Annulus Monitoring of CO_2 Injection Using Wireless Autonomous Distributed Sensor Networks

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National Energy Technology Laboratory
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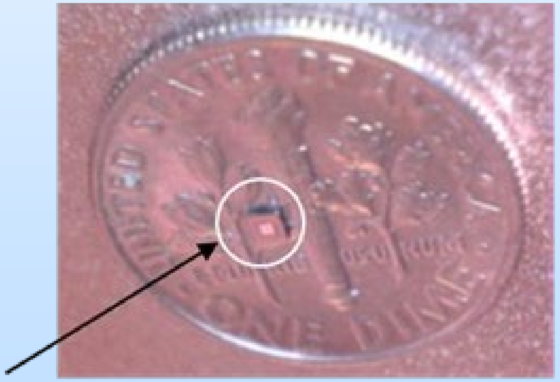
Presentation Outline

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

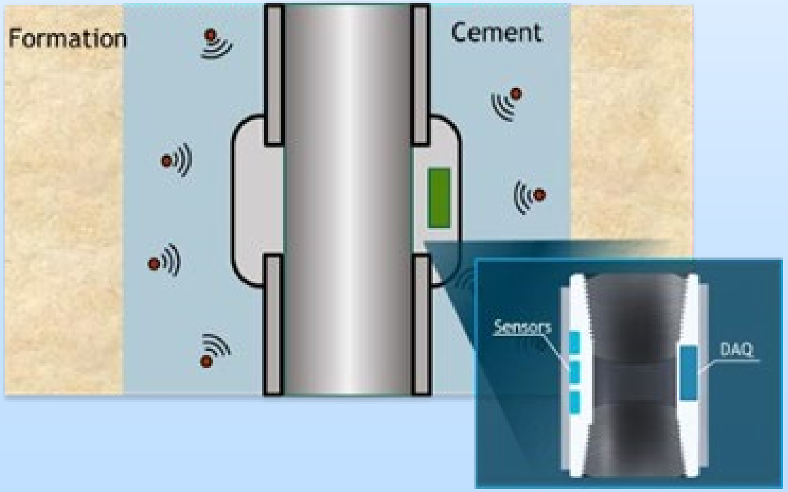
Project Overview

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, 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

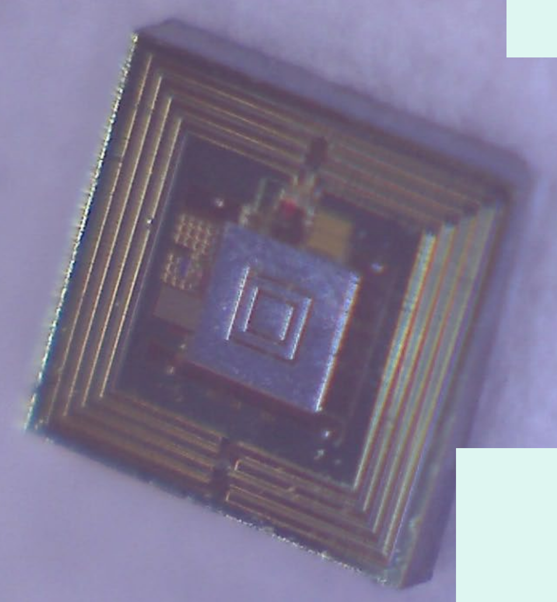


1mm System
on a chip (SoC)



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

Integration of CO_2 Sensor with CMOS Electronics, Caltech

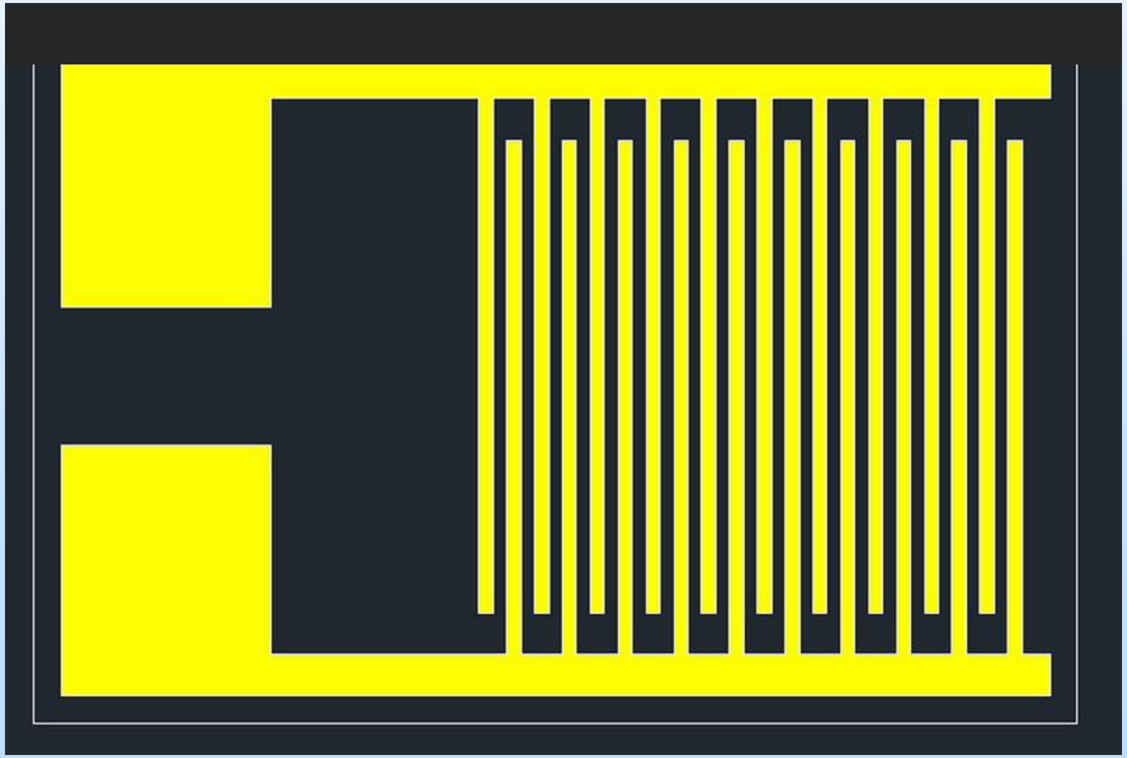


CMOS Potentiostat Circuit with 20,000 Transistors, 1.2mmx1.2mm in size

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

+

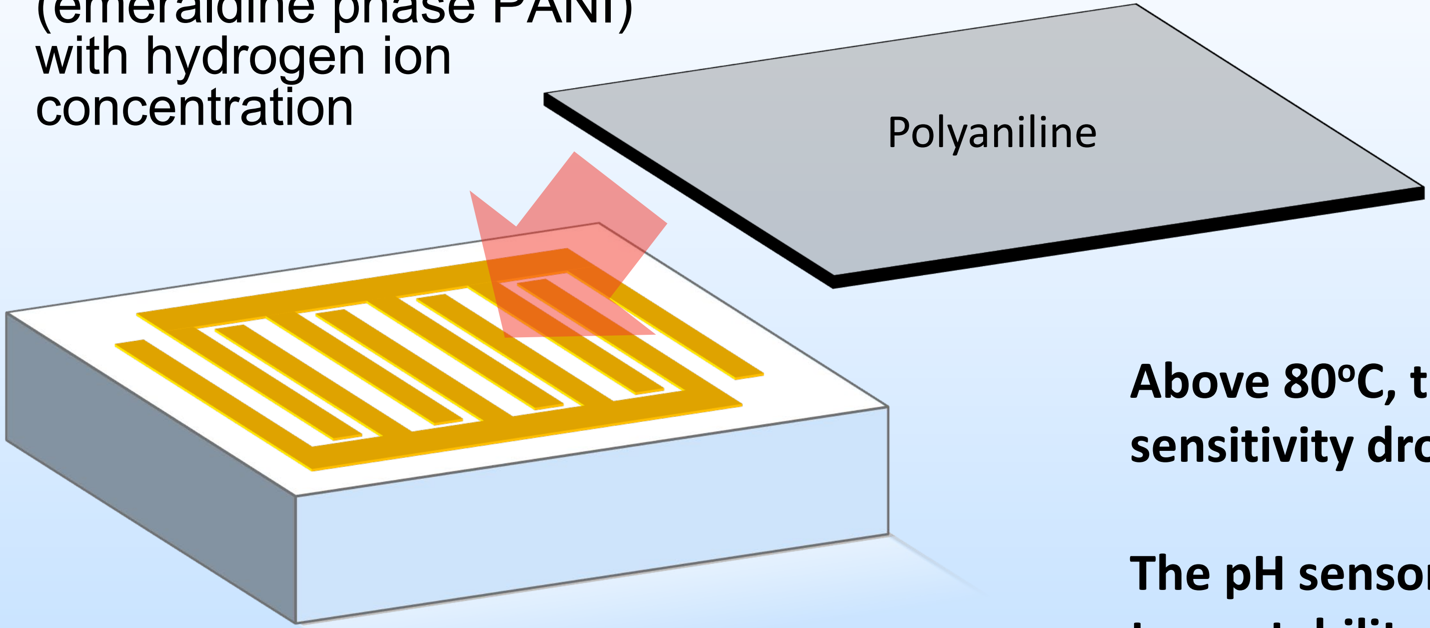
Temperature and CO_2 measurement must be measured for decades at ~80-120C at high pressure



