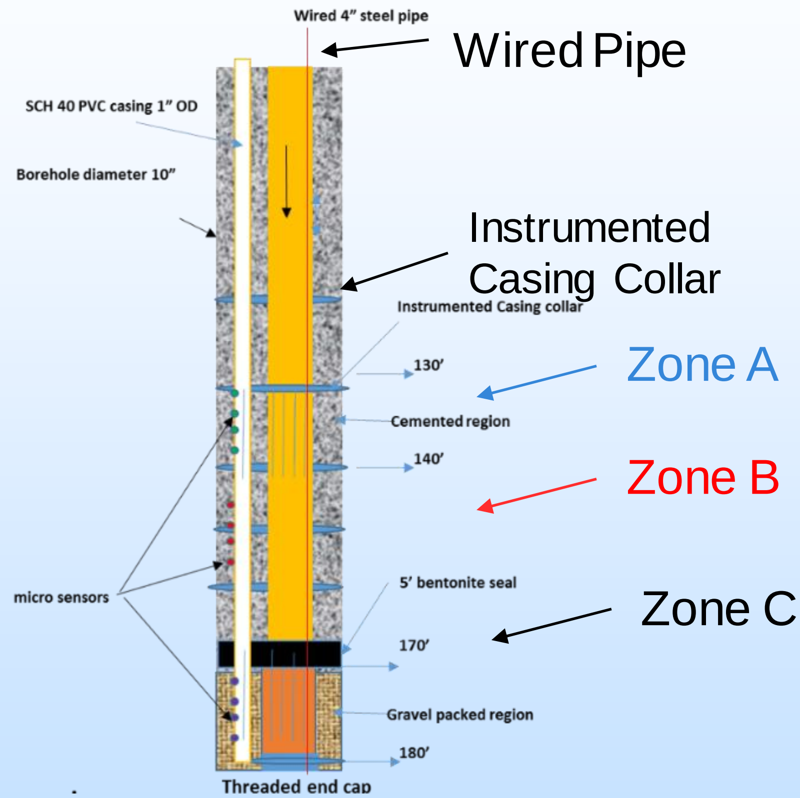
Instrumented Test Well- Design

Simplified test plan:

- 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)



BUREAU OF ECONOMIC GEOLOGY

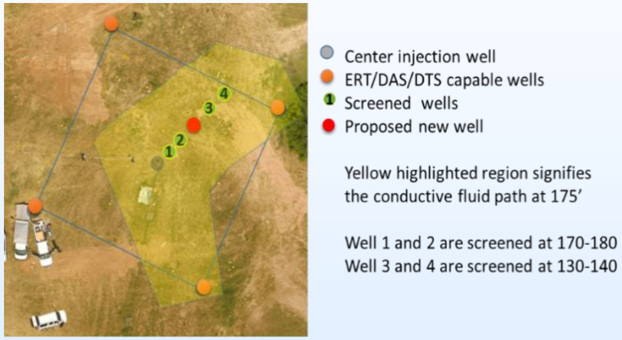
Technical Status: Dr. Mohsen Ahmadian

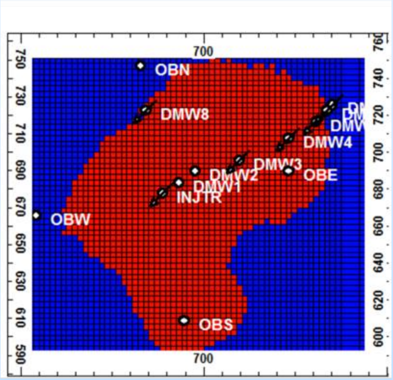
Field Test Plan and Timing, BEG

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 a 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.





Bureau of Economic Geology

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

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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

