Annulus Monitoring of CO_2 Injection Using Wireless Autonomous Distributed Sensor Networks

Project Number DE-FE0031856
Carbon Management Research Project Review Meeting
August 5, 2024

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U.S. Department of Energy
National Energy Technology Laboratory
2024 Carbon Management Project Review Meeting
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Funding Statement

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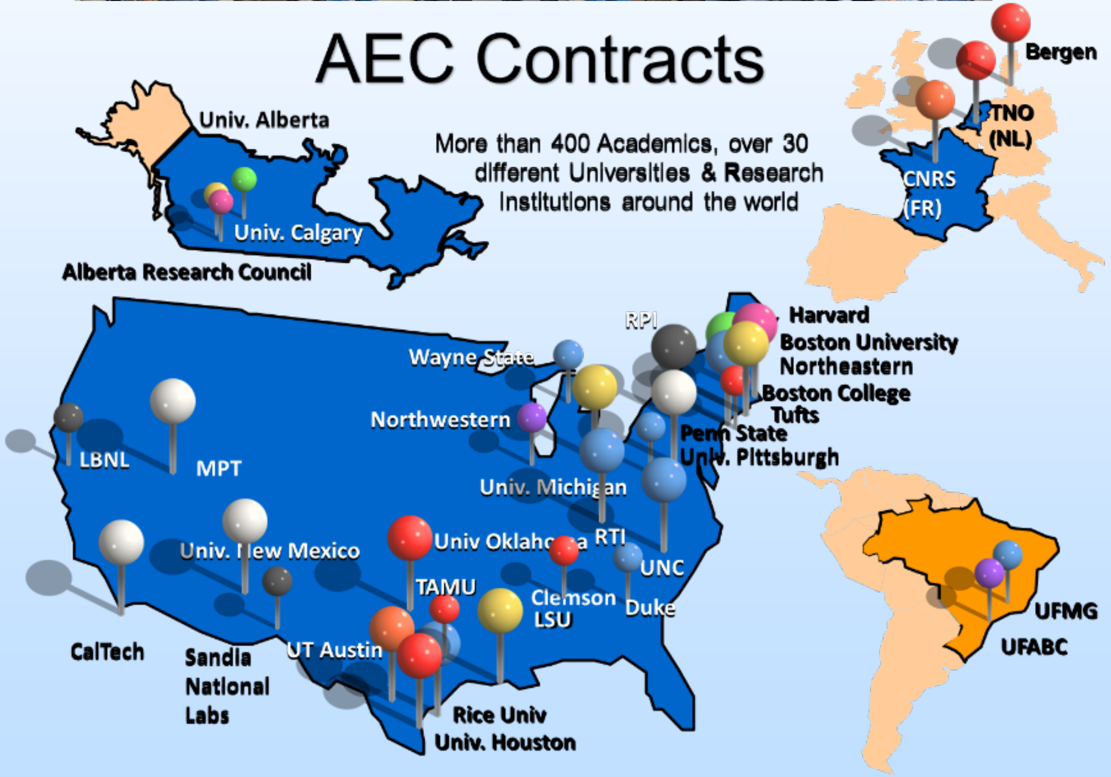
Presentation Outline

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

Mission:

Develops disruptive nanotechnologies for transformational improvements in subsurface sensing, energy production optimization, and environmental protection

Success Means: Invest in cultivating Mission-Driven Leaders and Leverage our stakeholders' resources to Expedite the Availability of AEC Technologies in the Market



ExxonMobil Shell TotalEnergies

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A Few of AEC's CCS MRV Programs

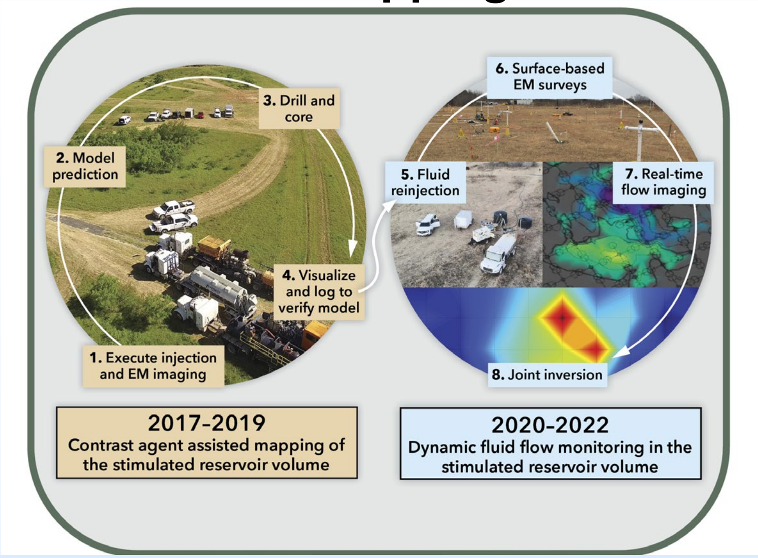
Microsensor Platforms

System on a Chip (1mm)
- Temp, Press, Resist, pH
- Thin film packaging
- RF powered, battery-less,
- 30yr lifetime

Stacked Chip (5-12mm)
- Temp/Pressure/Time 5Hz freq.

Includes miniaturized HighTemp rechargeable batteries

Real-time SRV and Flow Mapping



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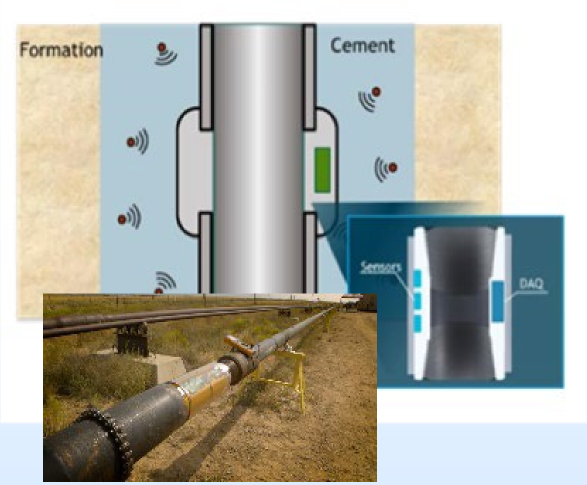
Real-Time Decadal Cement Integrity Monitoring RF

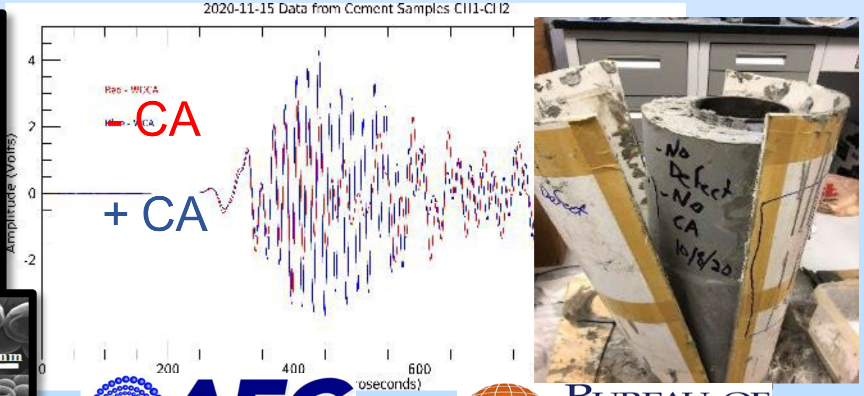
Today's talk



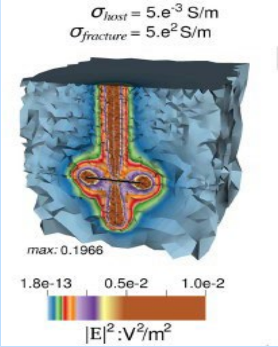
Pipeline and Flowline Monitoring

Smart Additives EM & Acoustic

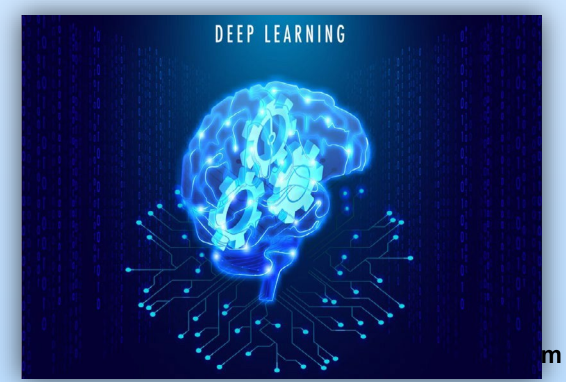
Decadal Cement and P&A Monitoring for Cement Fatigue



Energy Harvesting and Communication RF& Acoustic



ML-AI-Driven Sensor Fusion Analytics



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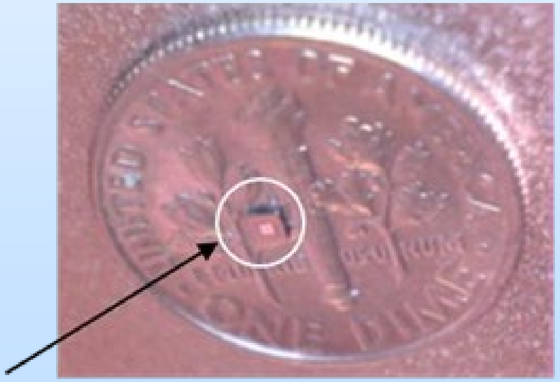
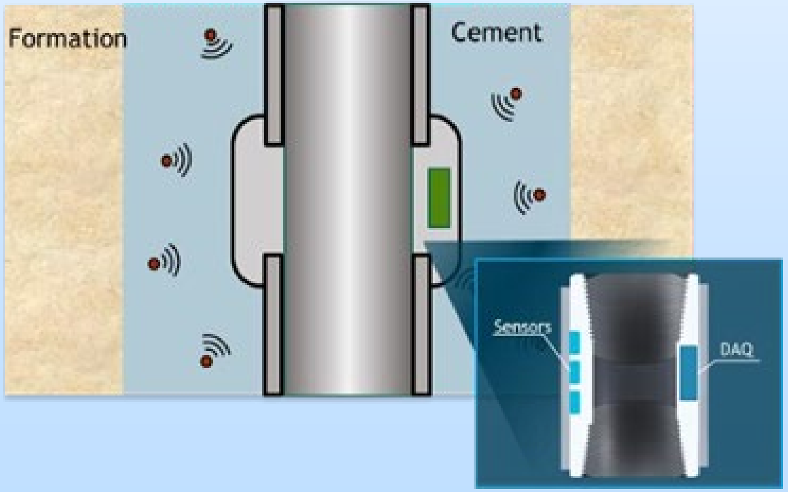
Project Overview

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, 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