Measuring pH with Thin Polyaniline Layers

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

When testing Polyaniline pH meters at elevated temperatures and in corrosive environments, we observed rapid deterioration:

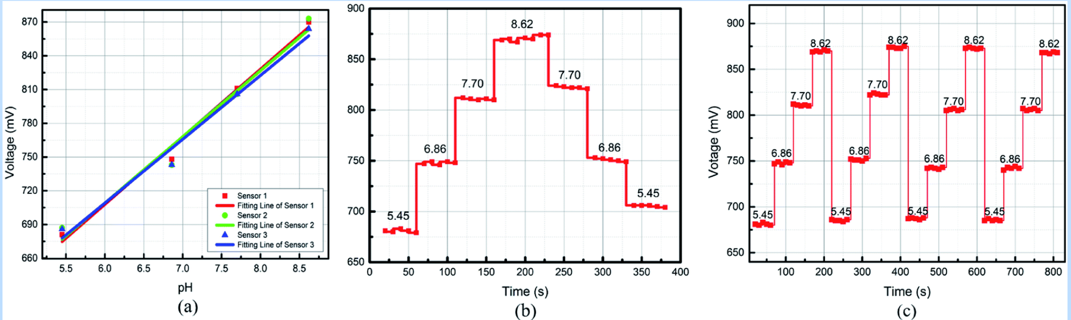


Above 80^{o}C, the Polyaniline deteriorates and the sensitivity drops rapidly

The pH sensors suffers from drift, limiting long-term stability and lifetime w/o a reference electrode

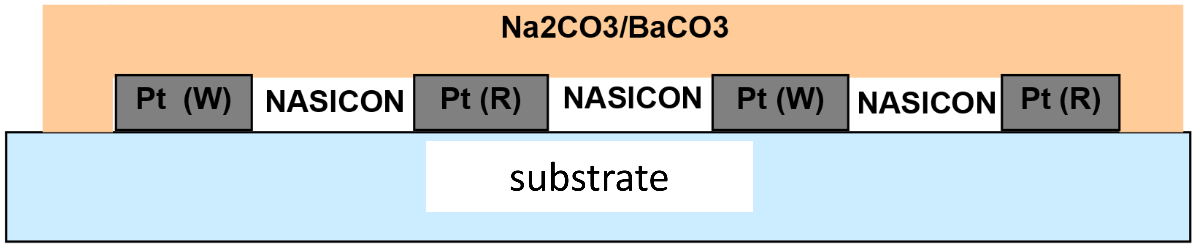
Reference electrodes (Pt/AgCl) limited lifetimes to weeks due to dissolution

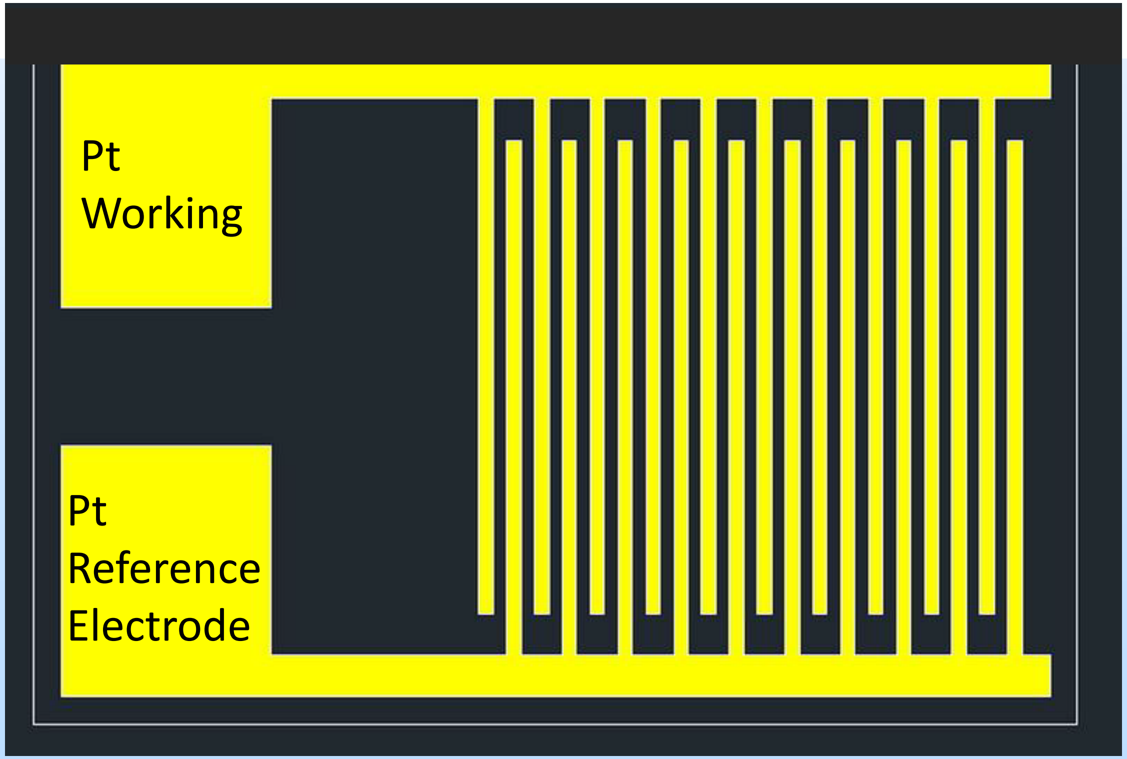
Sensitivity ~60 mV/pH | Hysterisis response | Repeatability Test



New Electrochemical CO_2 Sensor

- We use NASICON ($Na_3Zr_2Si_2PO_{12}$) as a solid electrolyte, and apply voltage to working electrode and monitor current between working and counter electrode
- CO_2 gas can be measured with our CMOS potentiostat
- Reference electrode (Pt) is stable
- Platinum contacts are used to measure current through the NASICON
- These sensors work at temperatures up to 500°C





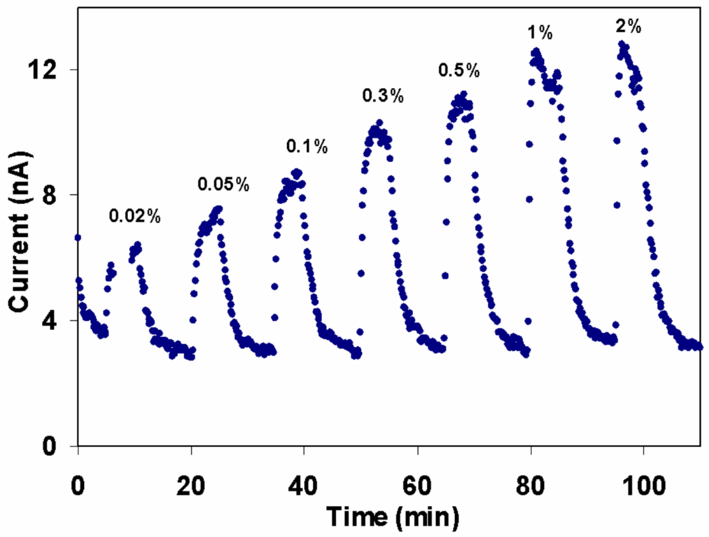
Device design is based on the Gary Hunter and J. Xu Patent 8702962: **"Carbon dioxide gas sensors and method of manufacturing and using same"**, filed in 2008

