# Annulus Monitoring of $CO_2$ Injection Using Wireless Autonomous Distributed Sensor Networks

Project Number DE-FE0031856
Carbon Management Research Project Review Meeting
August 28, 2023

**David Chapman & Dr. Mohsen Ahmadian**
University of Texas at Austin

**Dr. Axel Scherer**
California Institute of Technology

**Andrew Wright & Alfred Cochrane**
Sandia National Labs

**Dr. Mustapha Soukri & Nick Huffman**
Research Triangle Institute

---

U.S. Department of Energy
National Energy Technology Laboratory
2023 Carbon Management Project Review Meeting
August 2023

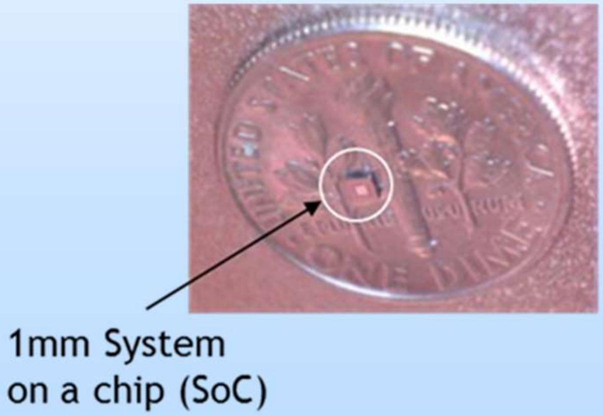
# Presentation Outline

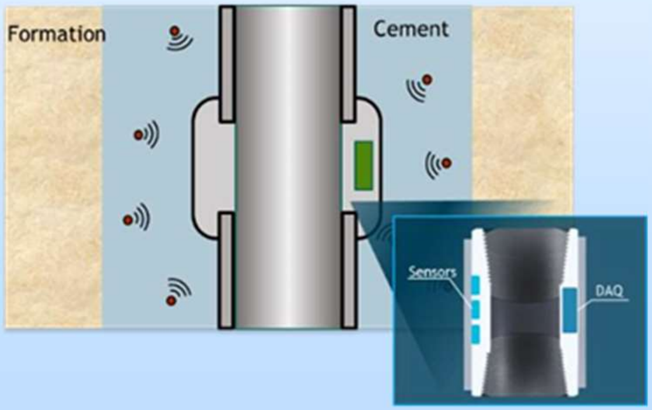
1. Overview
2. Technical Status and Forward Plans
   - Autonomous Microsensors: Caltech
   - Microsensor Encapsulations: RTI
   - Smart Casing Collars and Wired Pipe: Sandia
   - Field Experiment: UT Austin
3. Acknowledgements

# Project Overview

**System Description:** An distributed wireless sensor network system, providing near-wellbore reservoir monitoring in the casing annular space

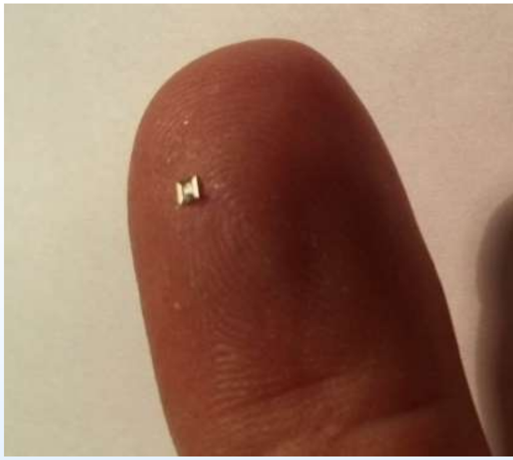
- Millimeter scale autonomous mix of microsensors measuring $CO_2$, pH, and temperature with surface coatings to facilitate survival, transport, and emplacement
- Smart casing collars and wired pipe, to facilitate real-time communications with surface automation



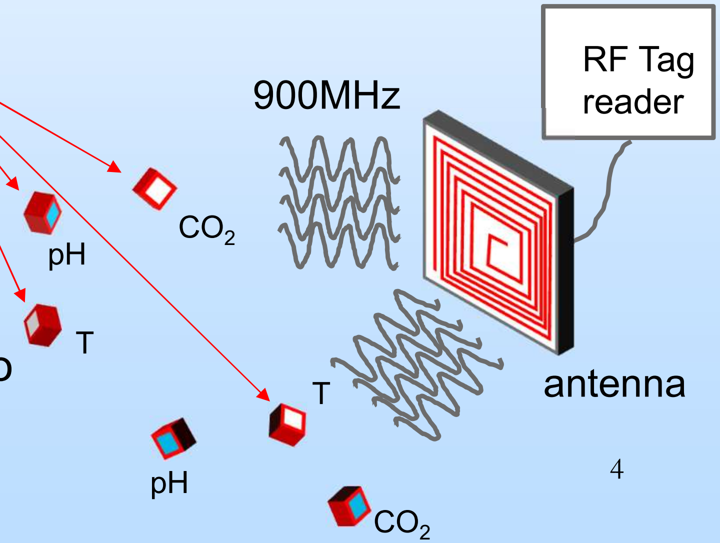

(Left) Sensor systems that communicate wirelessly with casing collars, (Right) providing real-time distributed sensor measurements in the casing annular space, and the formation

# Multi-Functional RF Tag Sensors



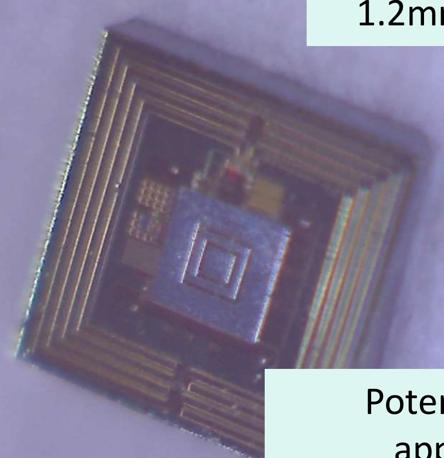
- Potentiostat circuits can be used to measure conductivity changes and currents during electrochemical reactions
- mm-sized CMOS chips can be functionalized to measure
  - Temperature
  - Resistivity
  - pH
  - $CO_2$ and $CH_4$ concentration
- One wireless RF tag reader can obtain information from multiple chips with different functionality
- The CMOS RF tags are powered from the reader and therefore do not require batteries