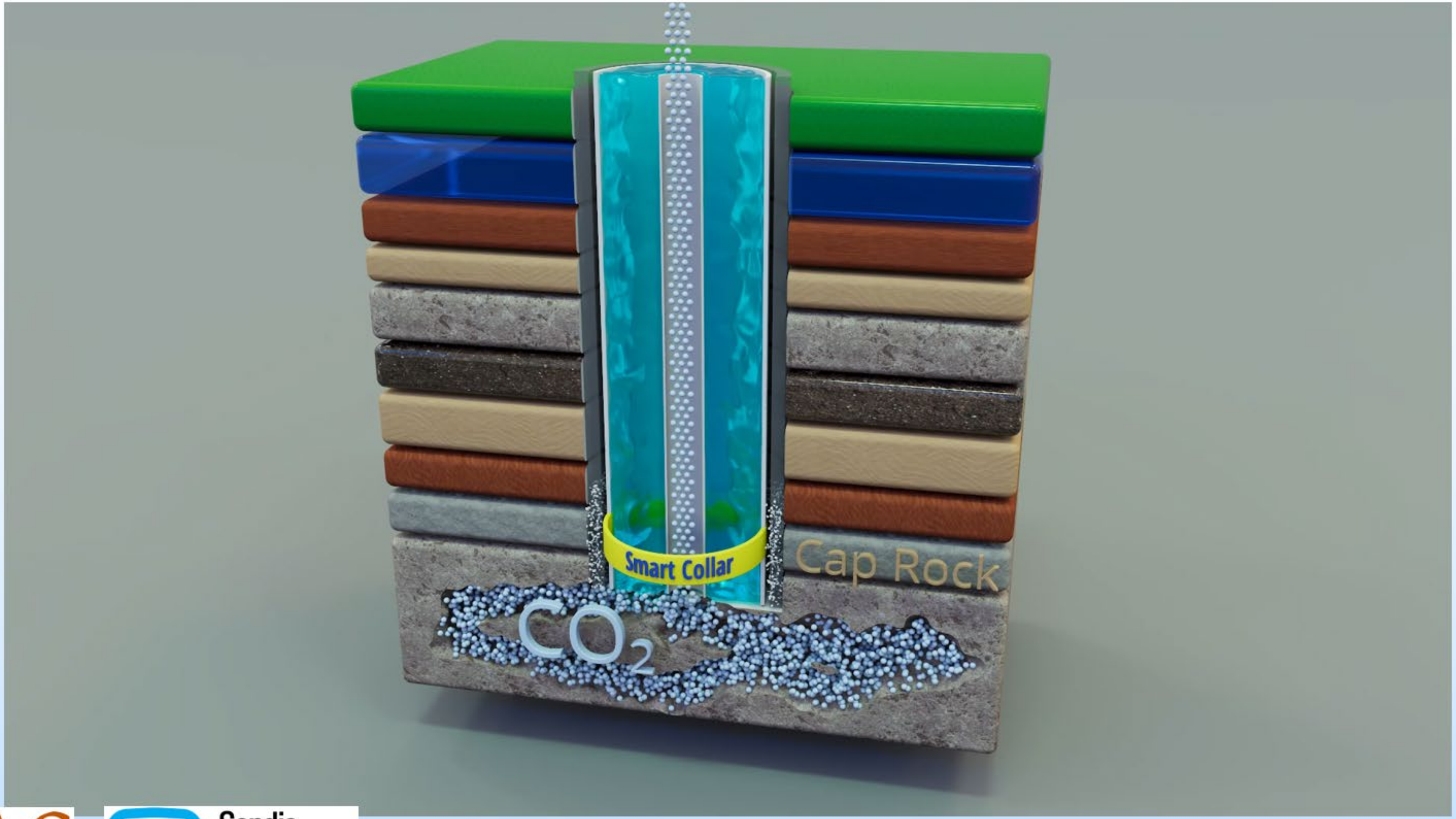


1mm System
on a chip (SoC)



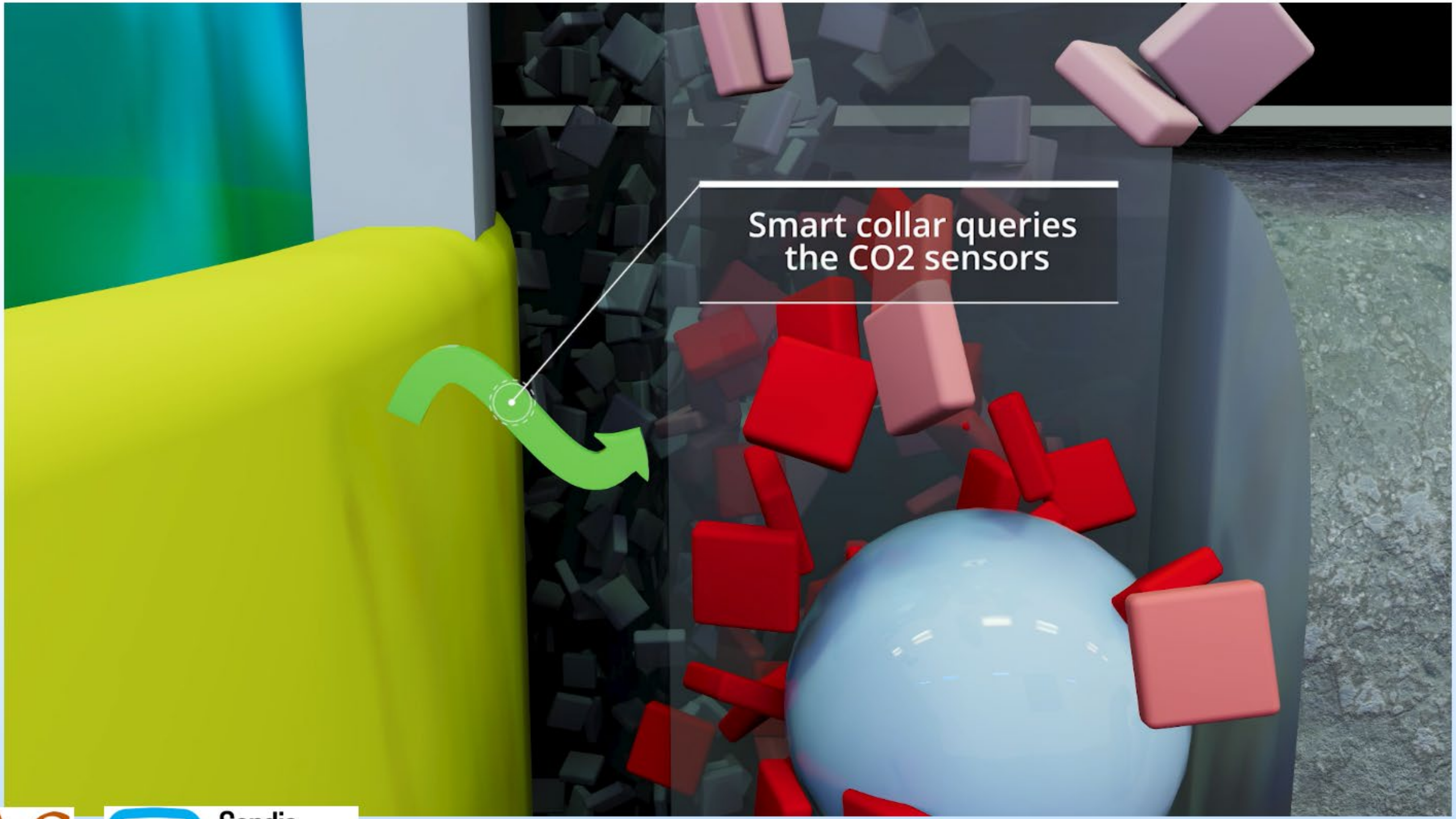
(Left) Sensor systems that communicate wirelessly with casing collars, (Right) providing real-time distributed sensor measurements in the casing annular space, and the formation

Project Overview



https://newsreleases.sandia.gov/smart_collar/

Project Overview



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https://newsreleases.sandia.gov/smart_collar/

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Project Overview

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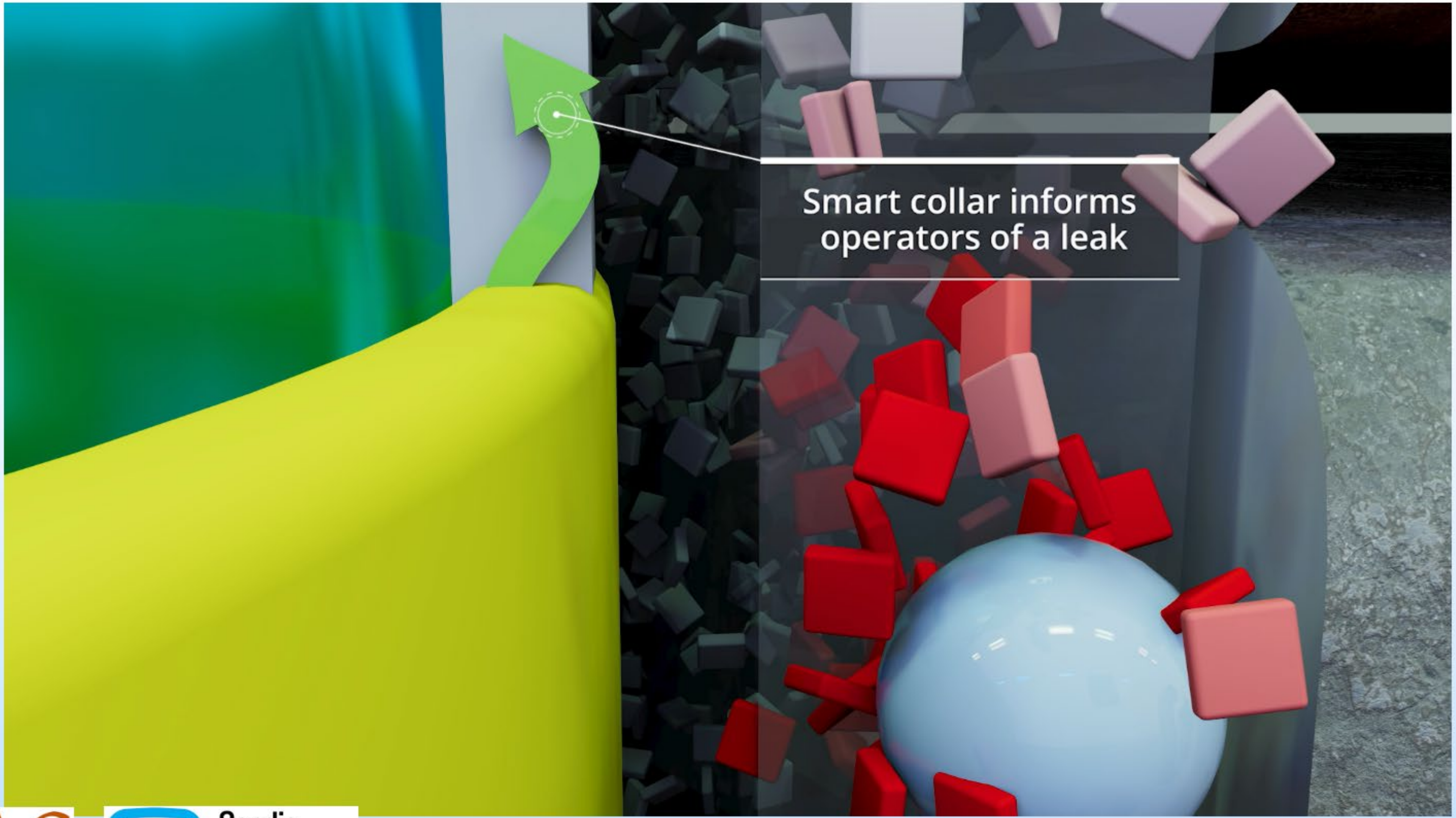