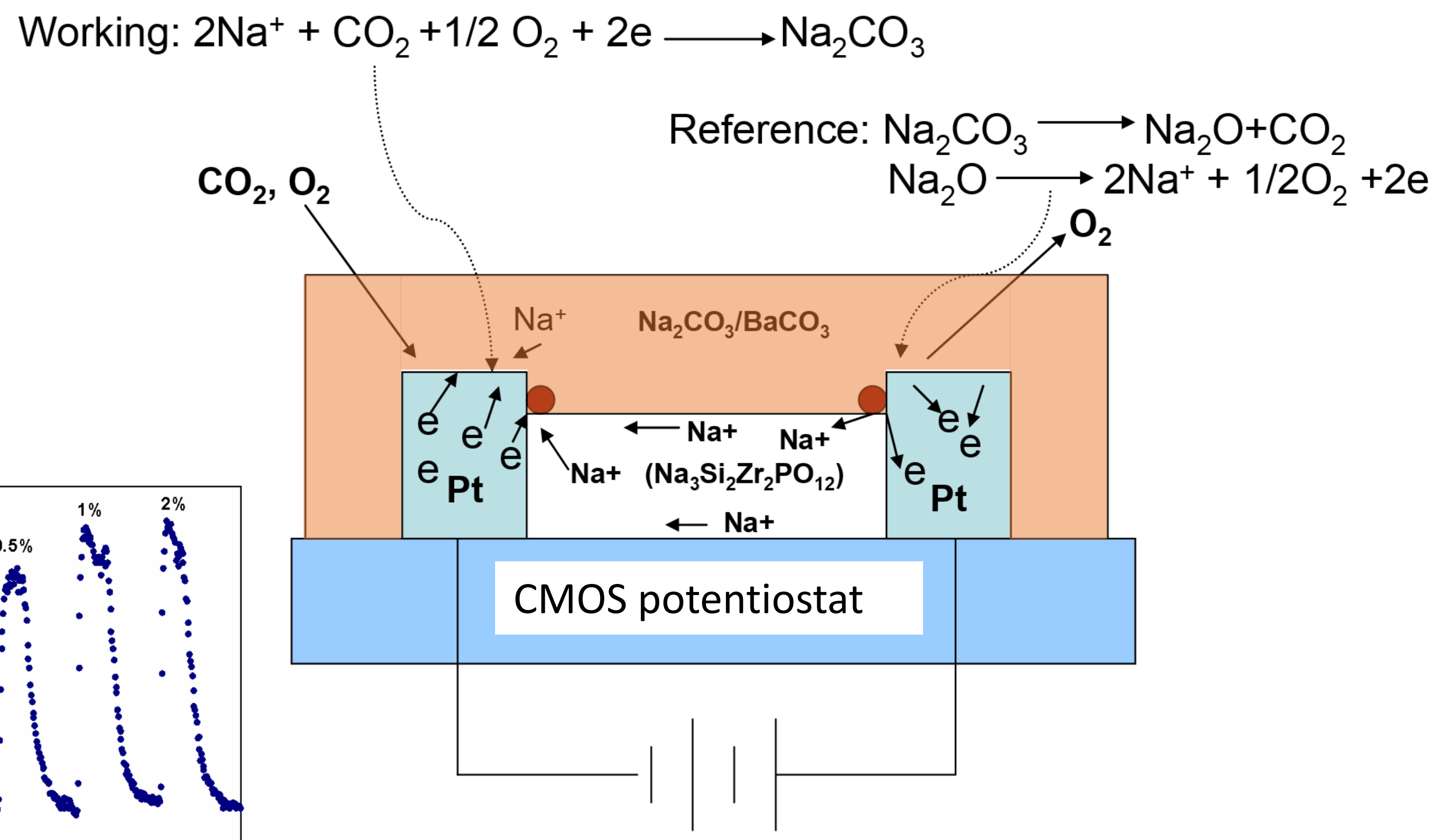
($Na_3Zr_2Si_2PO_{12}$) CO_2 Sensor

NASICON solid state electrolyte chemistry is very stable at high temperatures

We can measure the CO_2 with sensitivity over decades

First benchtop results show the NASICON sensors increasing current with increasing CO_2 concentration and matches the CMOS potentiostat capability

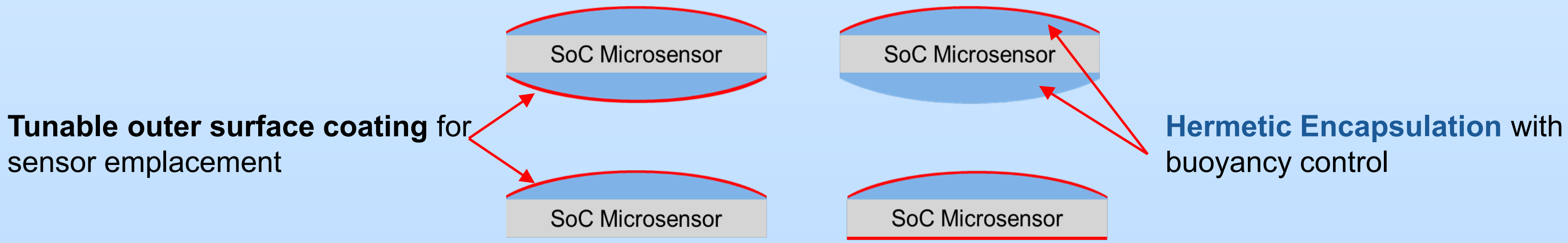




Microsensor Encapsulations, RTI

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.



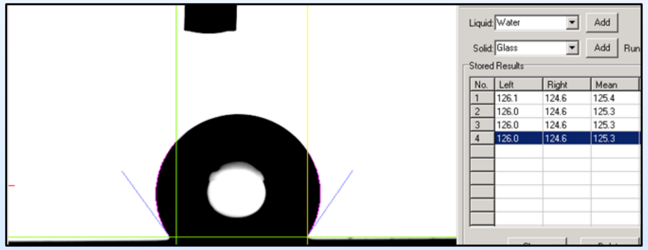
Microsensor Encapsulations, RTI

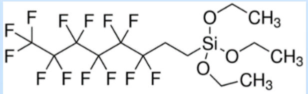
3 Low Surface Energy Surface Coating Types Developed:

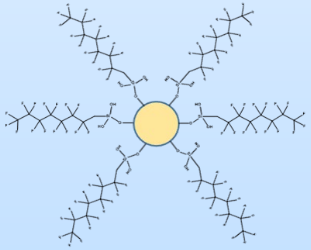
- Particle-based: highest contact angle
- Polymer-based (acrylate or siloxane-based): imparts impact resistance and can be weighted
- Particle/polymer hybrid: combines best contact angle with ability to control specific gravity → preferred design

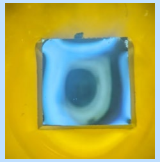
Coating Application Approach

- Spray – easiest and fastest; poor coverage control
- Dispense – slower but more accurate; wet-out/bleed issues
- Molding – slowest but allows fine control of specific density → preferred approach

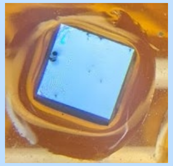




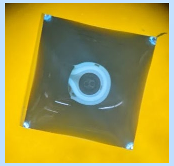




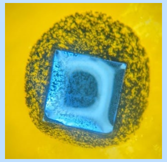
Acrylate as dispensed (1.5ul) on dummy sensor surface



Acrylate edge bleed during cure (100°C/20min)



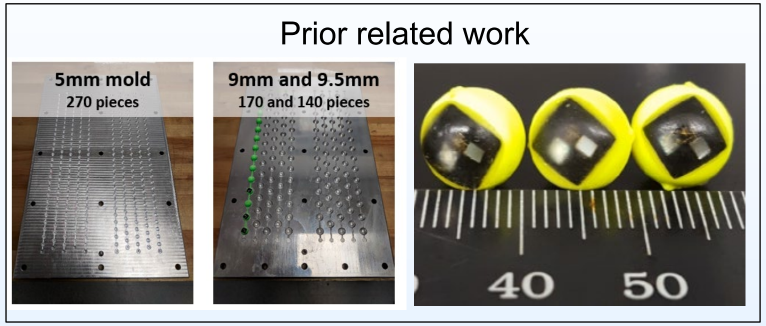
Acrylate with 5 wt.% Ferrite NPs in formulation

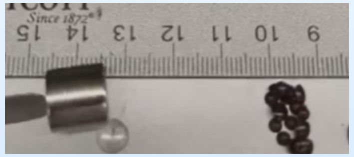


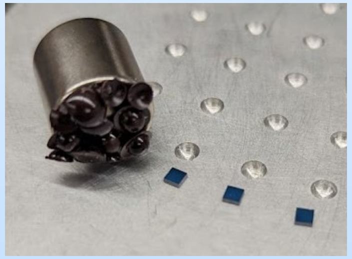
Acrylate/Ferrite edge bleed during cure (100°C/20min)