Individual sensors can be identified by unique tag signals



# Integration of $CO_2$ Sensor with CMOS Electronics, Caltech

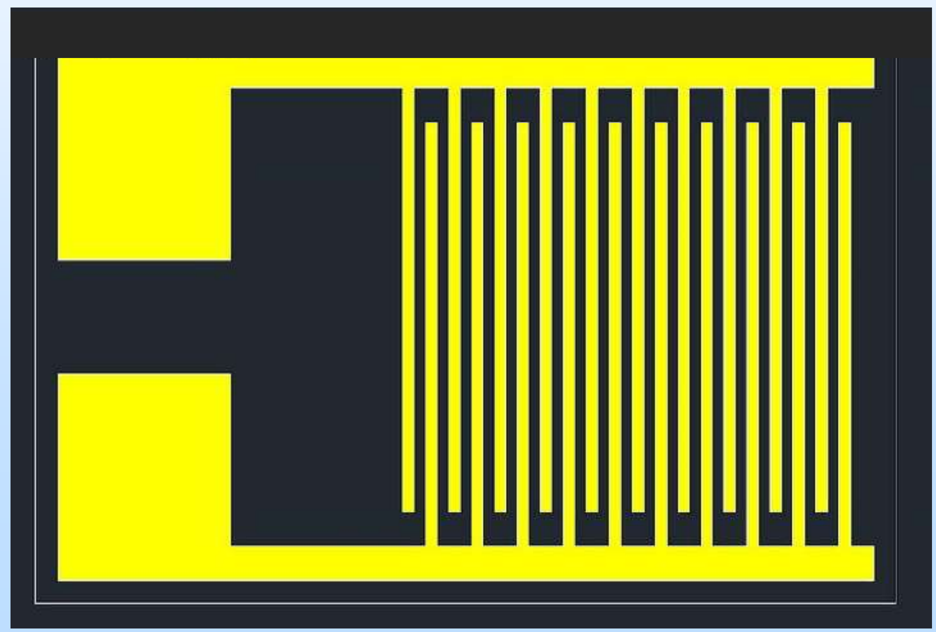
CMOS Potentiostat Circuit with 20,000 Transistors, 1.2mmx1.2mm in size



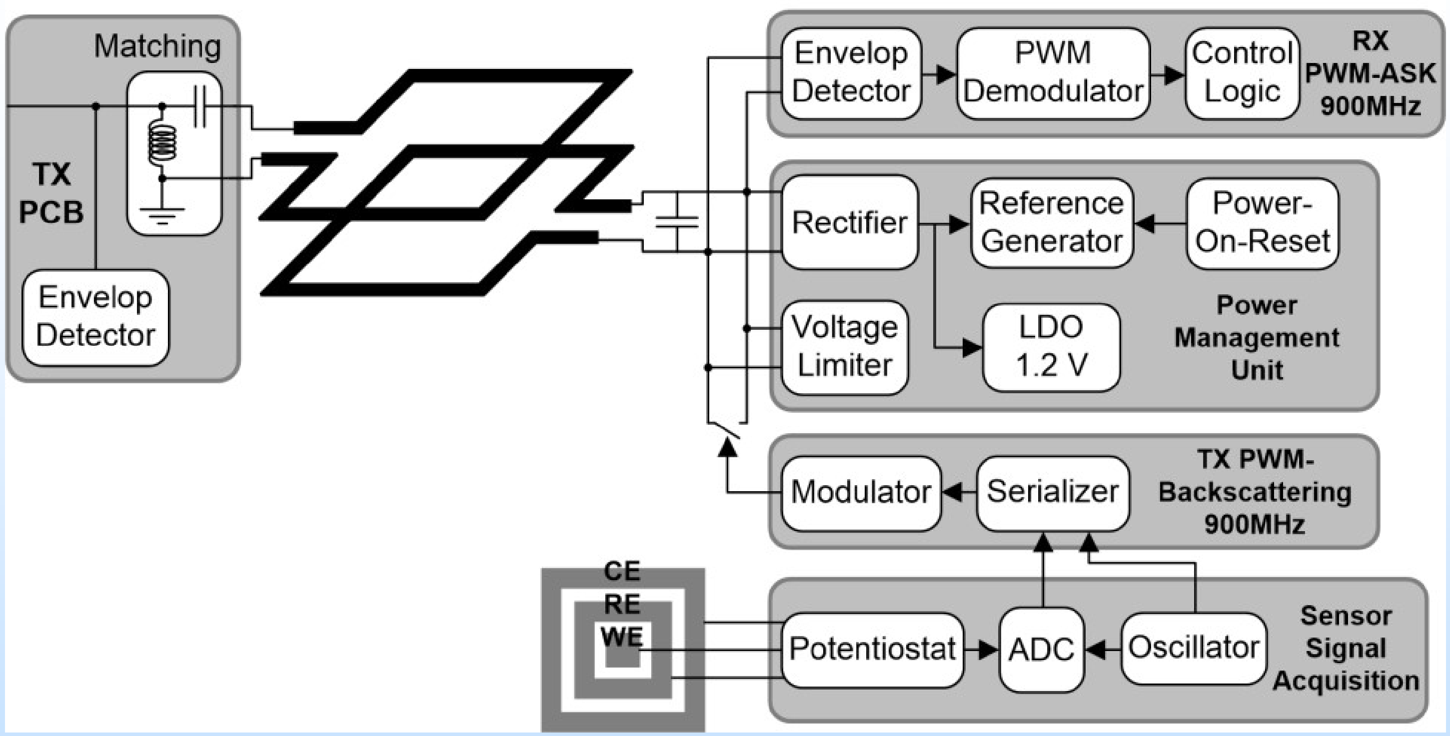
Potentiostat measures approximately 25 nA current – functions as a smart RF Tag, 902-928 MHz