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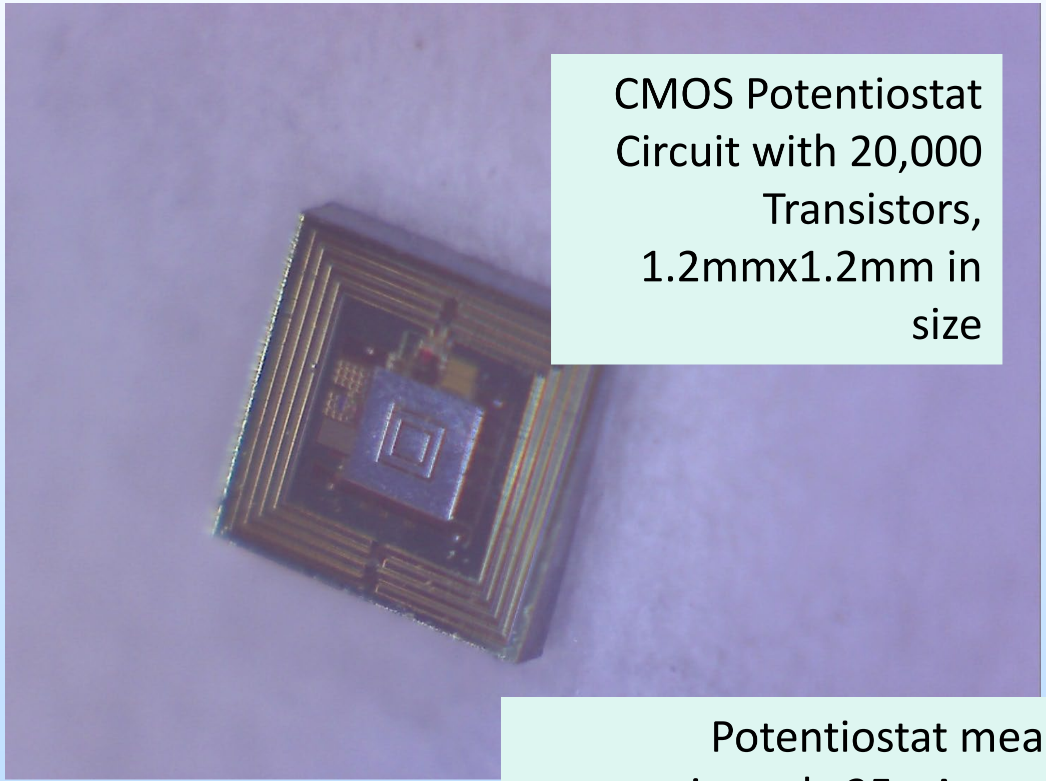
Autonomous Microsensors
Integration of pH Sensor with CMOS Electronics,

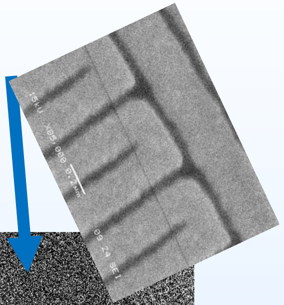
pH and T must be measured for
decades at ~ 80-120C at high pressure

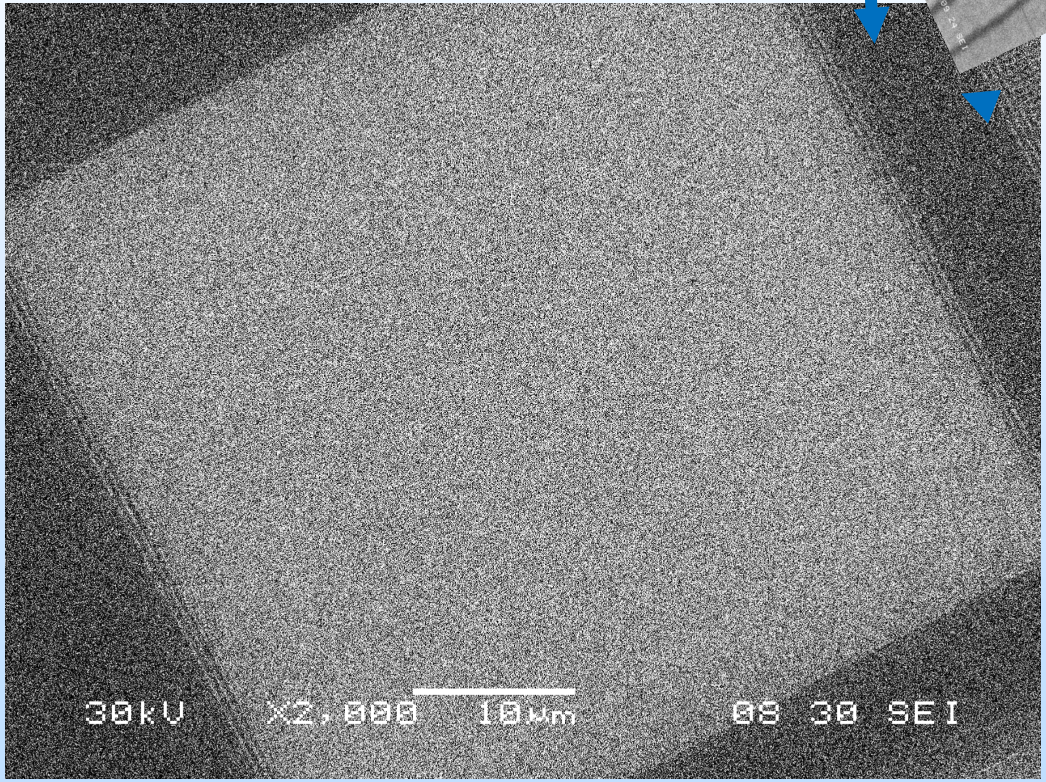


CMOS Potentiostat Circuit with 20,000 Transistors, 1.2mmx1.2mm in size

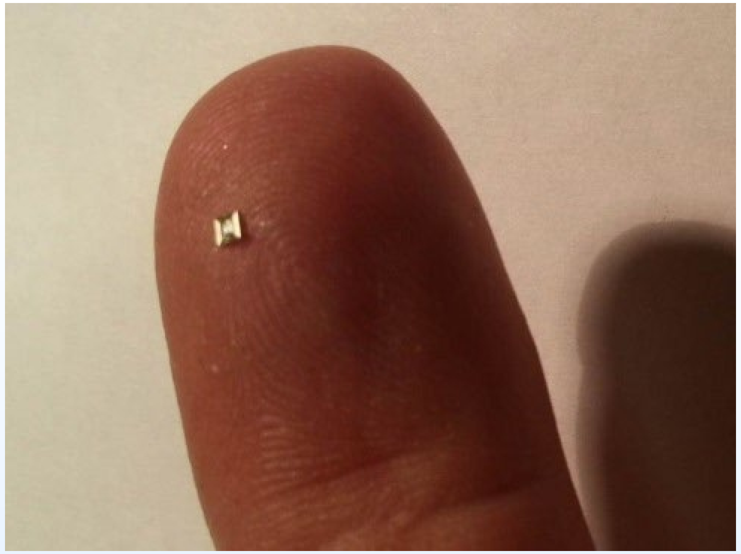
Potentiostat measures approximately 25 nA current – functions as a smart RF Tag, 902-928 MHz

+



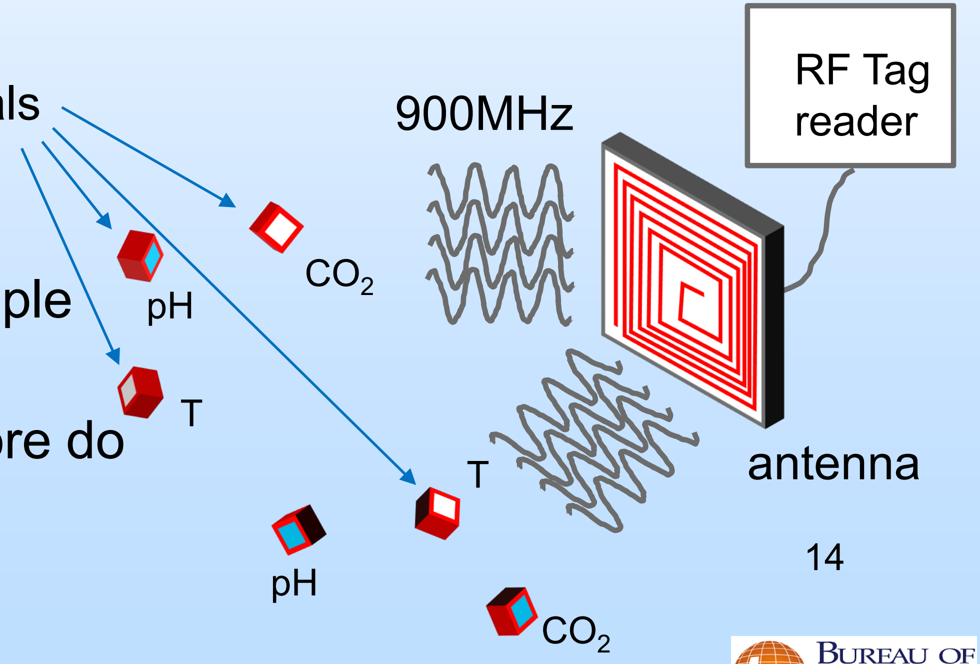


Multi-Functional RF Tag Microsensors (vision)



- 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 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