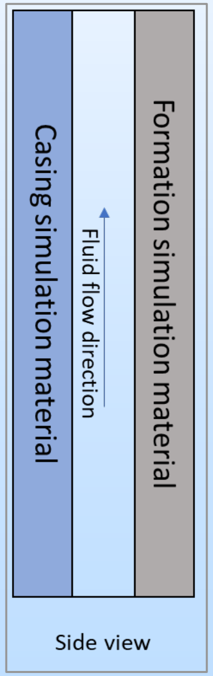
Microsensor Encapsulations, RTI

- Mold-based coating results:
  - Used 2mm x 2mm dummy sensors to develop mold-based coating procedure to enable precise control of coating specific gravity and resulting sensor buoyancy
  - 10-piece batch runs were produced with specific gravities of 1.0 and 1.1 utilizing 6” molds with a 3mm spherical cavity space resulting in a sensor with a buoyancy-controlled coating on one side
  - Demonstrated that the inclusion of nano-ferrite material rendered the encapsulated sensor magnetic under an applied field (paramagnetic) which could possibly be leveraged for sensor placement
  - Surface coating actuated mobility testing will be starting soon with drilling mud and cement fluids in confined space.





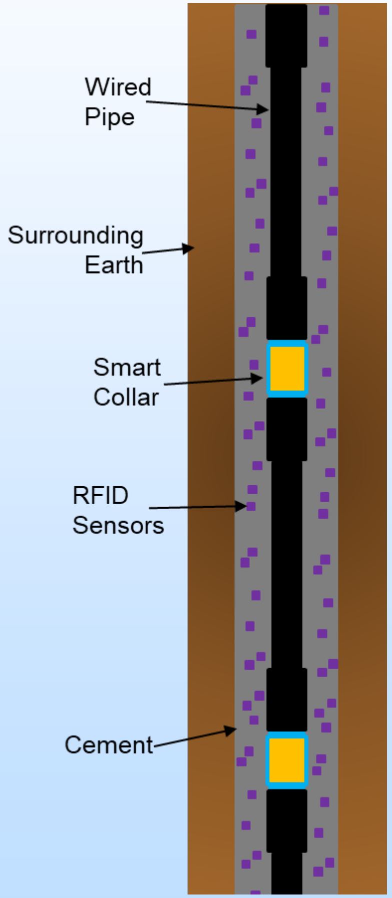




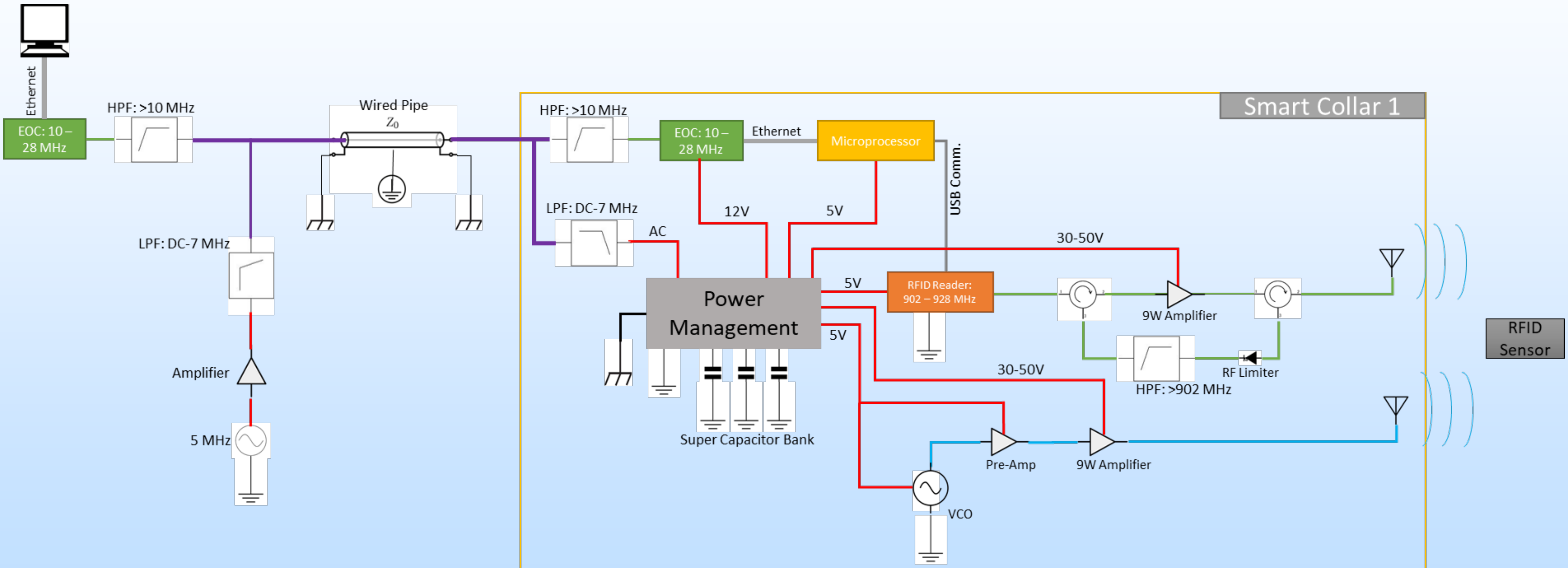
RTI INTERNATIONAL

Smart Collar Technologies, Sandia

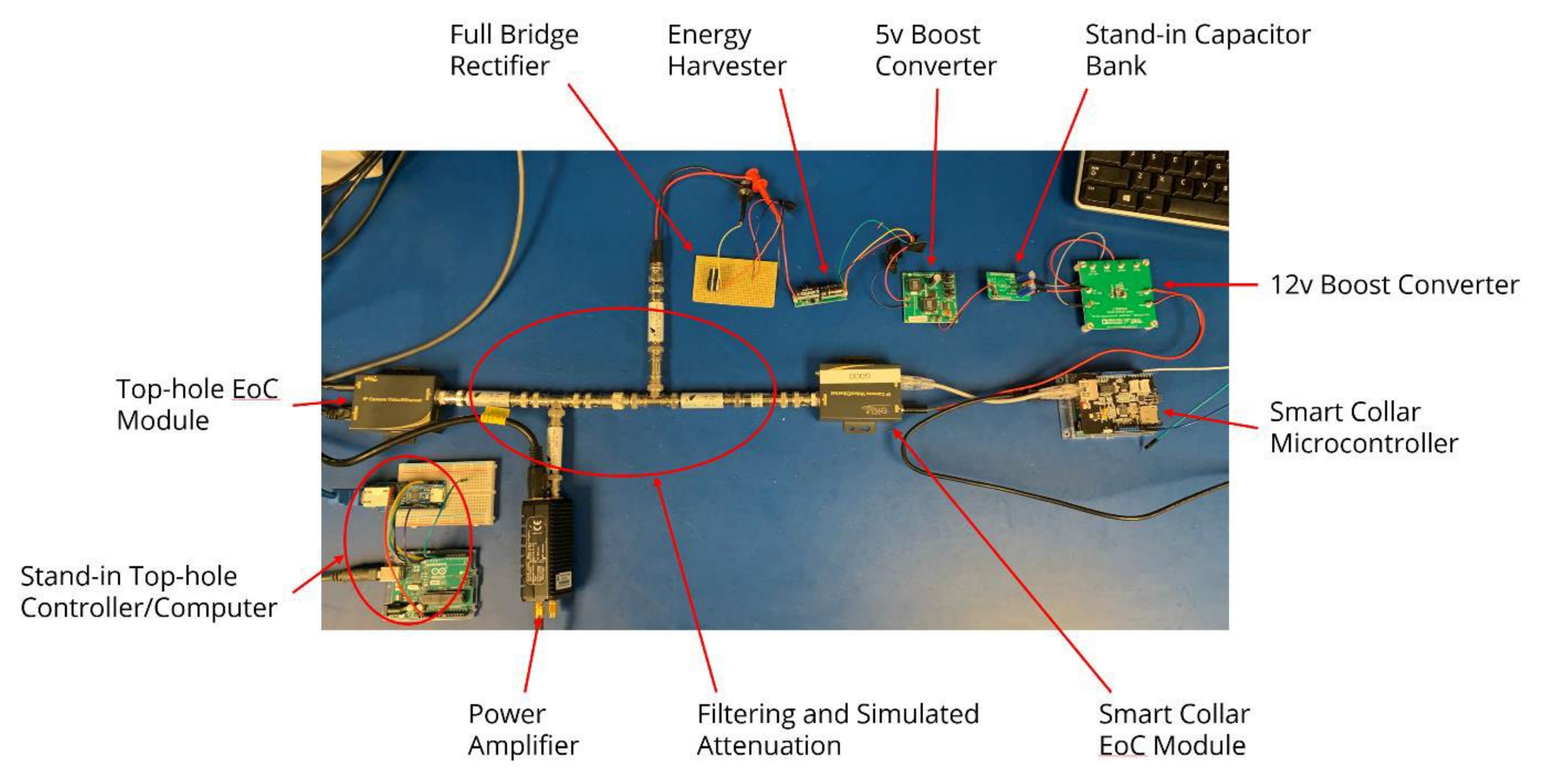
- Smart Collar connects to IntelliServ's wired pipe
- High speed communications and power
- Couples between two wired pipes
- Placed at various locations on the wired pipe
    - Expand RFID communication range
- Wireless RF signal powers and communicates with RFID sensor