+

Measurement must be measured for decades at ~ 80-120 C at high pressure



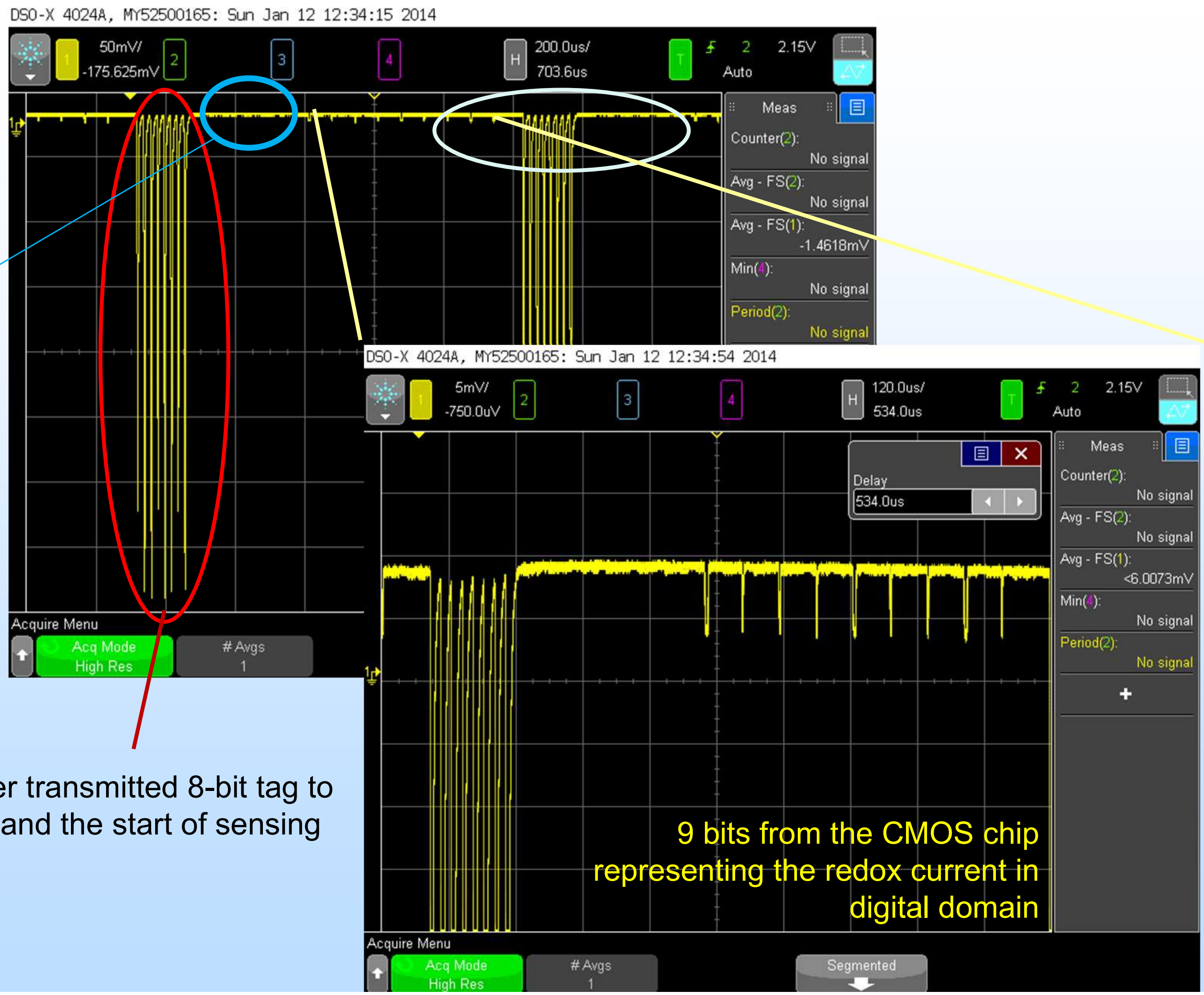
# System Block Diagram




- 900MHz power and data telemetry
- PWM backscattering for uplink communication (Similar to RFID)