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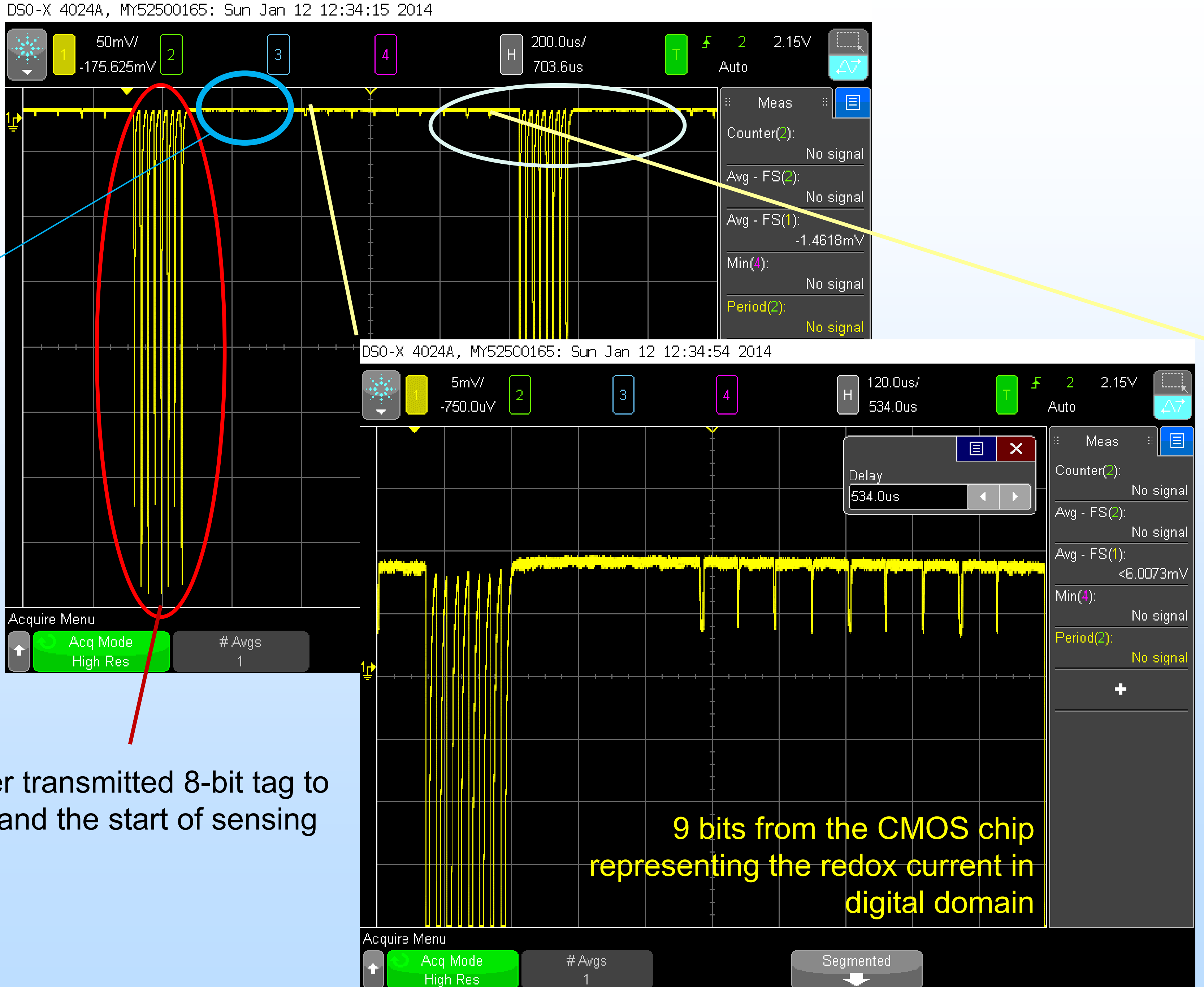
RF Tag Communications System

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

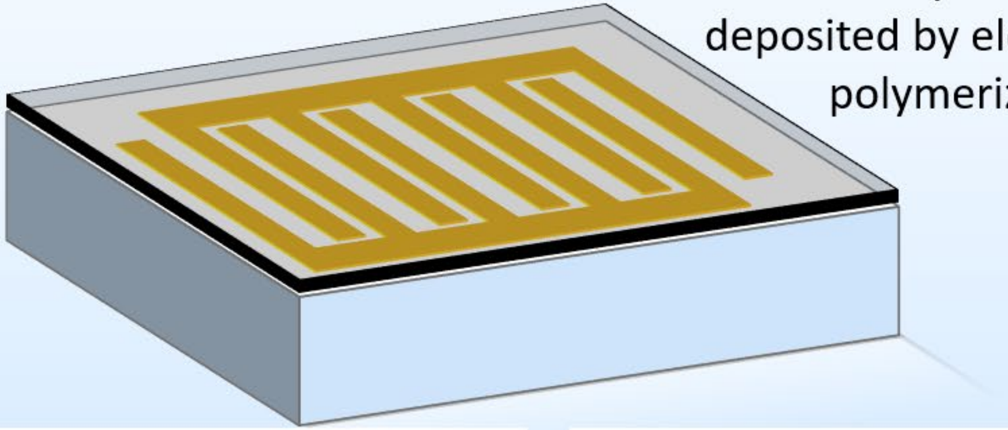


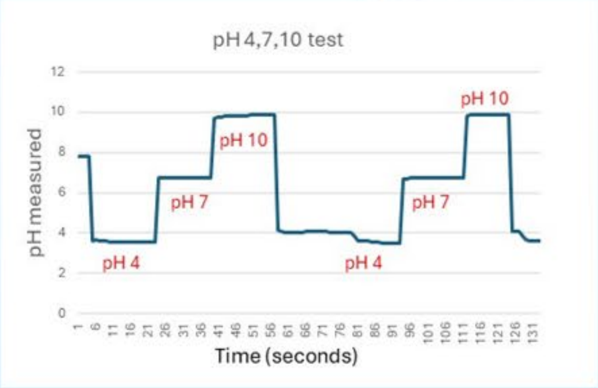
Reader transmitted 8-bit tag to command the start of sensing

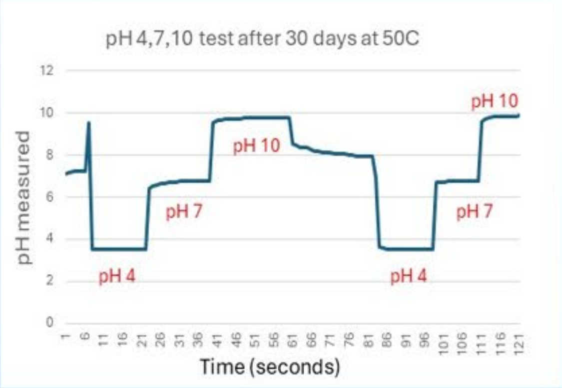
Measuring pH with Thin Polyaniline Layers

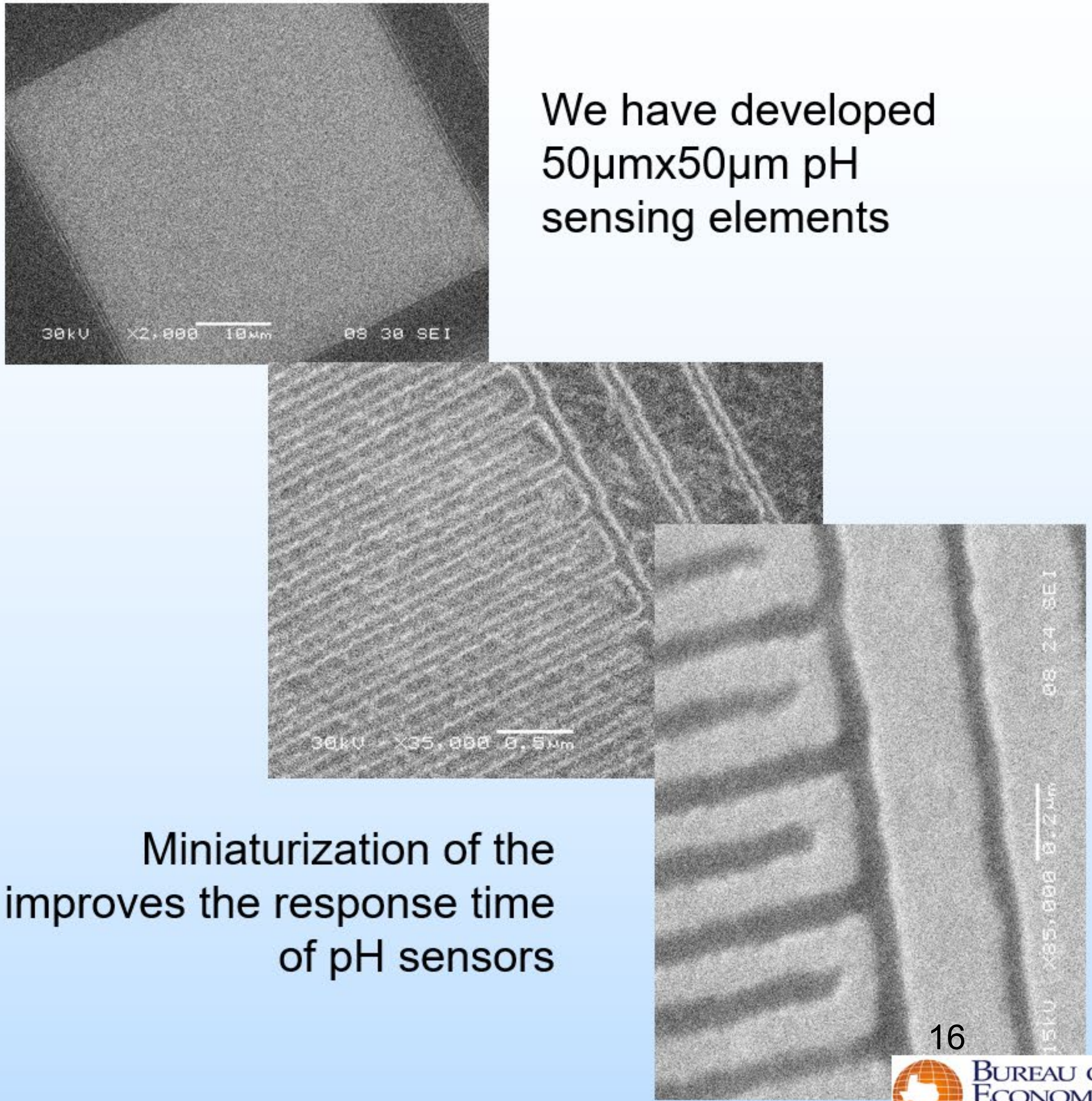
- We use the change in conductivity of Polyaniline (emeraldine phase PANI) with hydrogen ion concentration