Smart Collar – Comms, Power Block Diagram

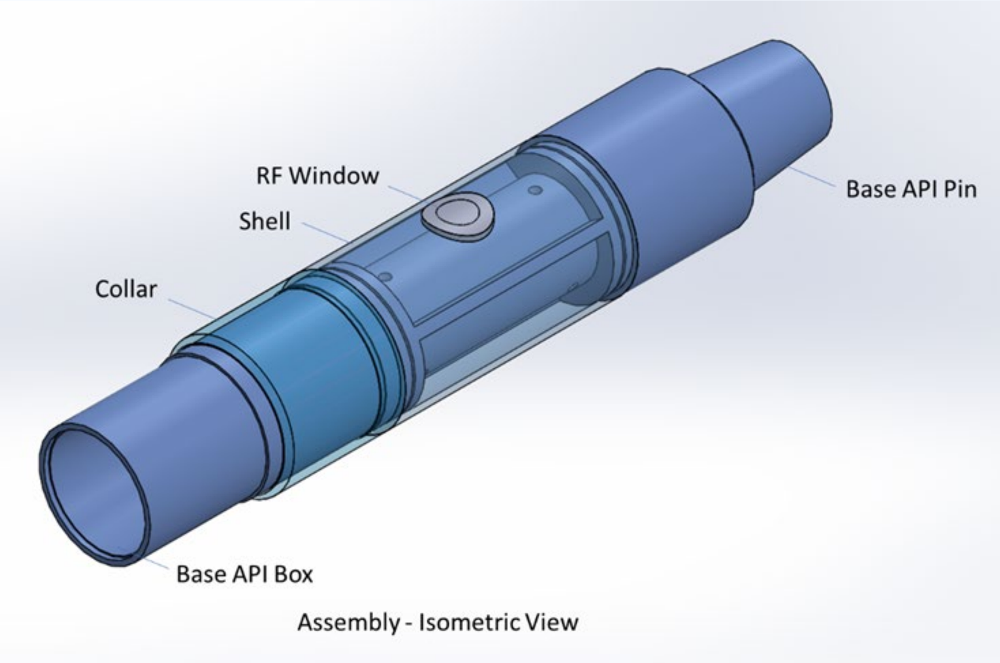


Smart Collar Communication and Power – Lab Prototype



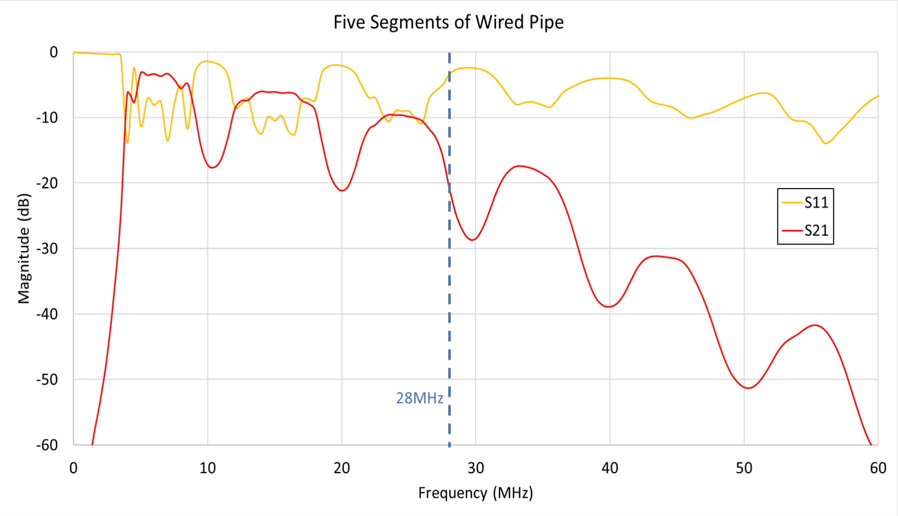
Housing and RF Transmission

- Inductive coupler for wired pipe
- Delrin shell
  - Seals against externals pressures
  - Allows RF propagation
- Compartment for electronics

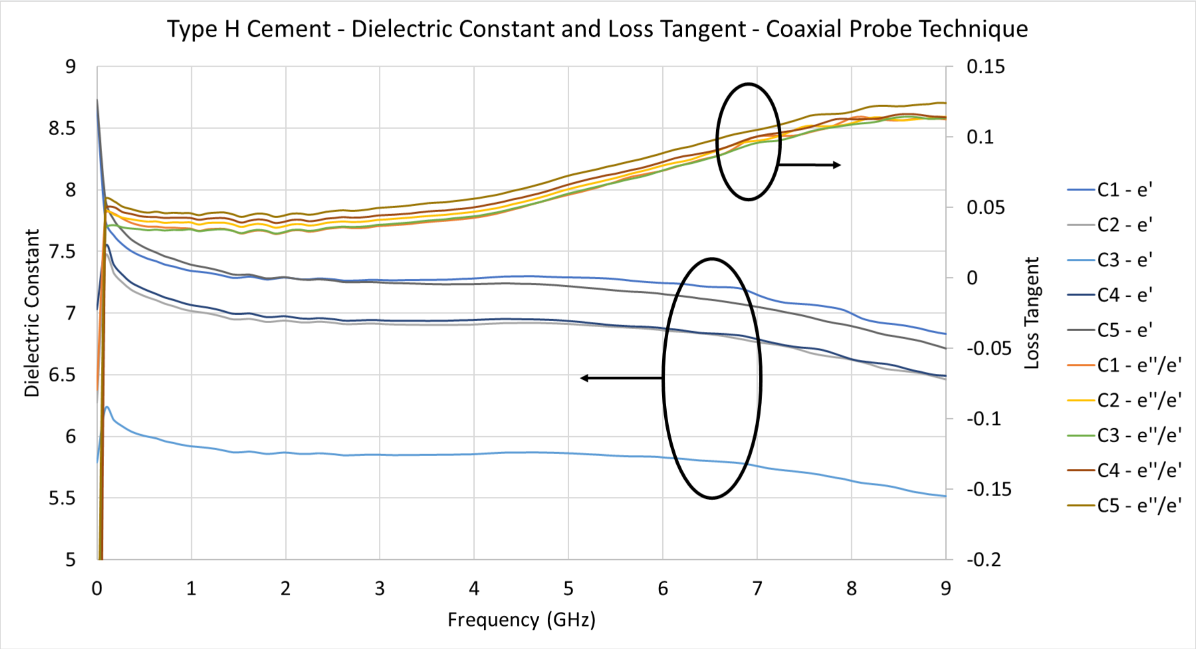


Wired Pipe Characterization

- S-parameters of wired pipe
  - Attenuation and reflection
- 4-21 dB attenuation across the EoC bandwidth
- AC power band at 4 MHz
- 85 Mbits/sec with EOC and wired pipe