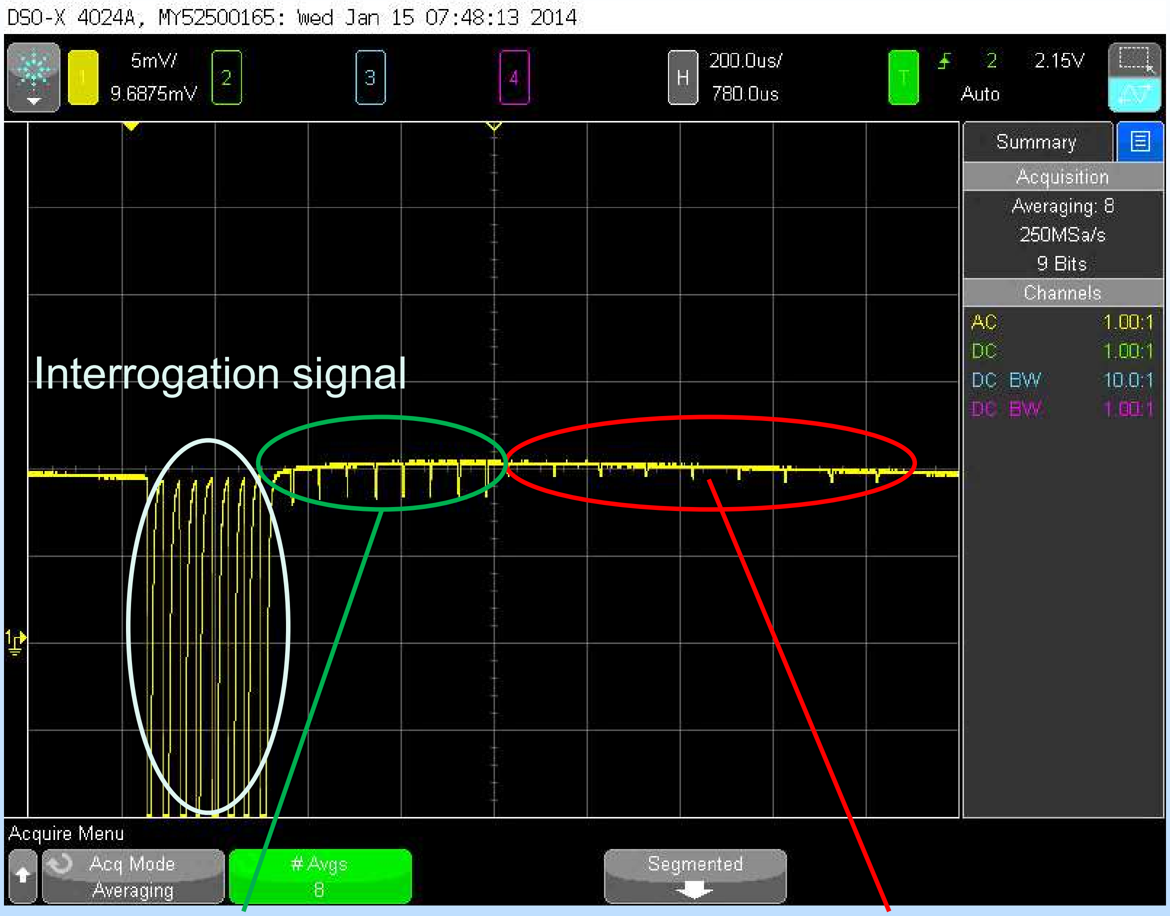
# RF Tag Communications System

Sensor measures and converts it into a 9-bit digital word




Reader transmitted 8-bit tag to command the start of sensing

# Simultaneous Communications with Two Sensors

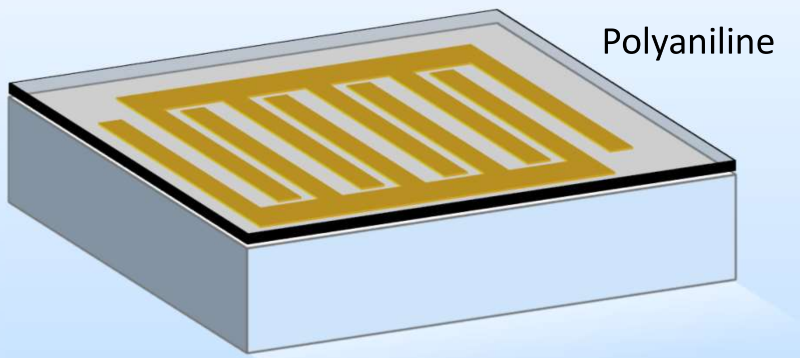



Data from the first device

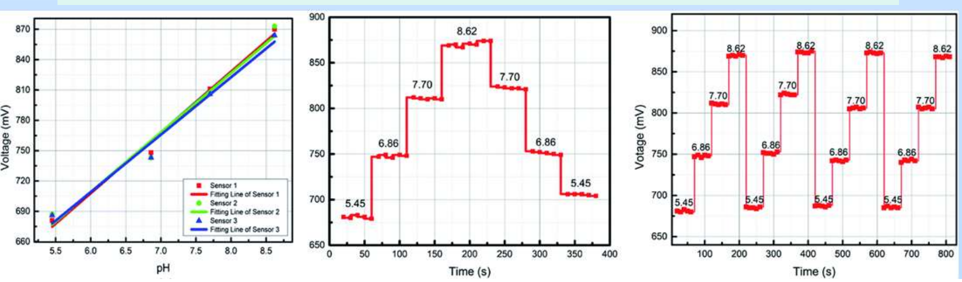
Data from the second device

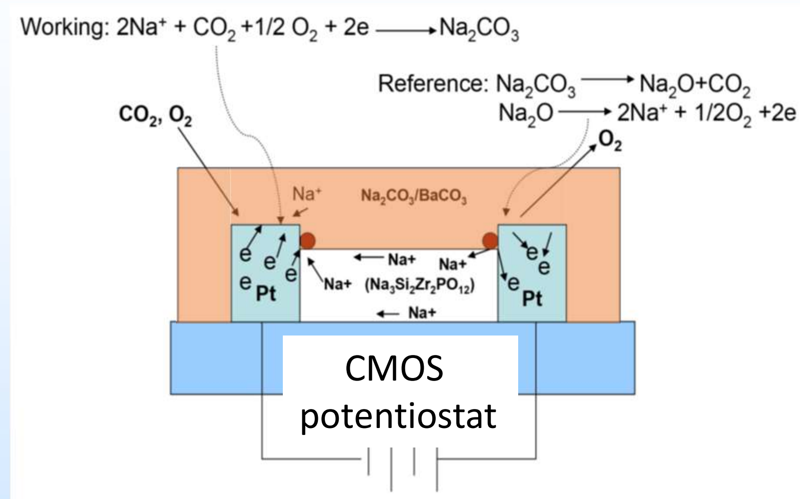
# Measuring pH with Thin Polyaniline Layers and $CO_2$ with NASICON

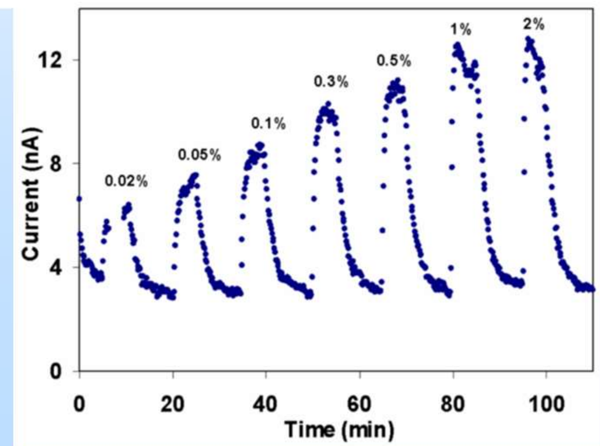
- We use the change in conductivity of Polyaniline (emeraldine phase PANI) with hydrogen ion concentration




Sensitivity ~60 mV/pH Hysterisis response Repeatability Test



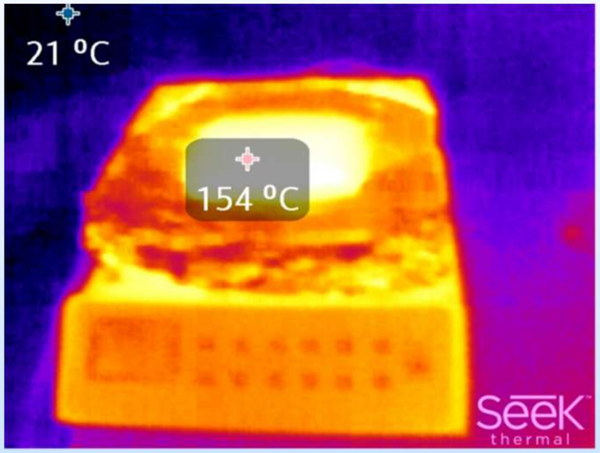



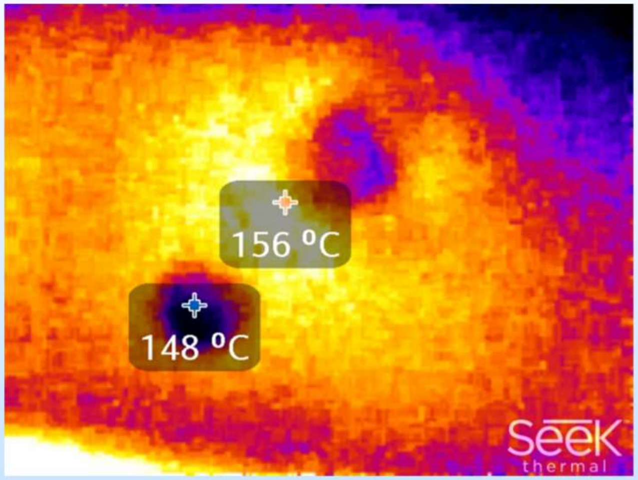



# Thermal Survivability Results

RF communication was confirmed successful while sensor chip was resting at 150° C

Most analog circuit functions could be measured even above 175C.



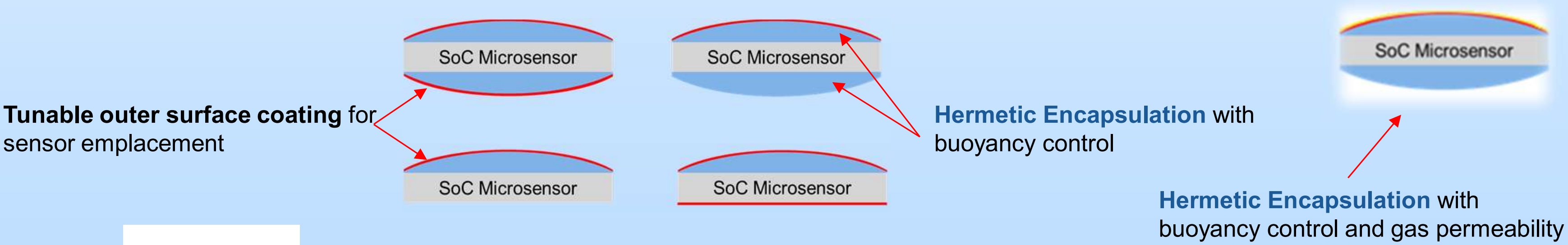




**Higher temperatures did not permanently damage the chip, it would begin communicating again afterwards.**

# Microsensor Encapsulations, RTI

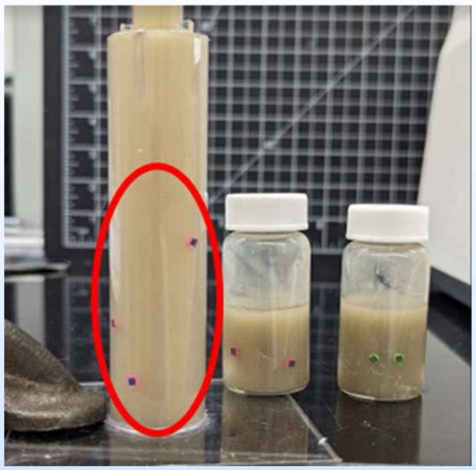
Task 3 Objective: RTI has developed coating formulations for microsensor systems to enable their survival and to facilitate their physical emplacement near the formation

- 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; consider encapsulation location and coating application technique
- Best performing materials have been down selected and applied to working sensors at the end of Year 1. Coated functioning SoC sensors were developed and demonstrated at the end of the first year of the project.