Polyaniline is deposited by electro-polymerization









We have developed 50µmx50µm pH sensing elements

Miniaturization of the improves the response time of pH sensors

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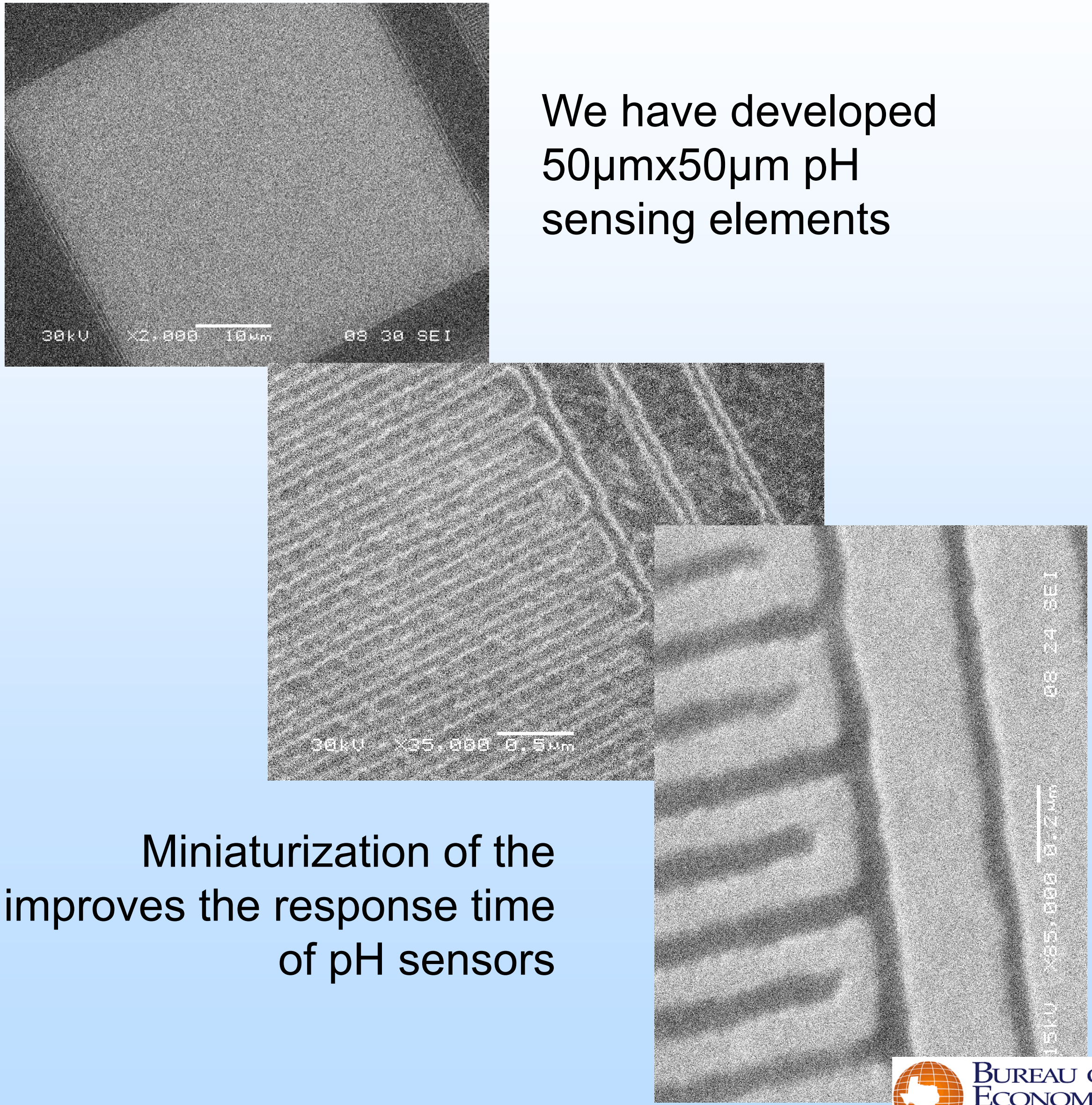

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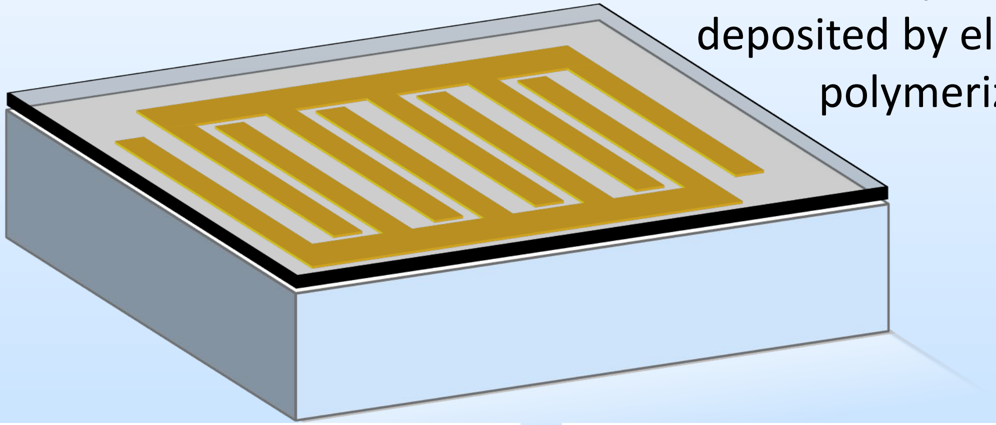
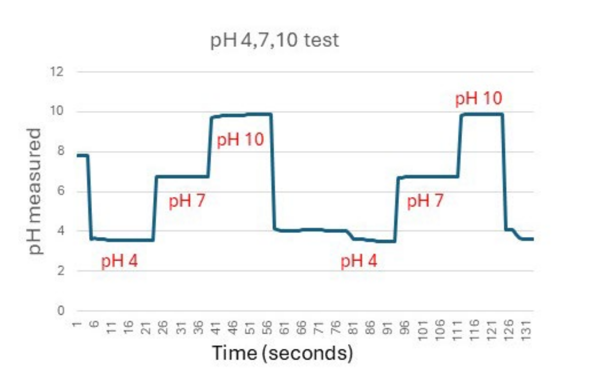
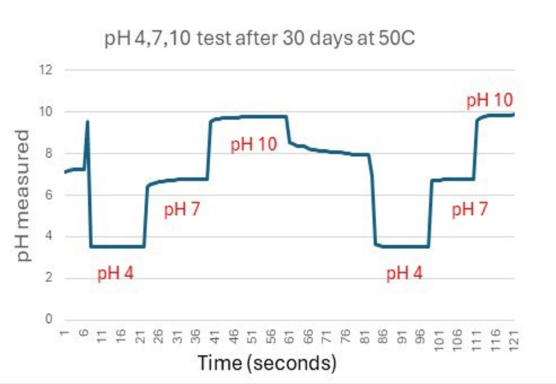


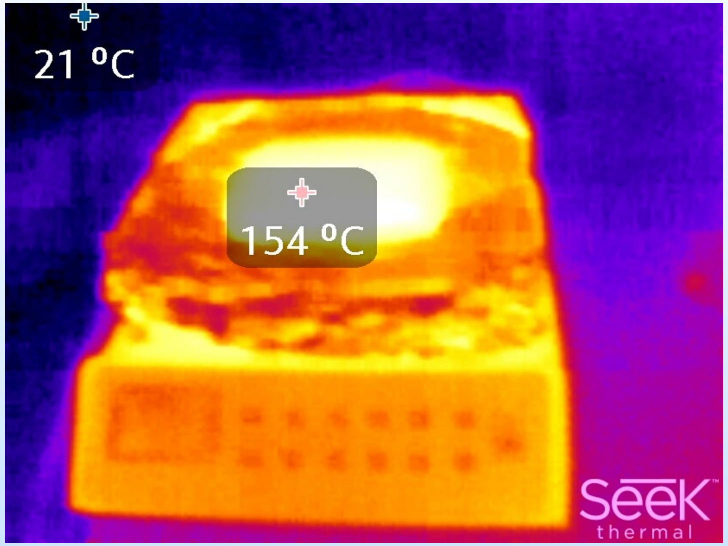


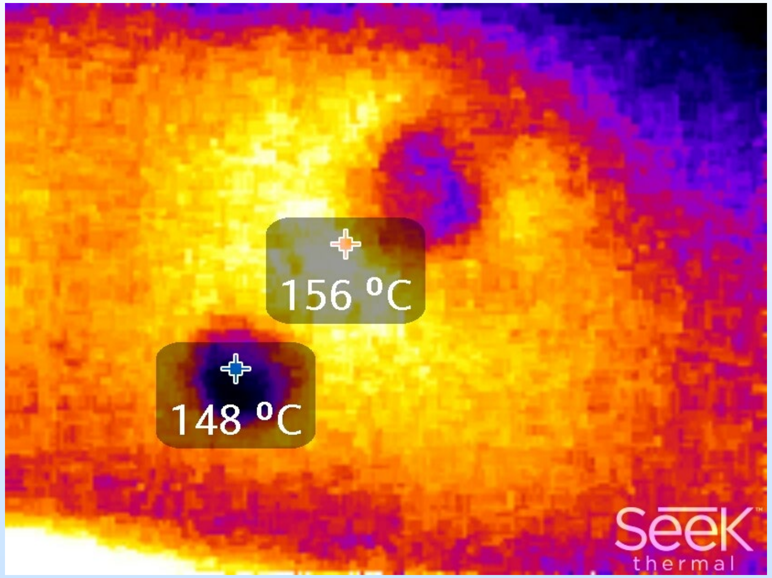


Miniaturization of the improves the response time of pH sensors

Potentiostat Thermal Survivability

RF communication was successful while sensor chip was resting at 150C. Most analog circuit functions could be measured even above 175C.



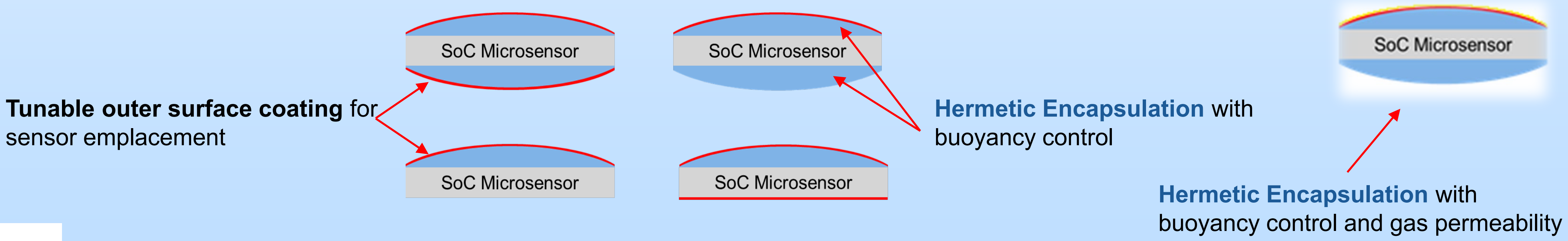


Higher temperatures did not permanently damage the chip, it would begin communicating again after cooling to 150C.