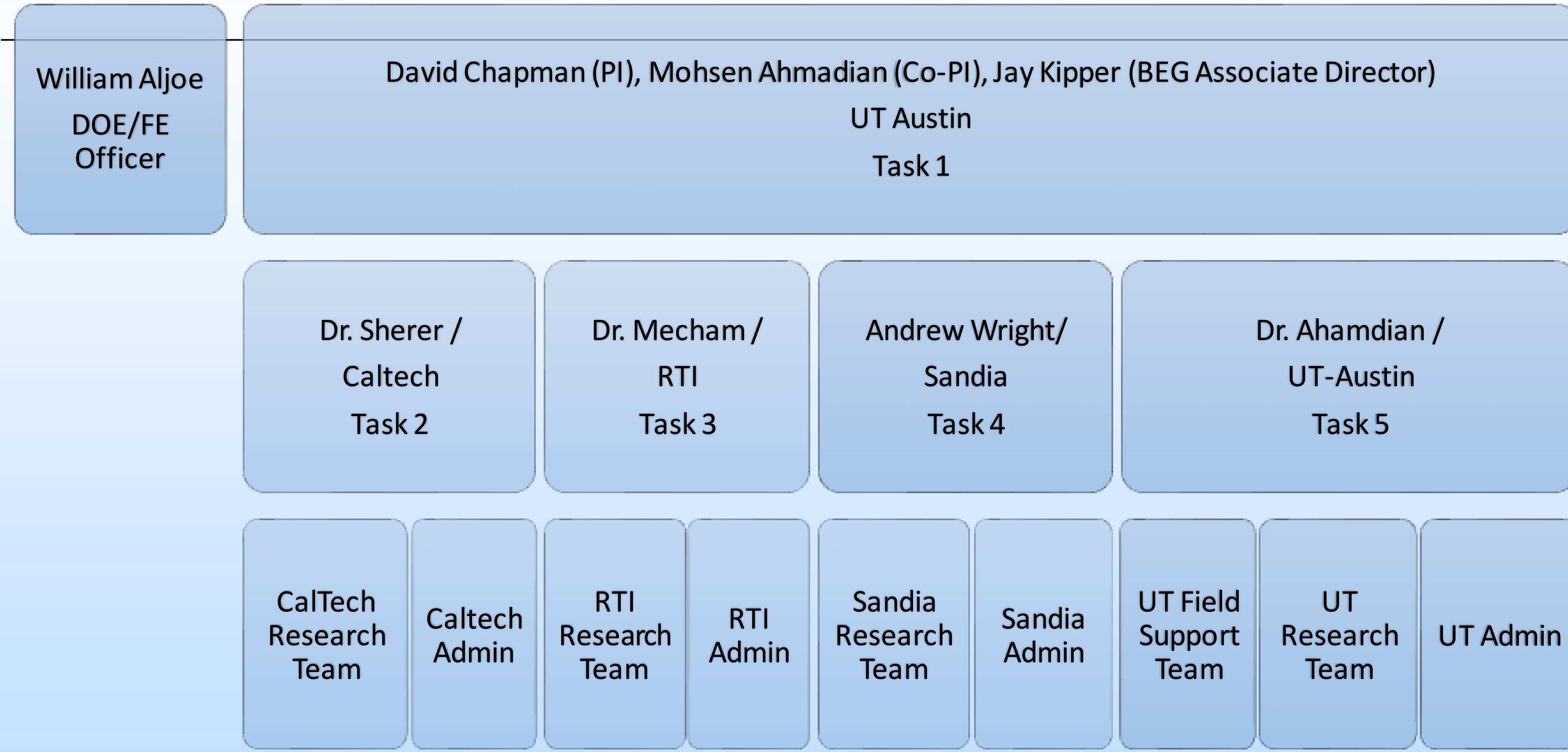
The **objective of this project** is to:

- 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)

Organization Chart



Communications Plan:

- Monthly calls with researchers
- Quarterly Written Reports to DOE

Gantt Chart

Tasks/Subtasks/Milestones		Leaders	Q1 Y1	Q2 Y1	Q3 Y1	Q4 Y1	Q5 Y1	Q6 Y1	Q1 Y2	Q2 Y2	Q3 Y2	Q4 Y2	Q1 Y3	Q2 Y3	Q3 Y3	Q4 Y3
1.0 Research Project Management		Chapman & Ahmadian, UT														
Milestone 1.3.1	Authorization for Selected Field Demonstration Site															
Milestone 1.3.2	Authorization to Conduct Field Laboratory Demo															
Task 2.0 – Autonomous Microsensor Development		Scherer, Caltech														
Milestone 2.2.2	Sensors Survive, Measure, and Communicate in the Lab, Under Relevant Conditions with Adequate Range and Sensitivity (TRL4)															
Task 3.0 – Surface Modification for Reservoir Emplacement		Mecham, RTI														
Milestone 3.2.1	Successful Lab Testing of Coating Technology															
Task 4.0 – Smart Casing Collars and Wired Pipe		Cashion, Sandia														
Milestone 4.1.1	Communications and Power Testbed Set Up at SNL															
Milestone 4.2.1	Laboratory Testing Complete for Full Scale prototype (TRL4)															
Milestone 4.3.1	Field Laboratory Downhole Deployment (TRL5)															
Task 5.0 – Field Laboratory Preparation and Demonstration		Ahmadian, UT														
Milestone 5.1.1	Experimental Plan and Fluid Modeling Complete															
Milestone 5.2.1	Permitting and Vendor Contracting for Construction and the Execution of Field Demo Complete															
Milestone 5.3.1	Field Laboratory Downhole Deployment and Demonstration Complete (TRL5)															

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

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