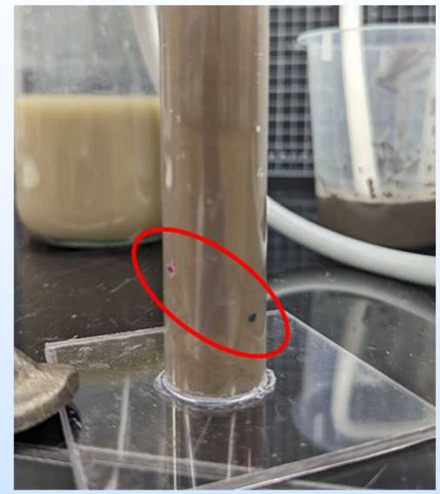


# Microsensor Encapsulations, RTI

## Demonstrated sensor emplacement throughout lab simulated cementing process

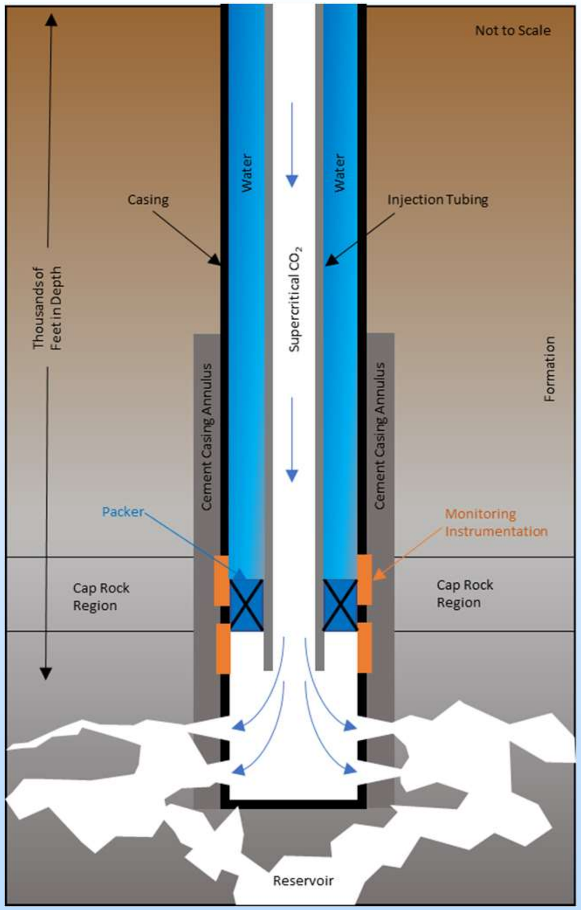


Peristaltic pump to pump Quick Gel and tubing (left) and the resulting emplacement (right, circled in red) Note that acrylate coated test samples remain emplaced and intact one month later (in borosilicate vials, right).



TXI lightweight cement was injected into the polycarbonate tubing with a peristaltic pump (left). The phantom sensors remained emplaced (circled, right) and intact throughout the cement injection procedure demonstrating sensor emplacement.