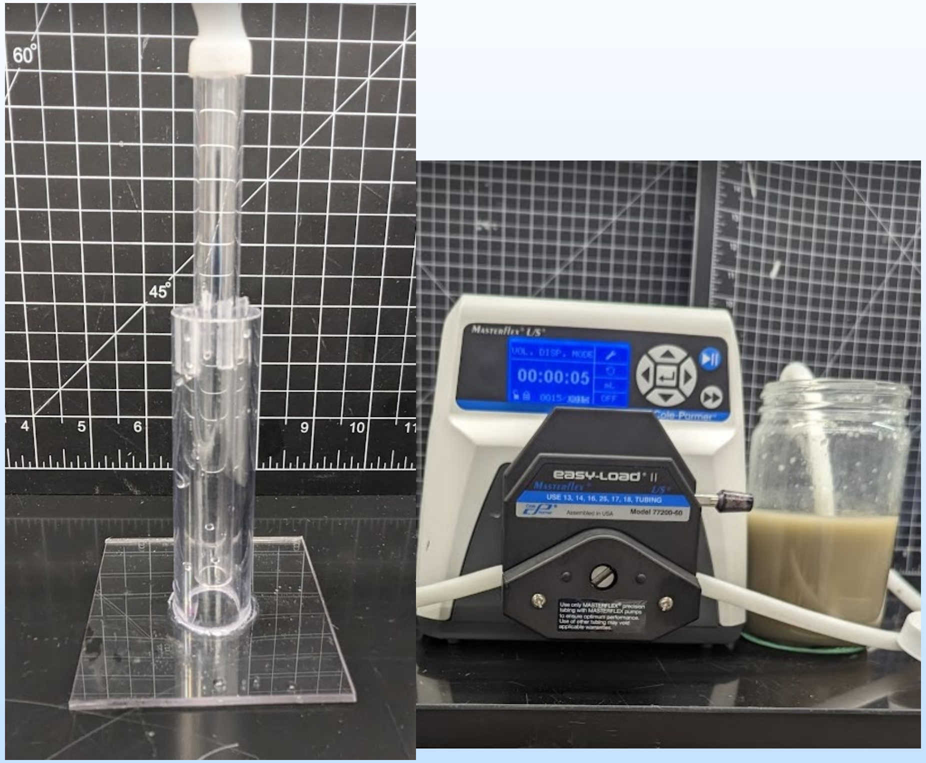
Microsensor Encapsulations, RTI

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

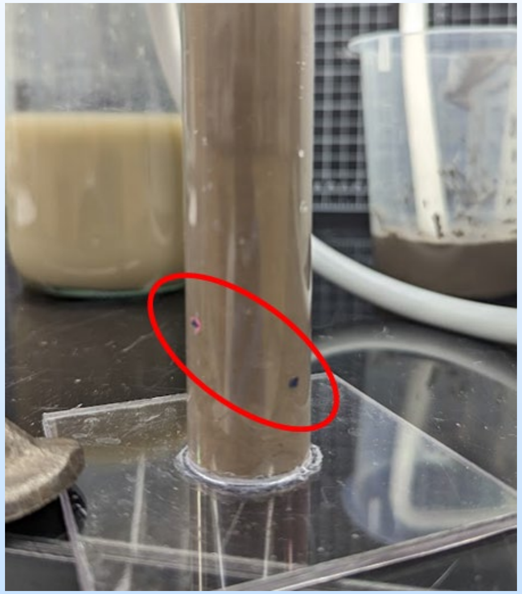
1. Develop coatings for hermetic encapsulation, abrasion resistance, and buoyancy/specific gravity
2. Apply tunable outer surface coating to provide driving force through injection fluid to proper sensor emplacement destination;
3. Best performing materials have been down-selected and applied to working sensors at the end of Year 1.



Microsensor Encapsulations, RTI
Demonstrating Sensor Partitioning and Emplacement



Peristaltic pump to pump cement in a mock wellbore



Quick Gel

Lightweight cement

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Smart Casing Collar

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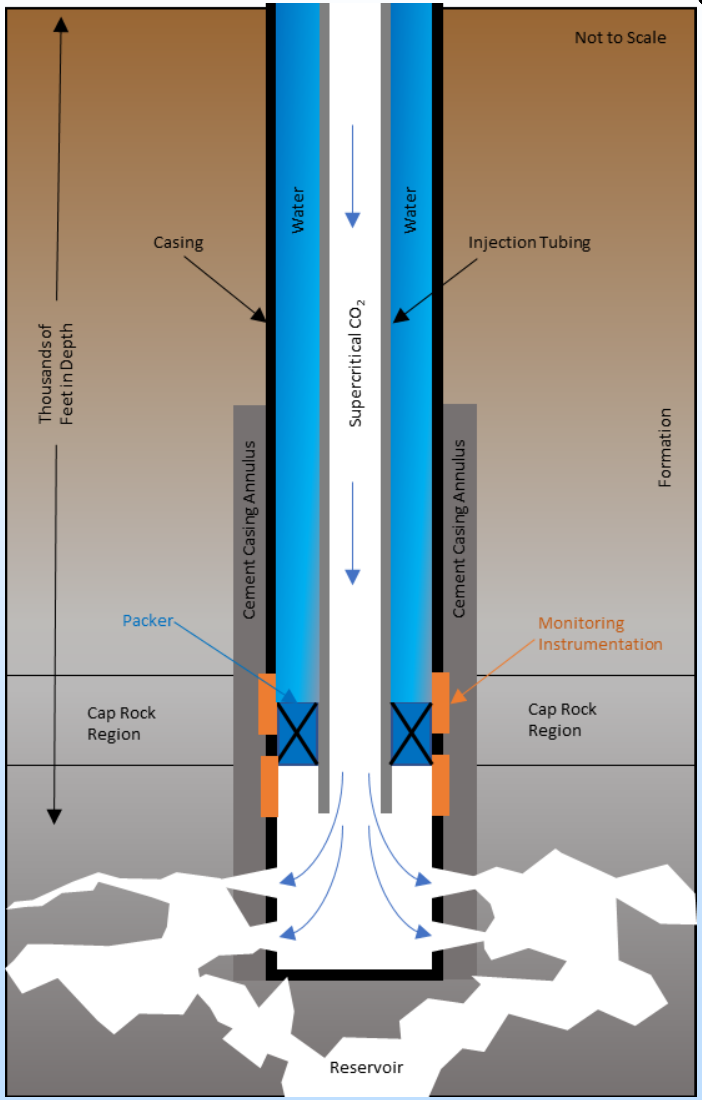
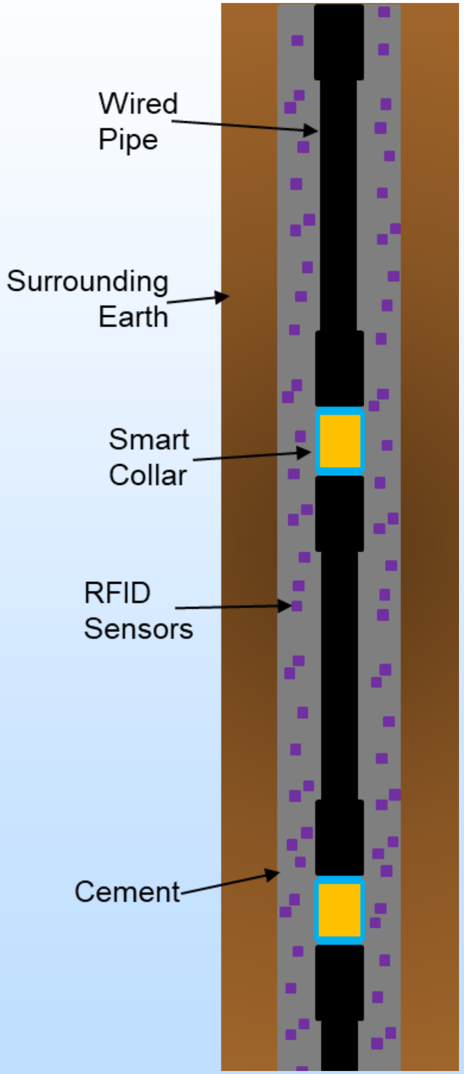


- Wireless sensors embedded in cement annulus
  - RFID communication/power
- IntelliServ's wired pipe
  - High-speed communications
  - Power transfer
- Emplaced near cap rock region



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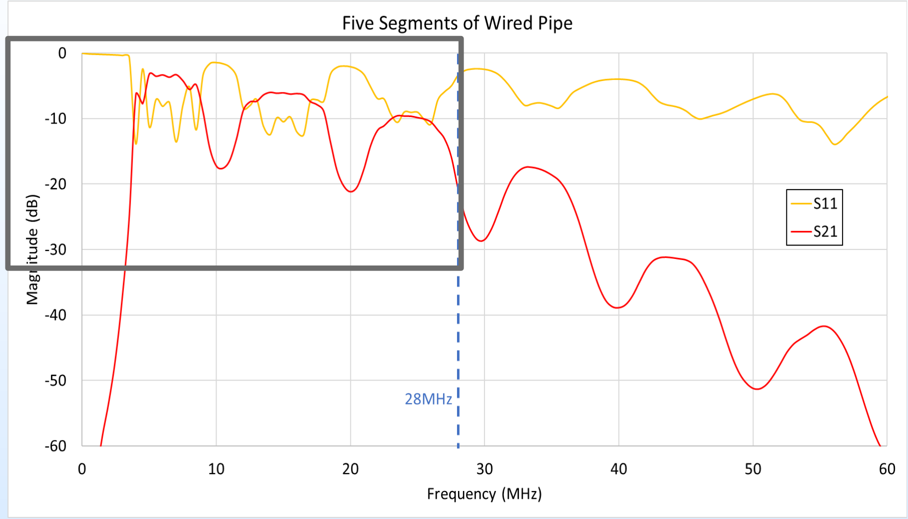
Characterization of Wired Pipe

- S-parameters (attenuation and reflected energy) of 160 ft wired pipe
  - EOC operates below 28MHz
  - Attenuation ~ 4-21 dB @ 10-28 MHz



- Chose AC power band of 4 MHz (near lowest attenuation)

- 85 Mbits/sec data rate with EOC and wired pipe

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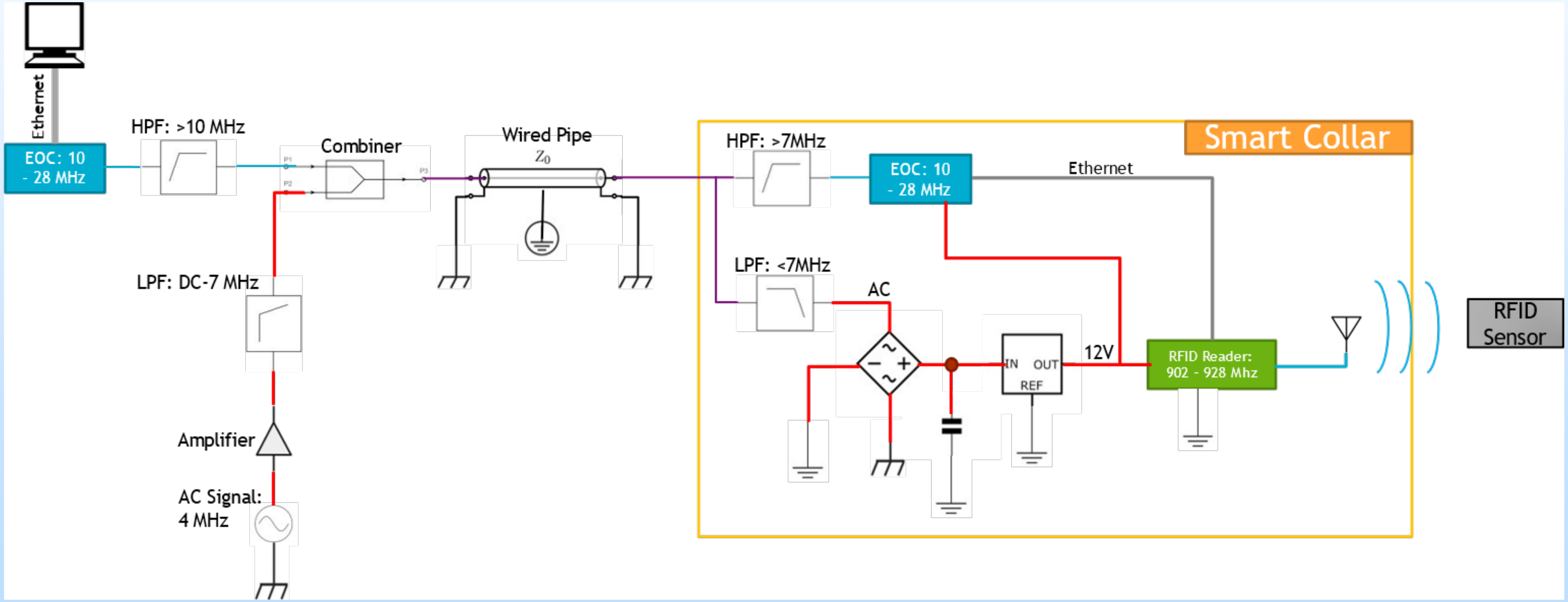
Smart Collar and Wired Pipe Schematic