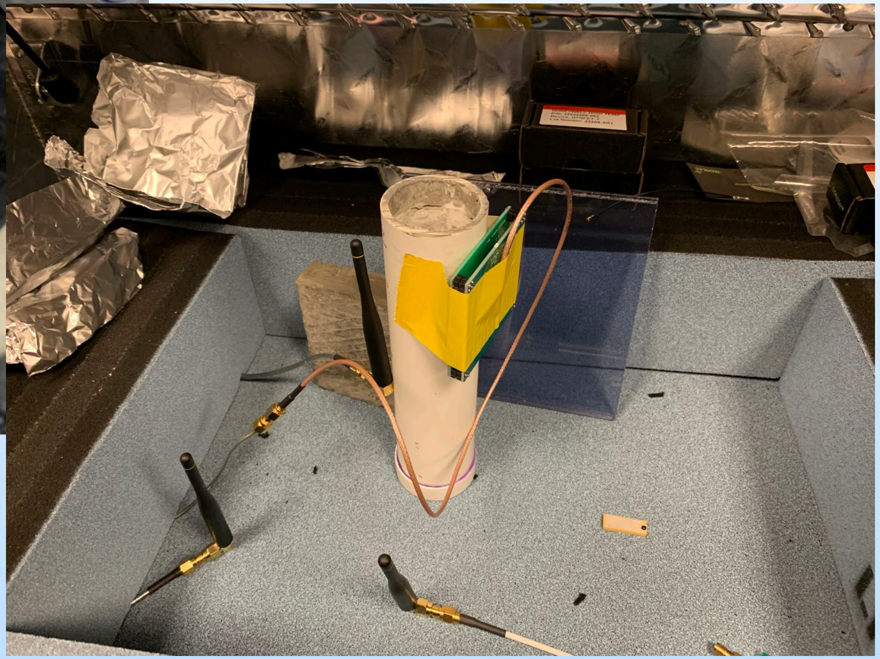
Characterize Dry Cement Samples



- Coaxial open-ended probe characterization technique
- Dry Sample: Loss tangent @ 1 GHz: 0.04 – 0.05, Dielectric Constant @ 1 GHz: 7 – 7.4
- Cement soaked in brine: 0.1%, 2%, and 10% for a couple weeks
  - Loss tangent @ 1GHz: 0.08(0.1%), 0.16(2%), 0.23(10%)
  - Dielectric Constant @ 1GHz: 9.5(0.1%), 10(2%), 14(10%)

Embedded RFID Tag Communications

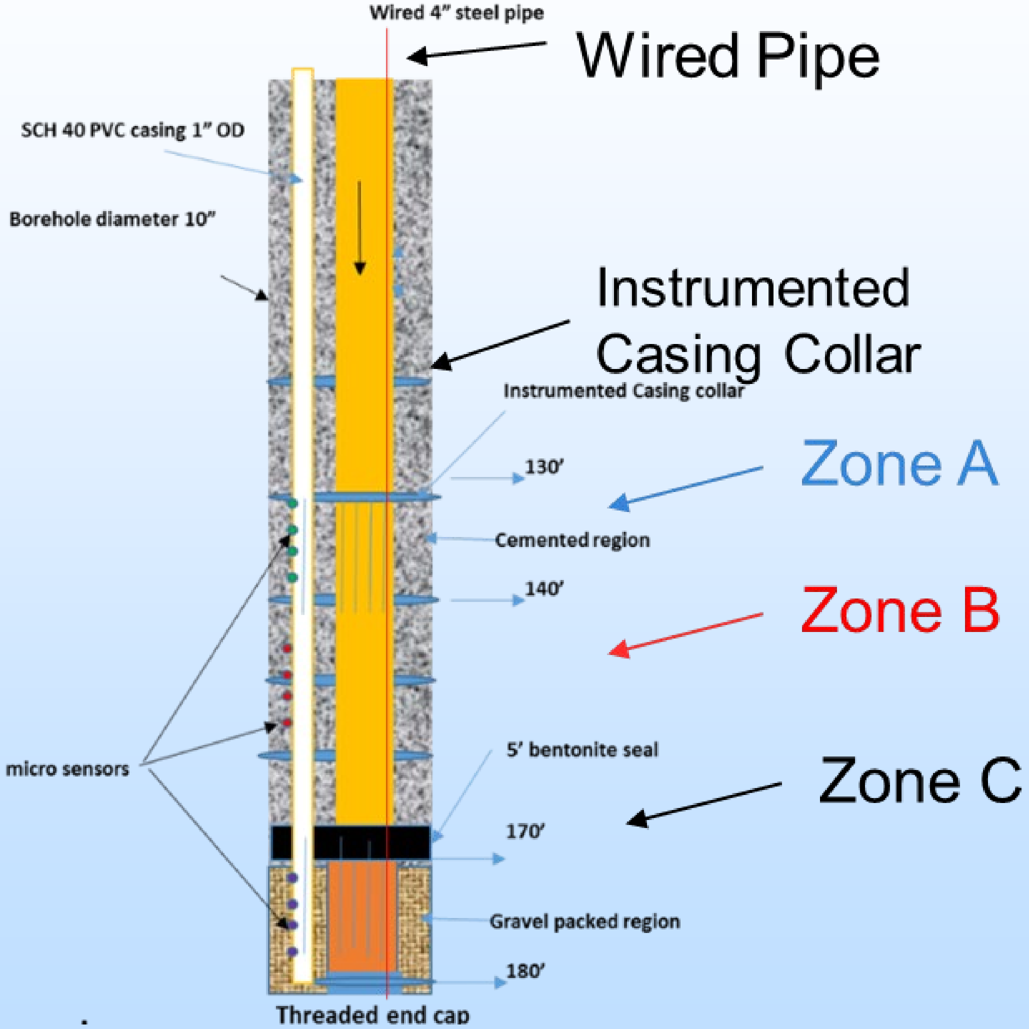
- Embedded Abracon RFID tags within 1.5” PVC, surround with cement
- Communications confirmed with tags
  - 1 watt RF comms.
    - CAENRFID circular polarized antenna
  - 2 watt RF power
    - Omnidirectional antenna



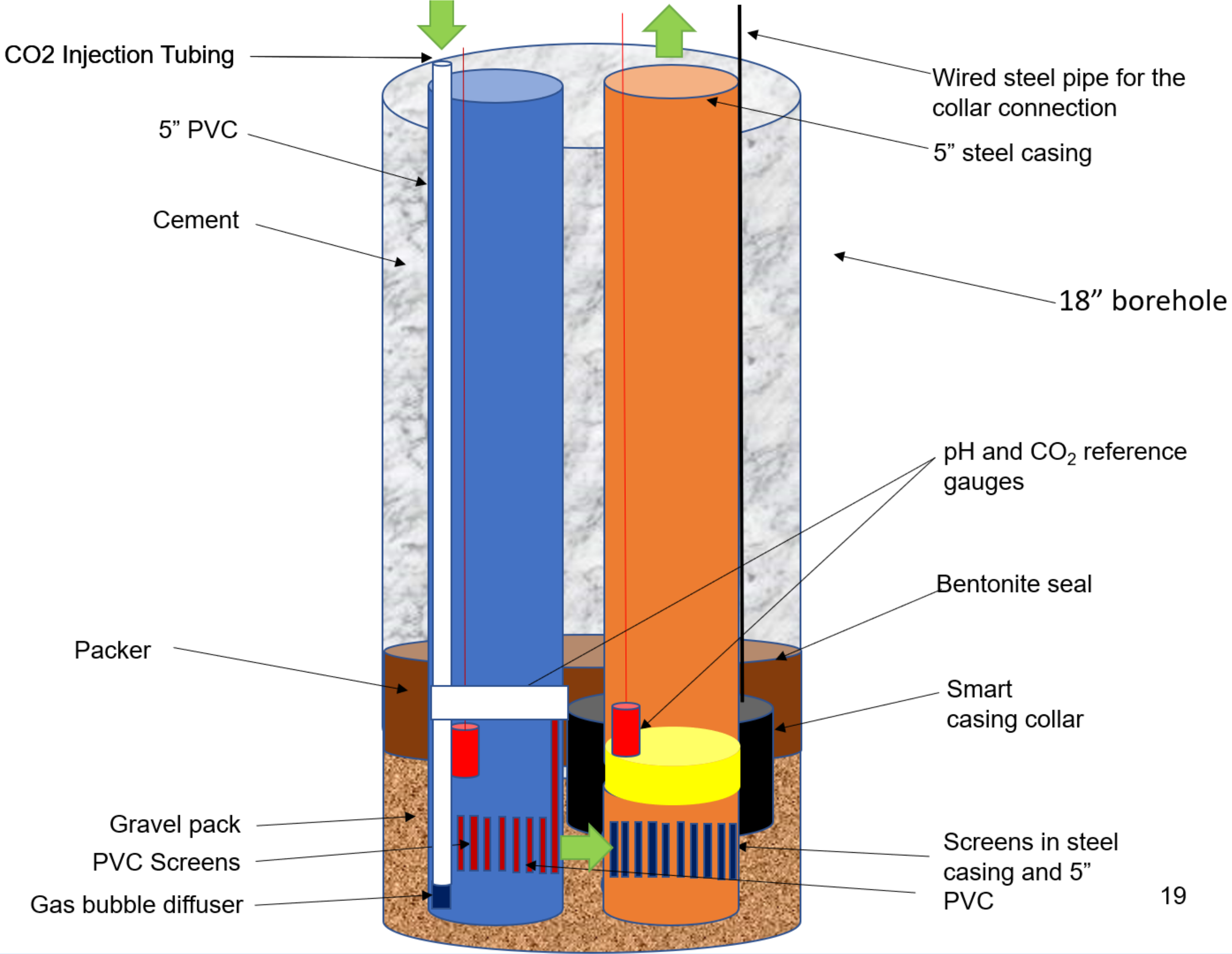
Field Experiment – UT's Devine Test Site