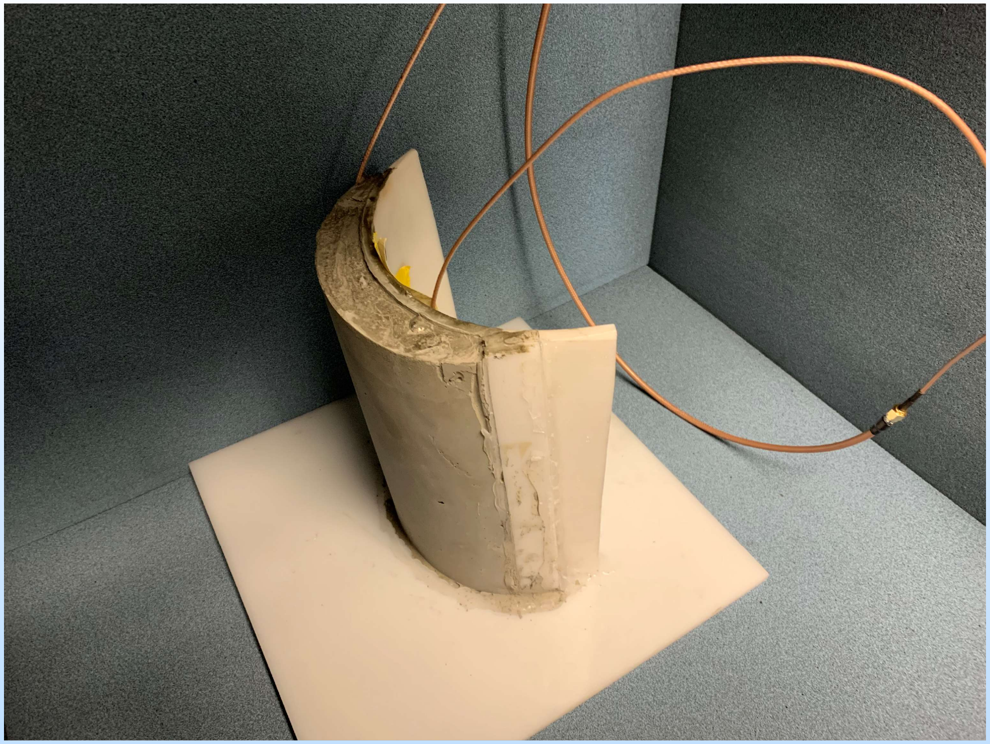
# Smart Collar Technologies, Sandia



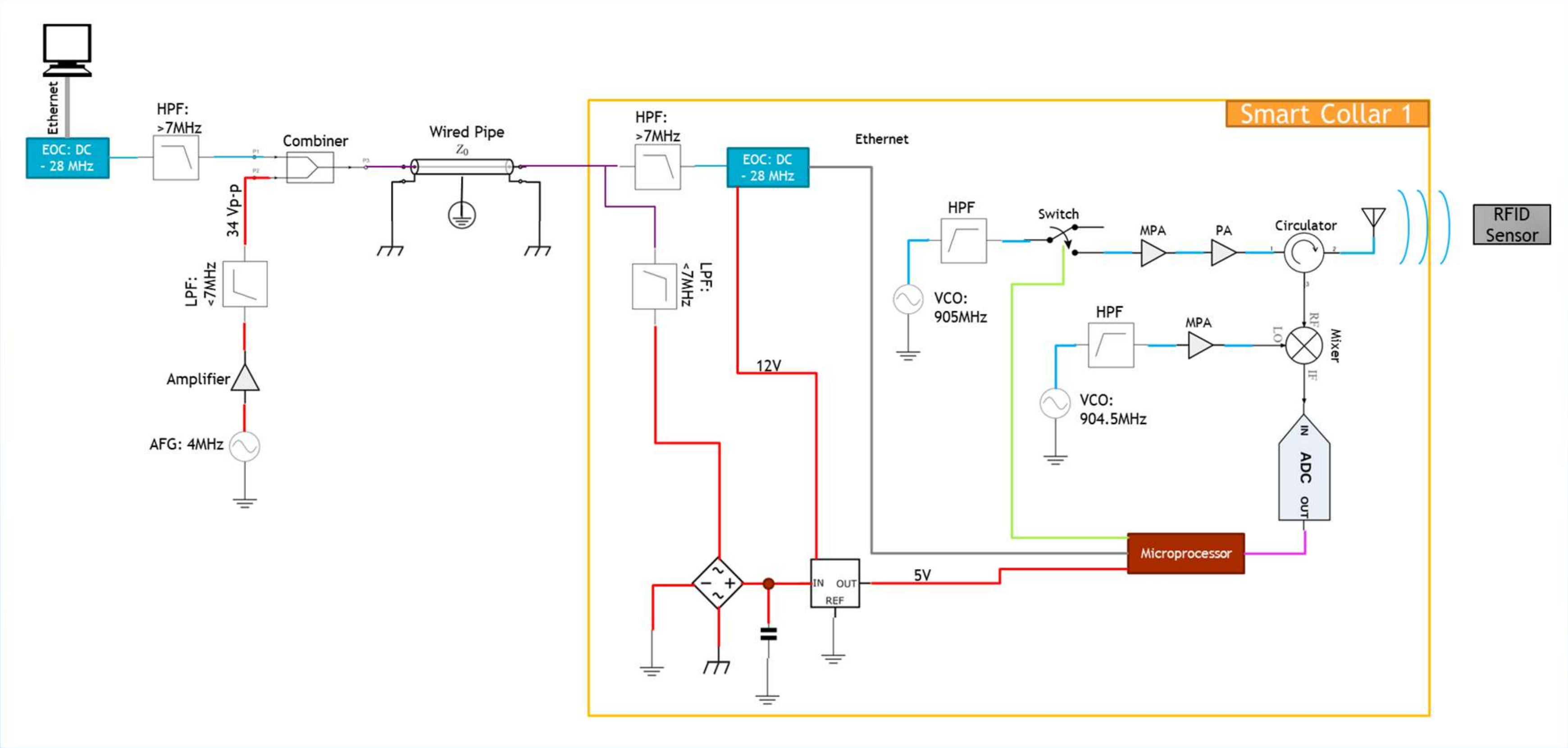

- Smart Collar communicates with the surface and receives power
  - Utilizes IntelliServ's wired pipe
  - Instrumentation inductively couples with wired pipe
- Smart Collar wirelessly communicates with Caltech's RFID sensor
  - Propagates signal through cement casing to embedded RFID sensors

# COTS RFID Cement Lab Experiments

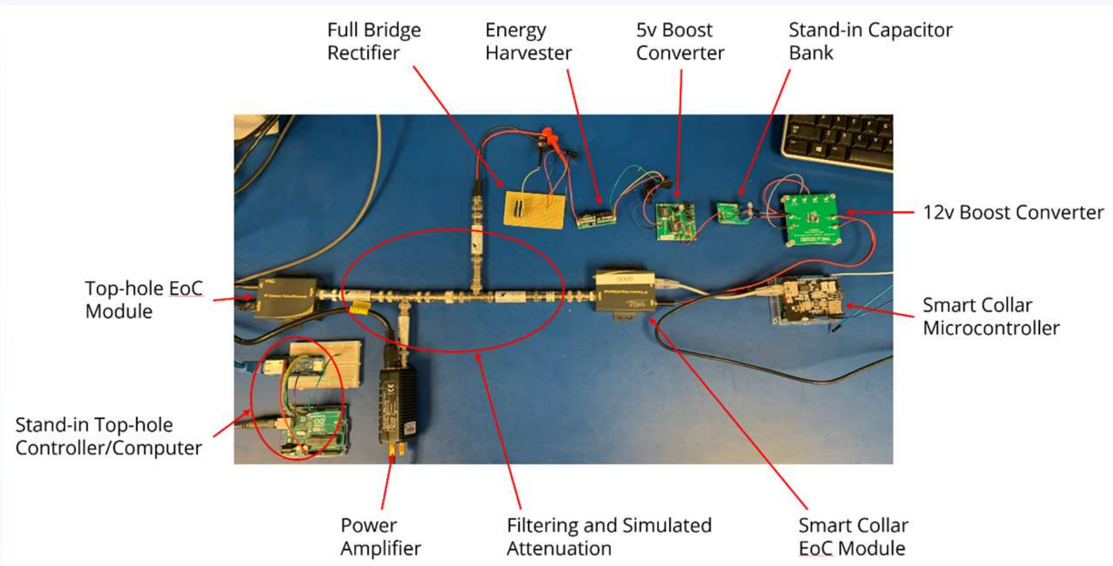
- Demonstrated RFID communications
  - COTS RFID Tag and Reader
  - 1” Cement
  - Circular polarized antenna