- Incorporates RFID Inc. RFID Reader



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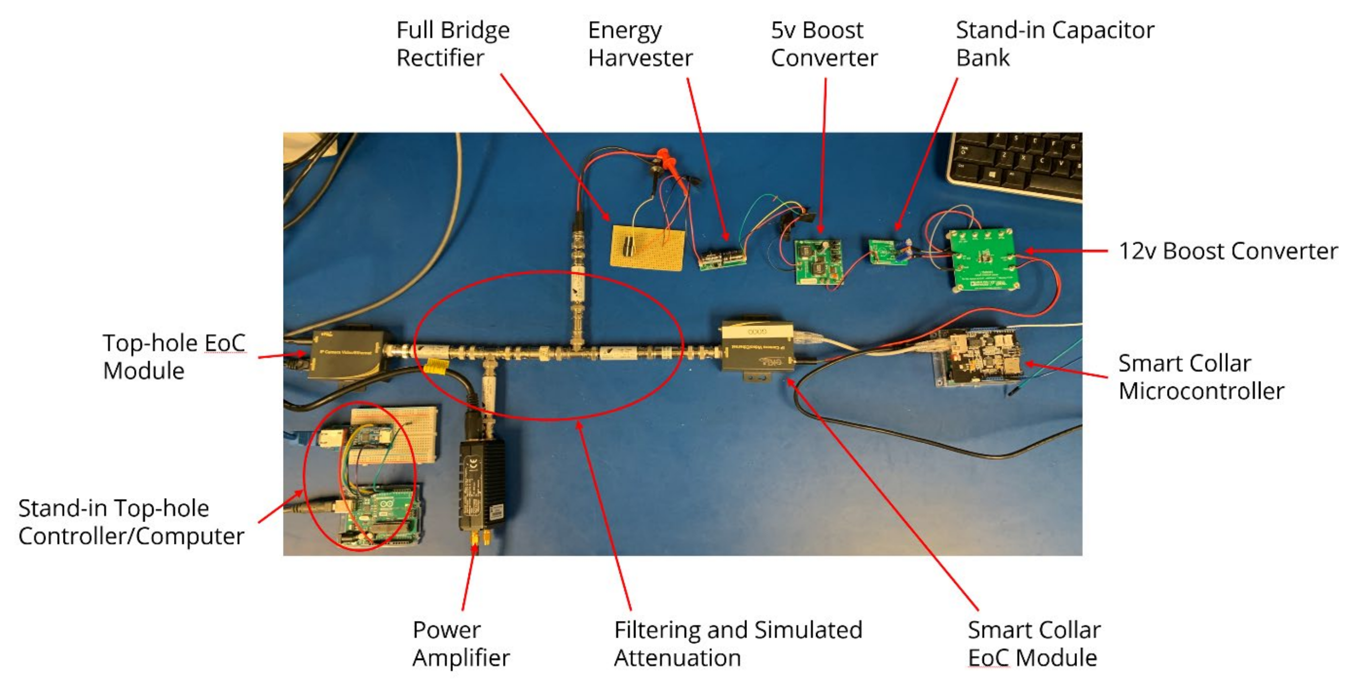
Smart Collar Communication/Power



- EoC used for communications
- Amplifier to transmit 4 MHz AC power
- 4 MHz energy harvester to collect energy into supercapacitors
- Energy regulated for electronics

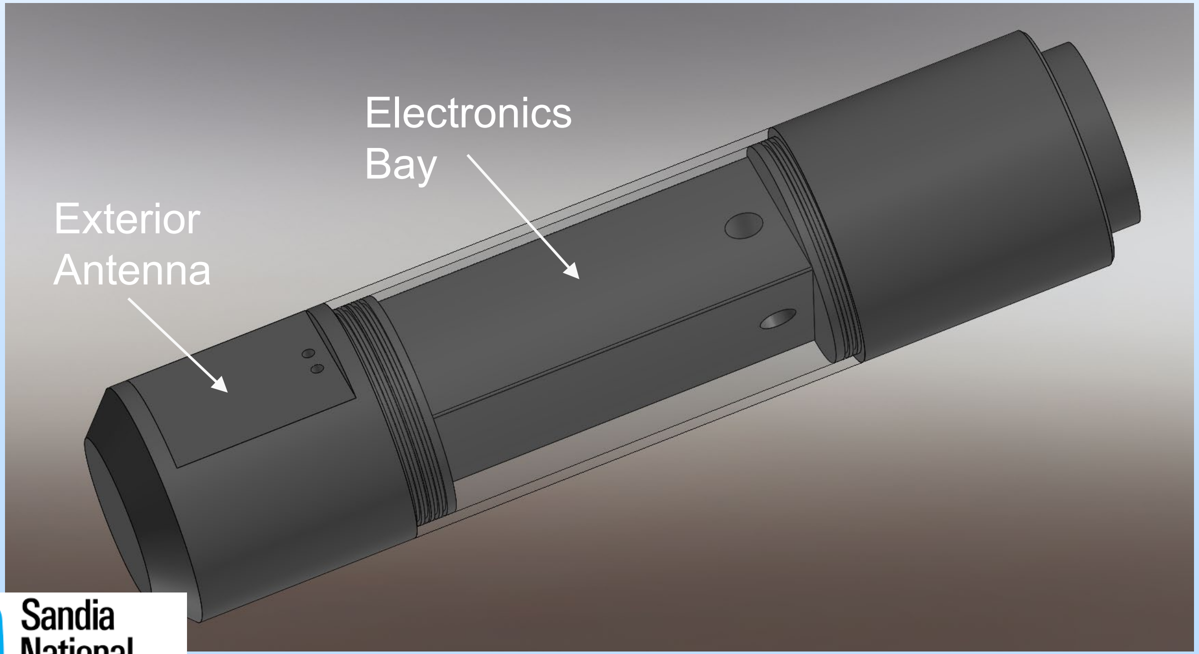
RFID Inc. Reader and Sensor

- Reader
  - Four antenna channels
    - 1 watt of output RF power
  - Ethernet communications
- Sensor
  - Temperature
  - 98x24x0.1mm

https://www.rfidinc.com/uhf-915-mhz-temperature-sensing-rfid-tags

Smart Collar Housing

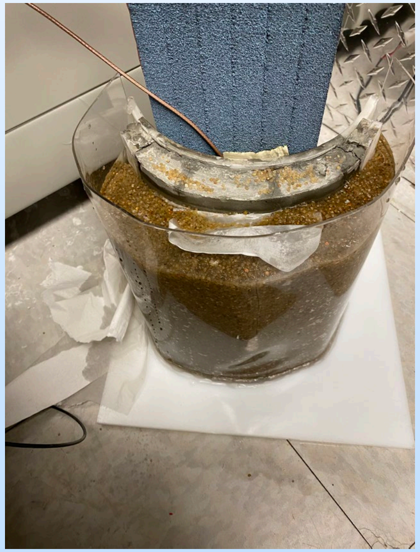
- Inductively couples with IntelliServ's wired pipe
- 3 compartments for power and communication electronics
- Housing will be notched to accommodate the custom antenna
- ~ 2-3 feet in length

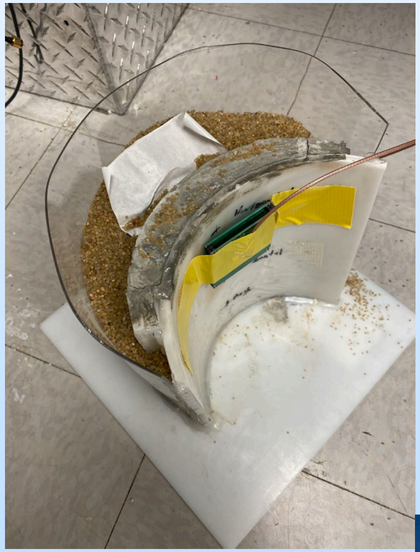


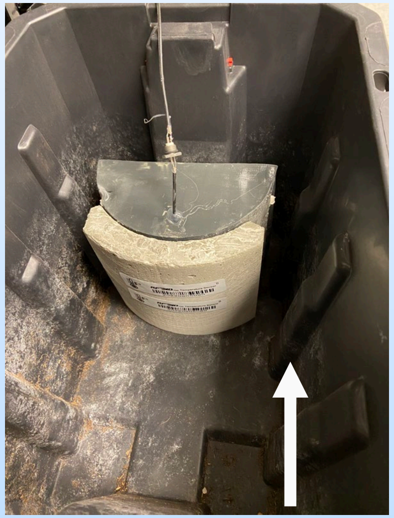
Lab Test Setup and Temp Measurements

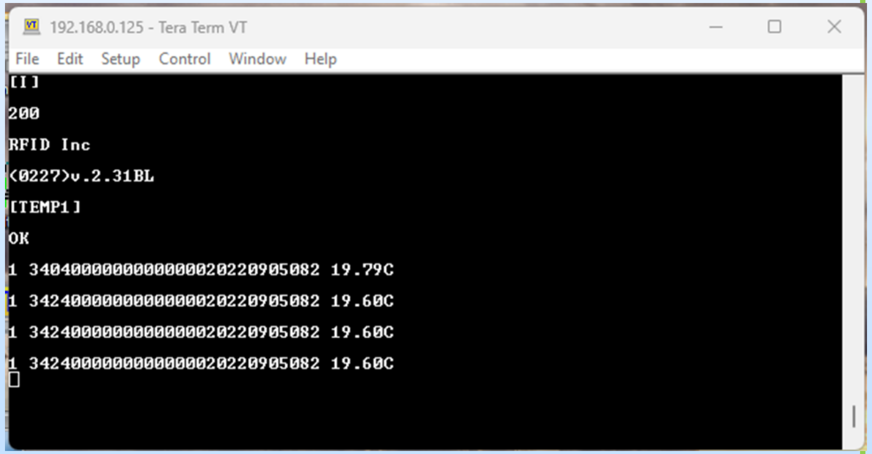
- RF Propagation through the mock smart casing collar shell and expected media
  - Antenna placed behind casing collar shell, and 1” thick cement.
  - Sensors tapped onto the back of the cement in wetted Devine test site soil
  - Communication confirmed with 1-watt power