Original Design

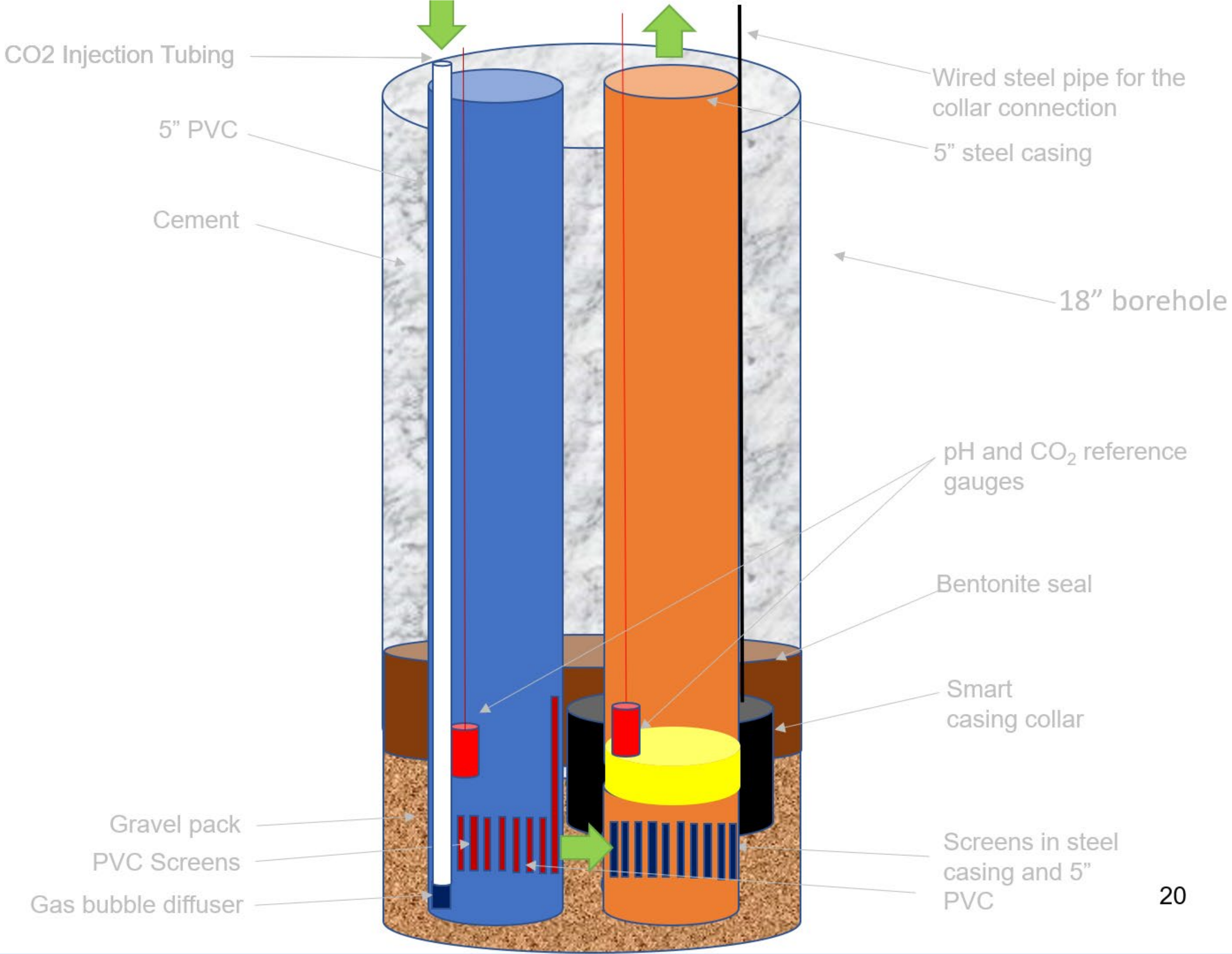
- Multiple smart collars in various test zones
  - A: In non-permeable cement - but in a permeable injection interval
  - B: In non-permeable cement - but in a fluid-deficient zone
  - C: in a permeable gravel pack –in a permeable injection Interval
- Sensors permanently placed in cement or attached to a conveyance rod - next to the casing collars
- pH adjusted fluid injection through adjacent wells at Devine



New Flexible Borehole Design

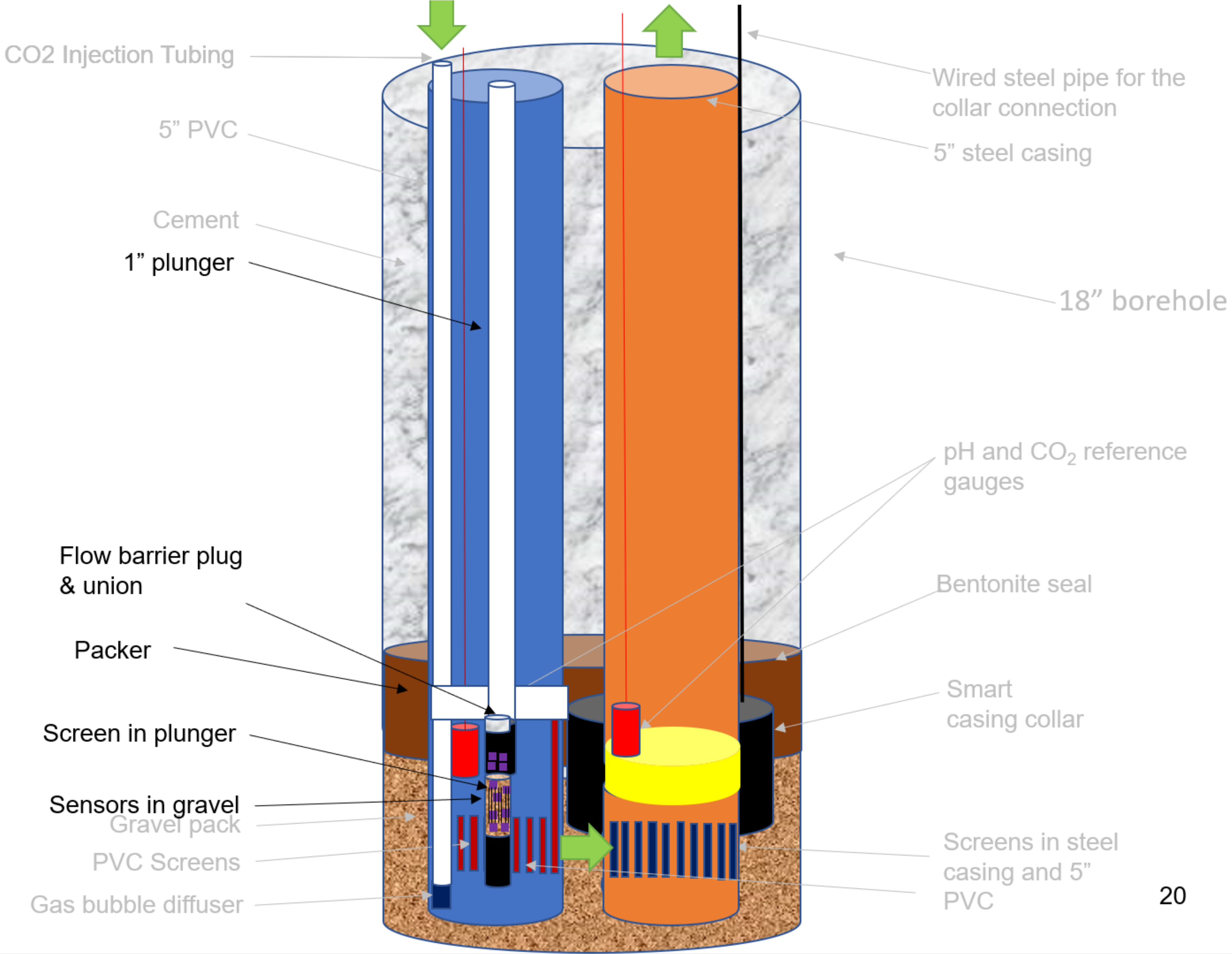


New Flexible Borehole Design:
Allows for testing multiple <u>variables</u> with one smart casing collar:



New Flexible Borehole Design:
Allows for testing multiple variables with one smart casing collar:

1. Distance to casing collar
2. Background material
3. Concentration of stimuli
4. Time of exposure
5. Sensor type
6. Gas or liquid injection
7. Reference gauges
8. Etc.