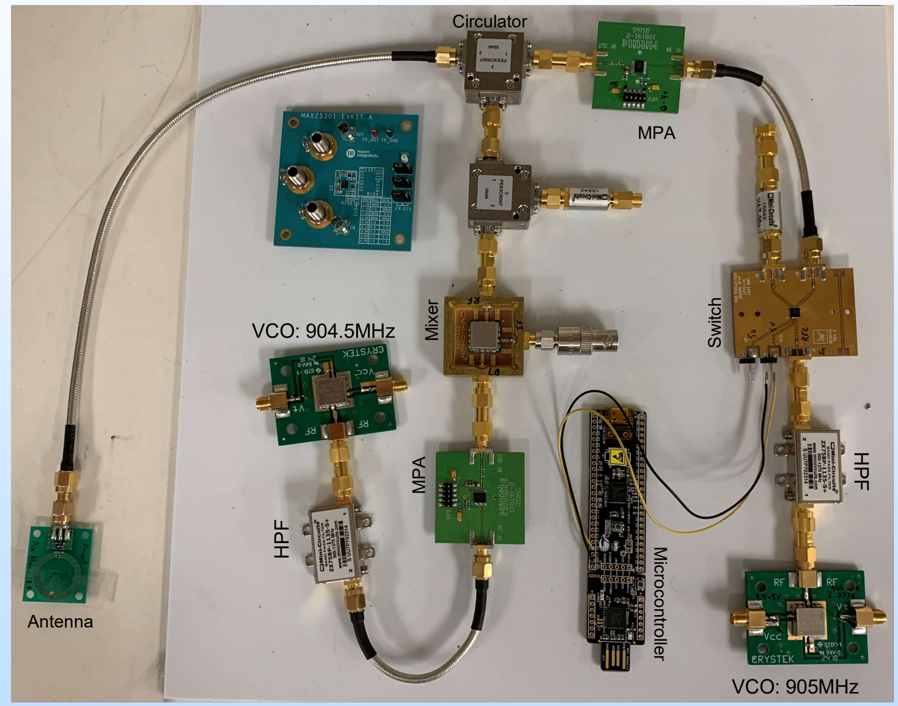


# Smart Collar and Wired Pipe Schematic



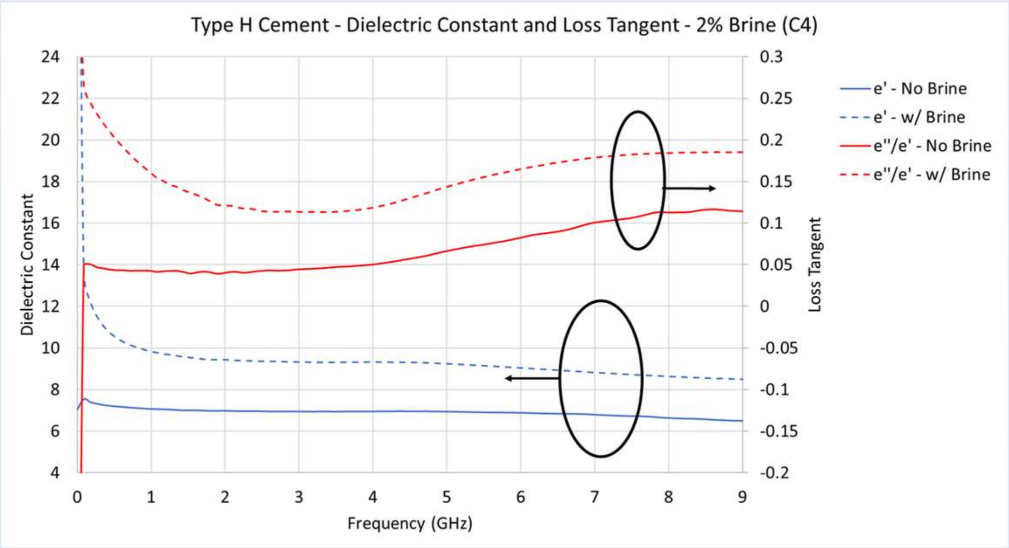
# Communications and Power

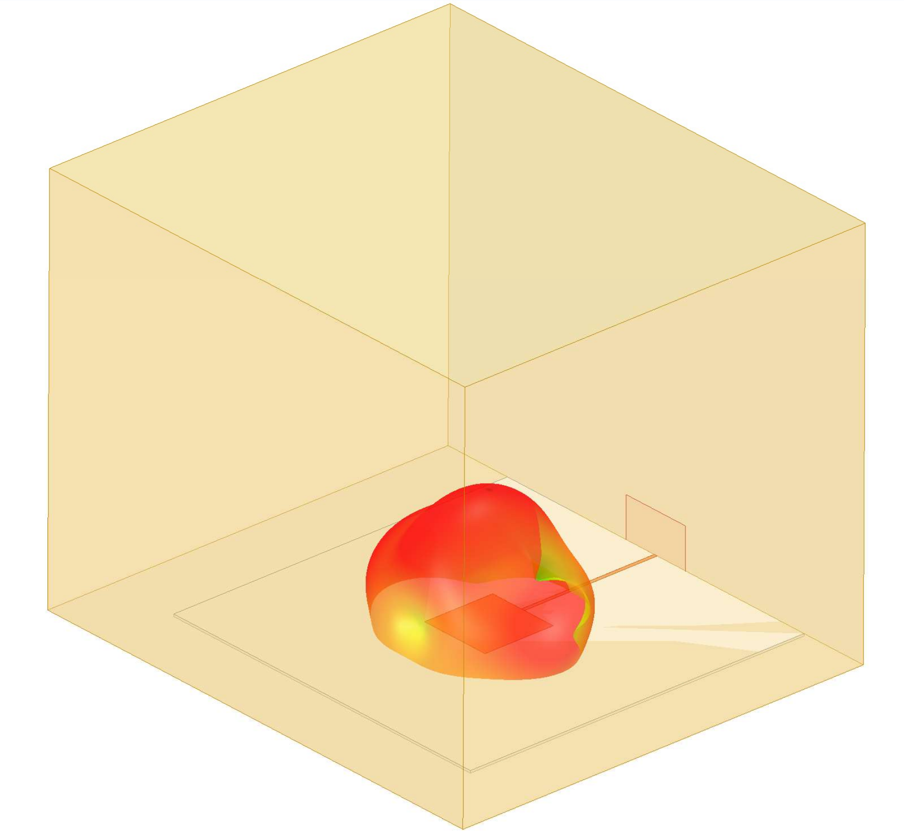


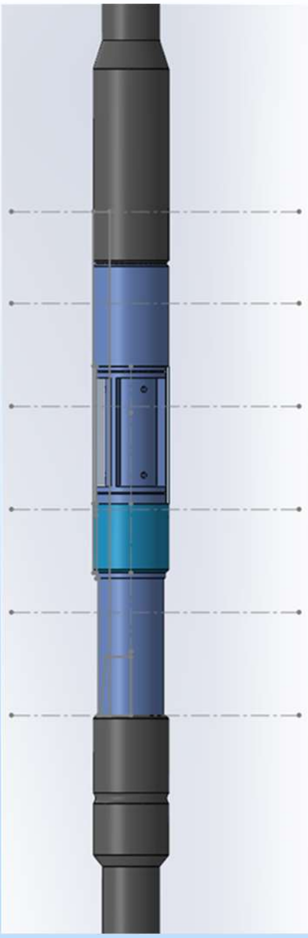
# RF Cement Antenna

- Simulated Patch Antenna
  - Tuned to cement
  - Alumina substrate



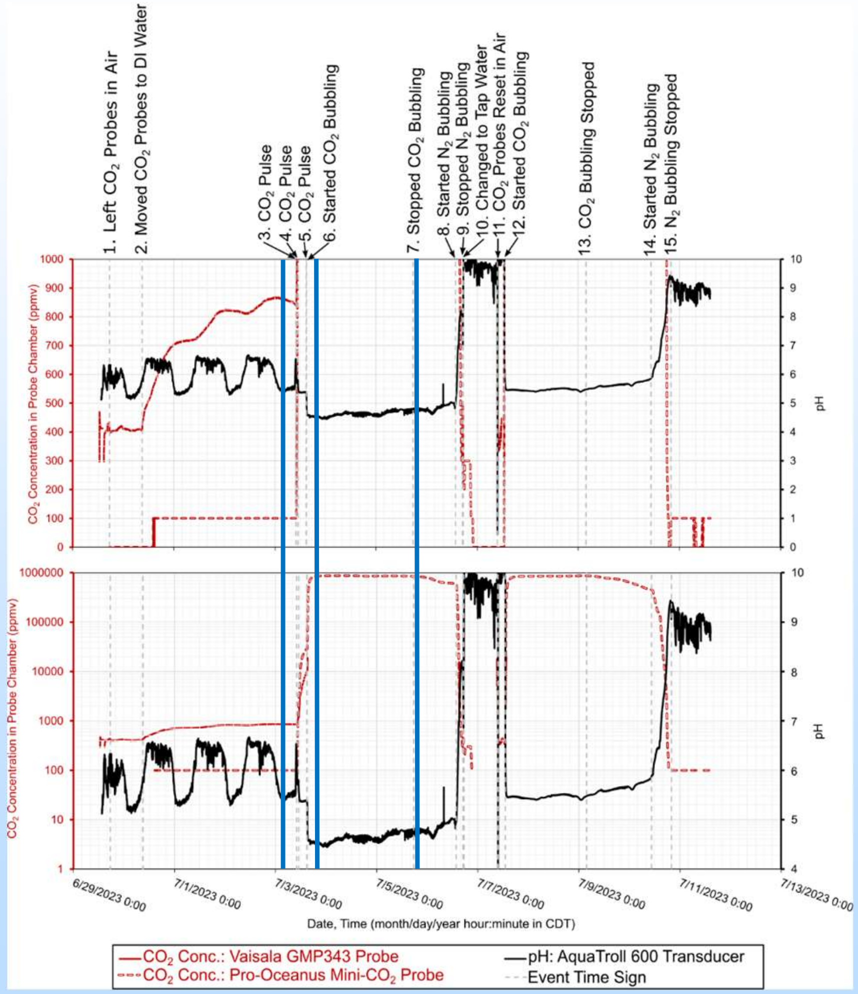



# Smart Collar Housing



- Threads and inductively couples onto wired pipe
- Compartment for electronics
- Shell will be notched to accommodate the custom antenna
- ~ Five feet in length