Antenna within Electronic Bay Shell



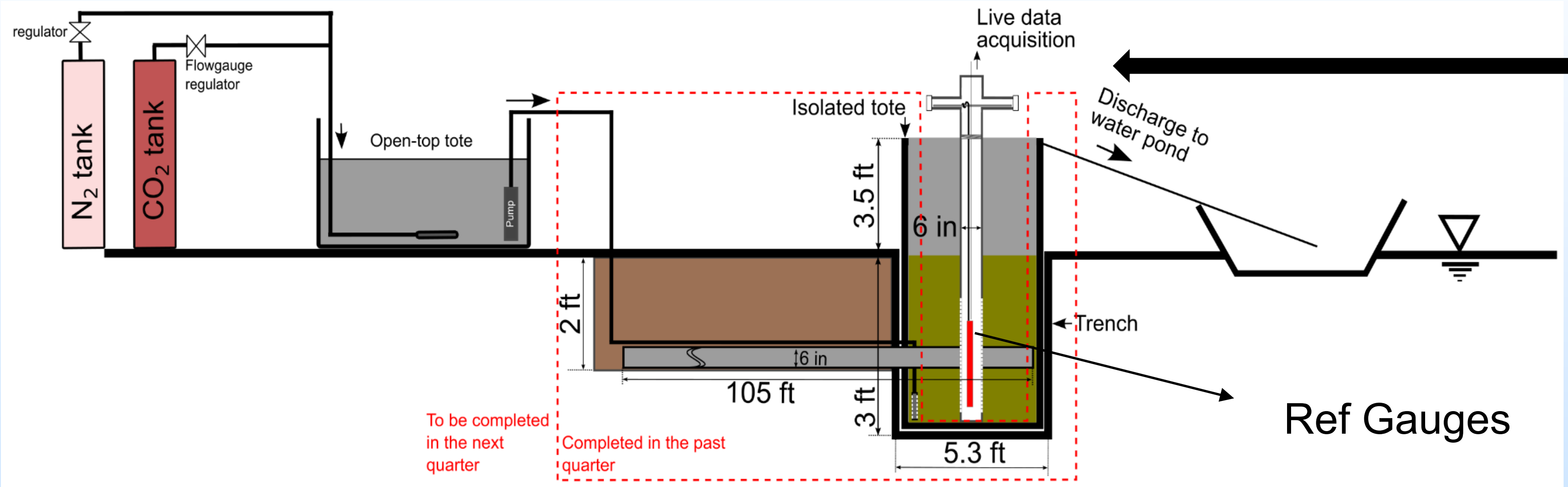


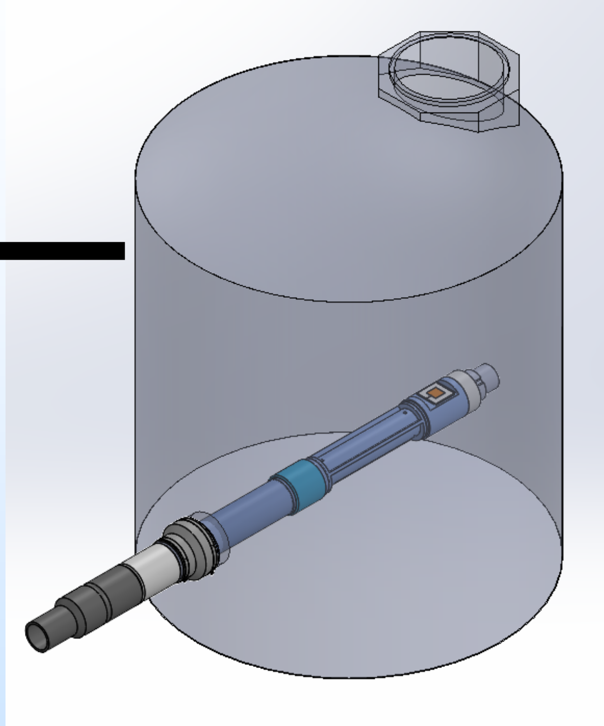




Read Temp Data

Field Experiment Setup





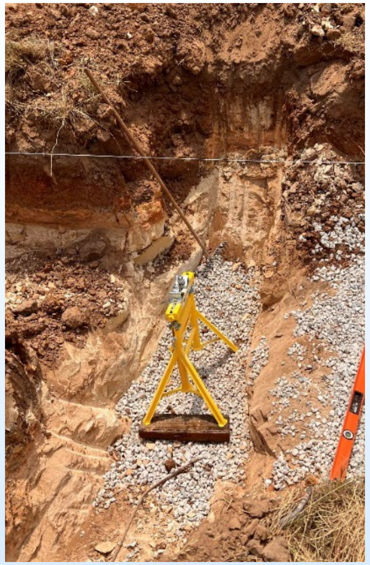
- Wired pipe will be placed within a trench alongside the tank
- Smart Collar will be placed within the tank
- 6” to 8” coupler will be used to seal between the tank and Smart Collar

Pilot Setup Construction at UT’s Devine Test Site

(1) NOV Pipes Shipped

(2) Trench Excavation

(3) Stand Placement

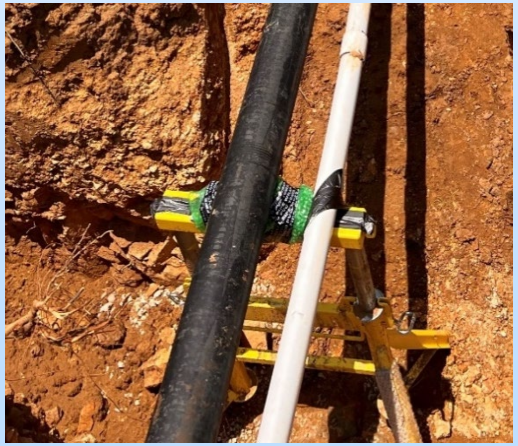


(4) Pipe Placement and Assembly

(5) Base Preparation for Tank

(6) Height adjustment - Inclination Toward Tank

(7-8) Injection Pipe Assembly



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Pilot Setup Construction at UT's Devine Test Site - Continued

(9) Water tank placement in trench

(10) Water tank alignment with the pipe

(11) Centralize drilling pipe with tank opening

(12) Backfilling the trench

(13-14) Installation of safety signs and ribbons around the tank area

Lessons Learned

- The developed NASICON CO_2 sensors are very sensitive to humidity
- Polyaniline-based pH sensors have been developed and are adequate for the DTS environment
- However, T> 60C and pH > 9 deteriorate the Polyaniline layers and limit the lifetime of these pH sensors
- Currently investigating another rev of pH microsensors with inorganic alternatives (titanium oxynitride films)
  - The film can be sputter-deposited onto our platinum electrodes and promises to provide longer lifetimes at higher temperatures and pH
- Distances between Caltech RF tag sensors and reader are currently limited due to:
  - Miniaturized antenna size
  - Associated frequency of operation
  - Attenuation by subsurface fluids and wellbore materials

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RTI International

Next Steps - BP3

Caltech: Continue optimizing temperature and pH sensors in the lab. (We are Testing sputter-deposited titanium oxynitride films for a new pH-sensitive layer).

Preparing wire bondable sensors for Sandia for attachment to commercial antennas.

RTI: Will apply any hermetic coatings needed for these sensors.

Sandia: Finishing the assembly and testing of the Smart Collar and preparing to incorporate the unit with the field experiment.

Benchmarking a) commercial Temp sensors vs. b) Caltech's hybrid temp sensors (wire-bondable Caltech Temp sensors attached to commercial antennas), and c) Caltech miniature RF sensors

UT: Complete the experimental setup at the Devine Test Site. Conduct a preliminary injection to test all the fittings and reference equipment.

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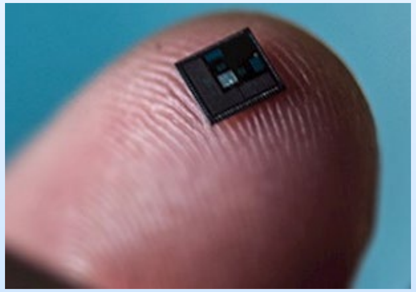
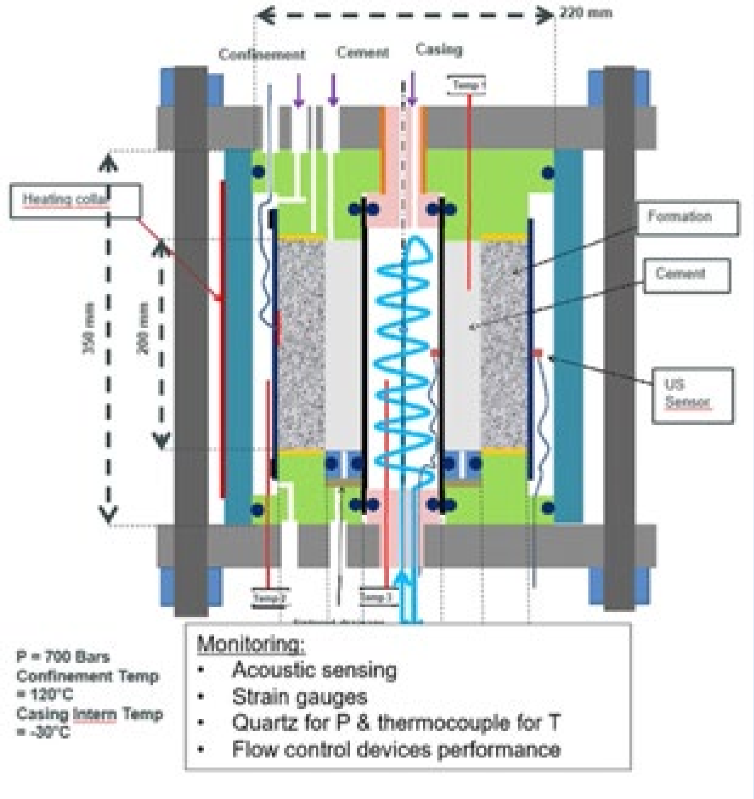
Future Direction

- Harden sensors for harsher environment testing with an industrial partner
- Improve wireless robustness and communications/power distances by comparing ASIC vs. RFIC and Acoustic Options:

Prototype ASIC CO Sensor





- Investigate power harvesting for casing collars
- Test prototype system at depth via AEC partners

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Opportunities for Synergies

- AEC and its university and industry partners
- PNNL:
  - Engineering Integrated Sensing, Power, Telemetry, and Data Processing Systems for Complex Subsurface Environments FWP-80754
- NETL RF Sensors for harsh environment
  - FE0031912, FE0031895,
- DOE FECM:
  - FE0031784

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Thanks for your attention
I appreciate your comments and collaboration

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