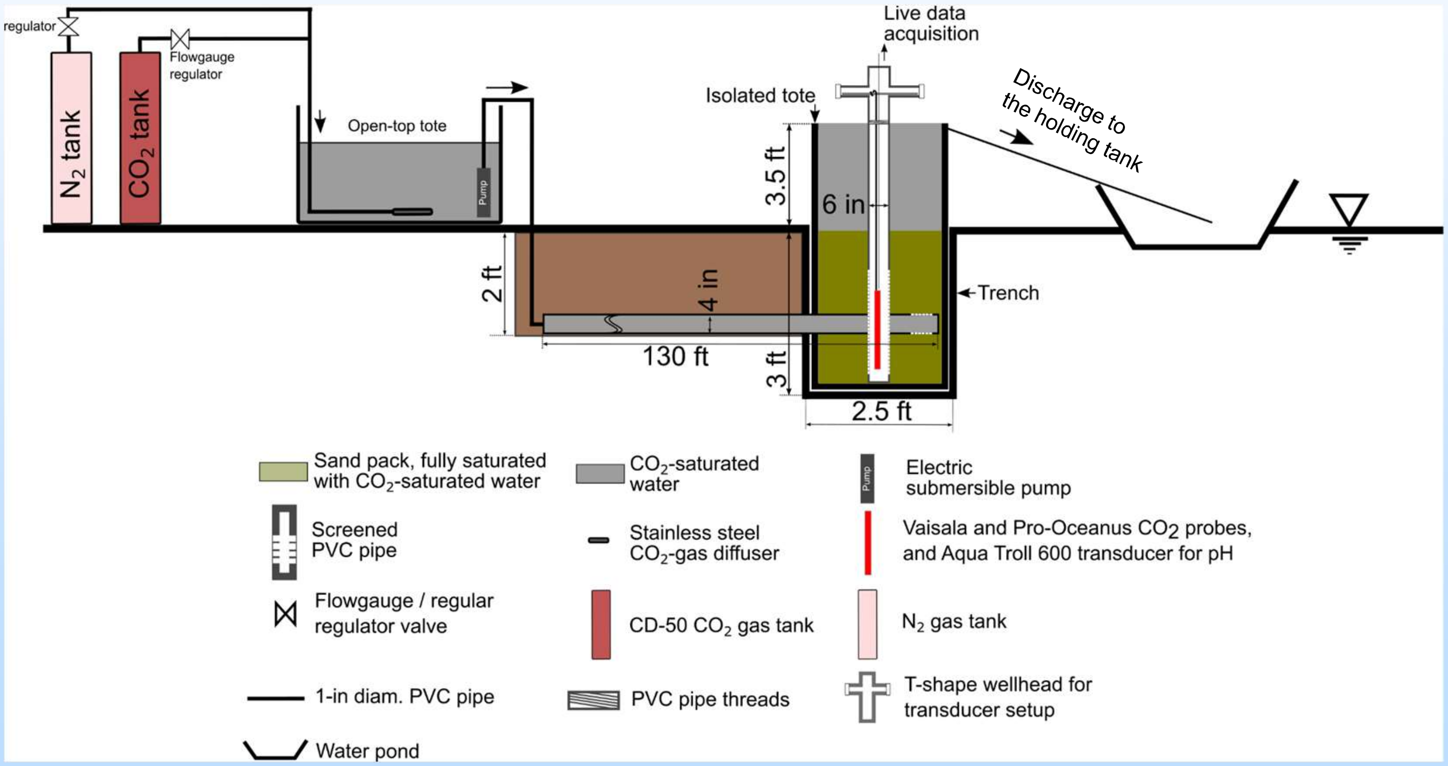
# Monitoring of $CO_2$ Concentration in Water Using Two Reference Probes and a pH Probe, Evaluated in $CO_2$ Bubbling Experiments




- Verified Vaisala's GMP343 probe for 0-2% v/v, and Pro-Oceanus Mini-$CO_2$ probe for 0-100% v/v.
- Consistent measurement of $CO_2$ conc. increase by both probes during $CO_2$ pulses.
- Verified $CO_2$ conc. recordings using Phreeqc models at 3 points (blue lines).

# Devine Test Site Experiment Design for Monitoring of $CO_2$ Concentration in Downhole Conditions Using Reference Probes

- Injection of fully saturated water with $CO_2$ into a sand pack, simulating downhole conditions, through a buried casing, and monitoring of $CO_2$ concentration using reference $CO_2$ probes.
- The under-construction $CO_2$ microsensors and data-acquisition collar will be deployed inside the simulated downhole, and their performance will be evaluated in comparison with the reference probe measurements.



# Next Steps

Prepare sensors and casing collars for field experiment:  Compete temperature sensor post fabrication, optimize deposition methods for Nasicon and fabricate $CO_2$ sensors, fabricate pH sensors, fabricate casing collar

Create hermetic encapsulations with buoyancy control and gas permeability for NASICON sensors

Complete simulation and planning for field experiment and conduct field experiment

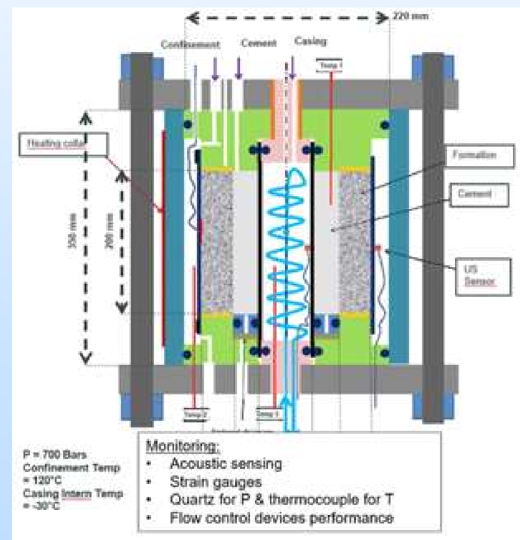
# Future Potential

Harden sensors for harsher environment testing with industrial partner

Improve wireless robustness and communications/power distances

Investigate power harvesting for casing collars

Test prototype system at depth and look at Methane and Hydrogen applications




AEC
ADVANCED ENERGY CONSORTIUM

# Funding Statement

This presentation describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the presentation do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

# Acknowledgments

Funding for this project provided by DOE Fossil and NETL. Early development on the microsensors was funded by the BEG's Advanced Energy Consortium. Wired drill pipe used under this effort was purchased from IntelliServ. SNL would like to thank IntelliServ for allowing to utilize the wired pipe technology to enable this new approach for Carbon Sequestration subsurface monitoring. We also deeply appreciate contributions by Mahdi Haddad from BEG, the support and guidance of our program manager Natalie Iannacchione, and conversations with the AEC and its member companies.

We will have a demo Tuesday evening with sensors and readers to demonstrate this concept and our vision. Please come by for a conversation!

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

AEC ADVANCED ENERGY CONSORTIUM