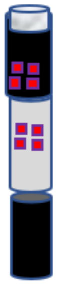


Lower portion of plunger can be changed with different wellbore construction materials and/or sensors types:

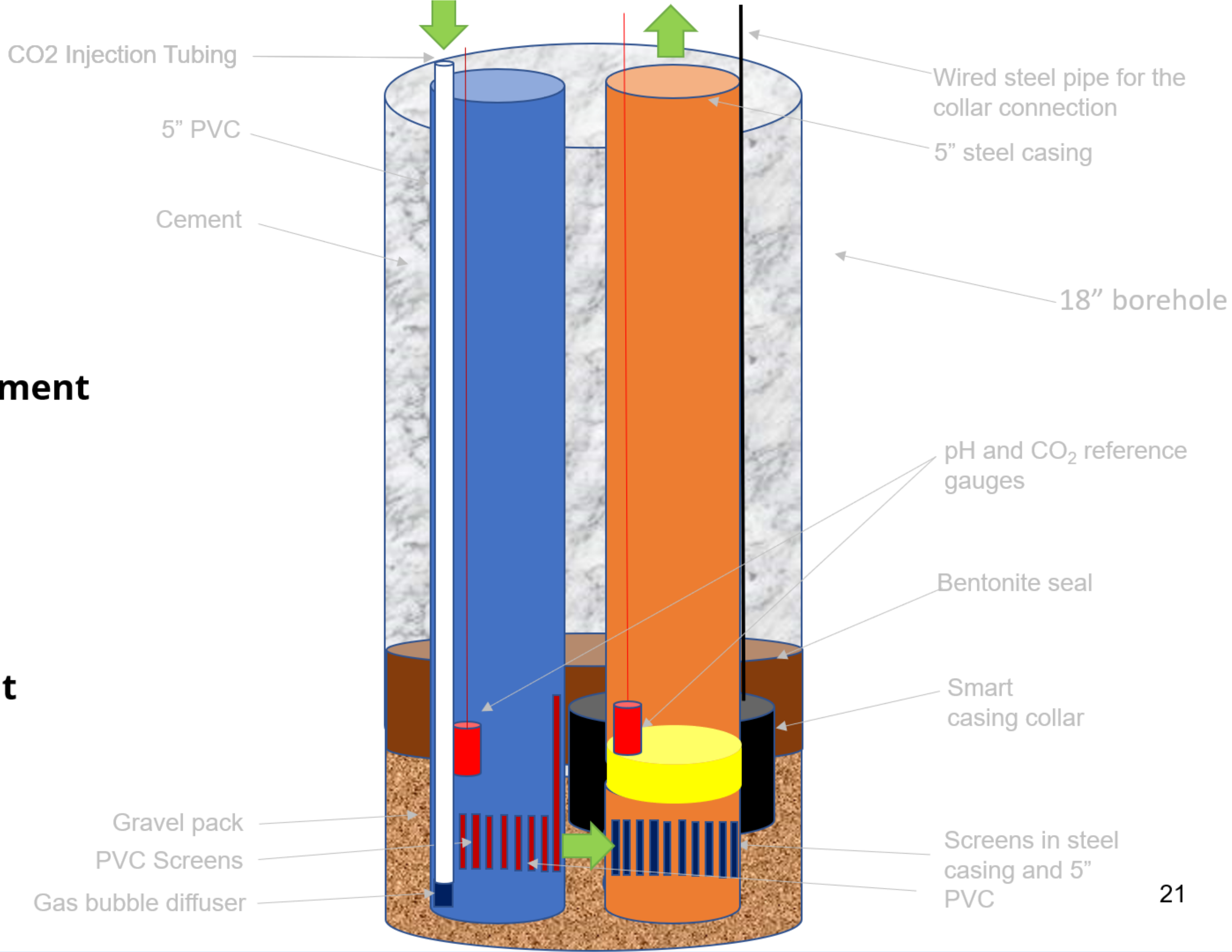
Sensors in Crushed Cement

Sensors attached on top of the PVC act as positive control for each section

Sensors in Intact Cement



Sensors embedded in intact cement act as negative control



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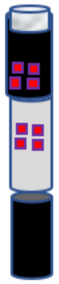

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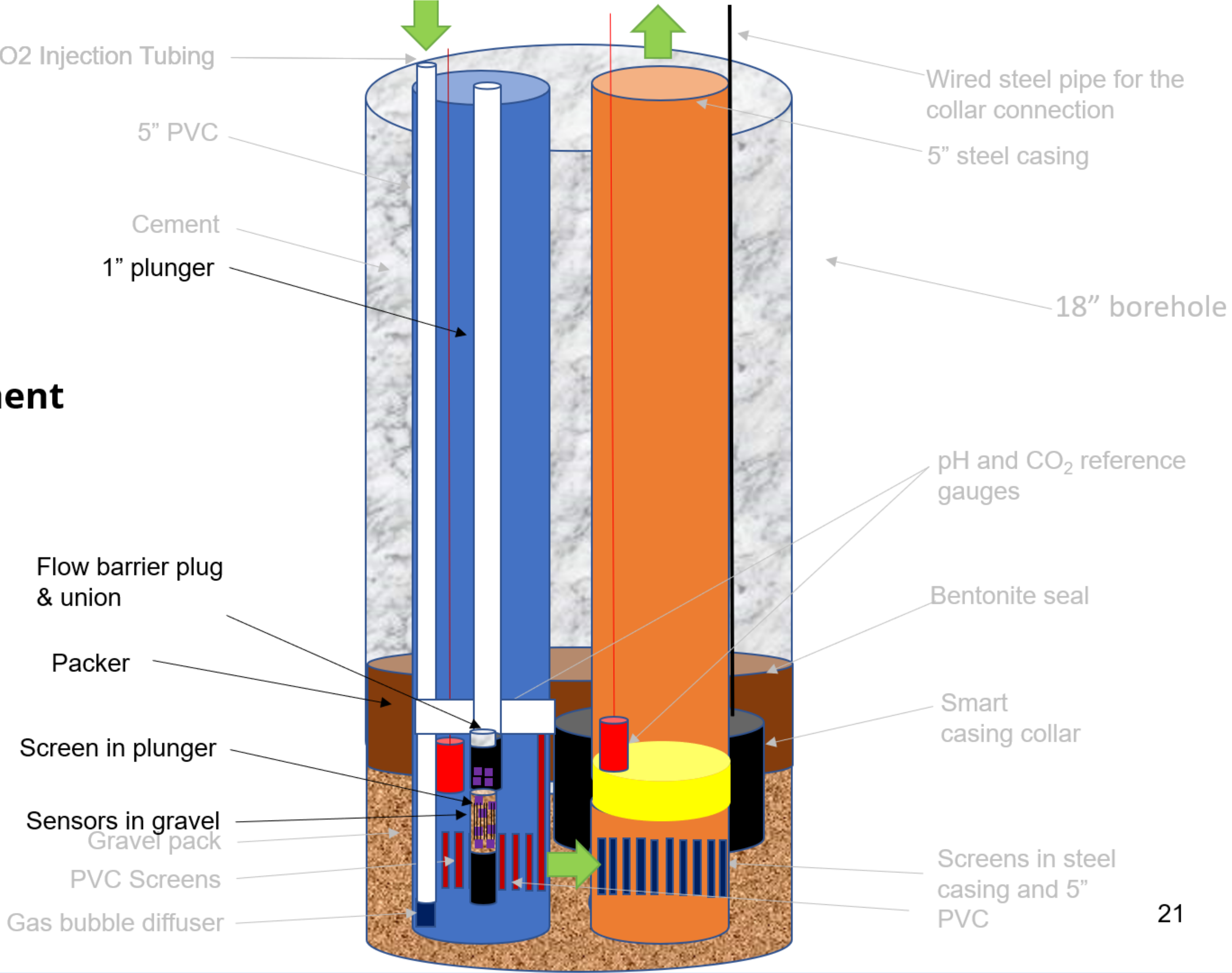
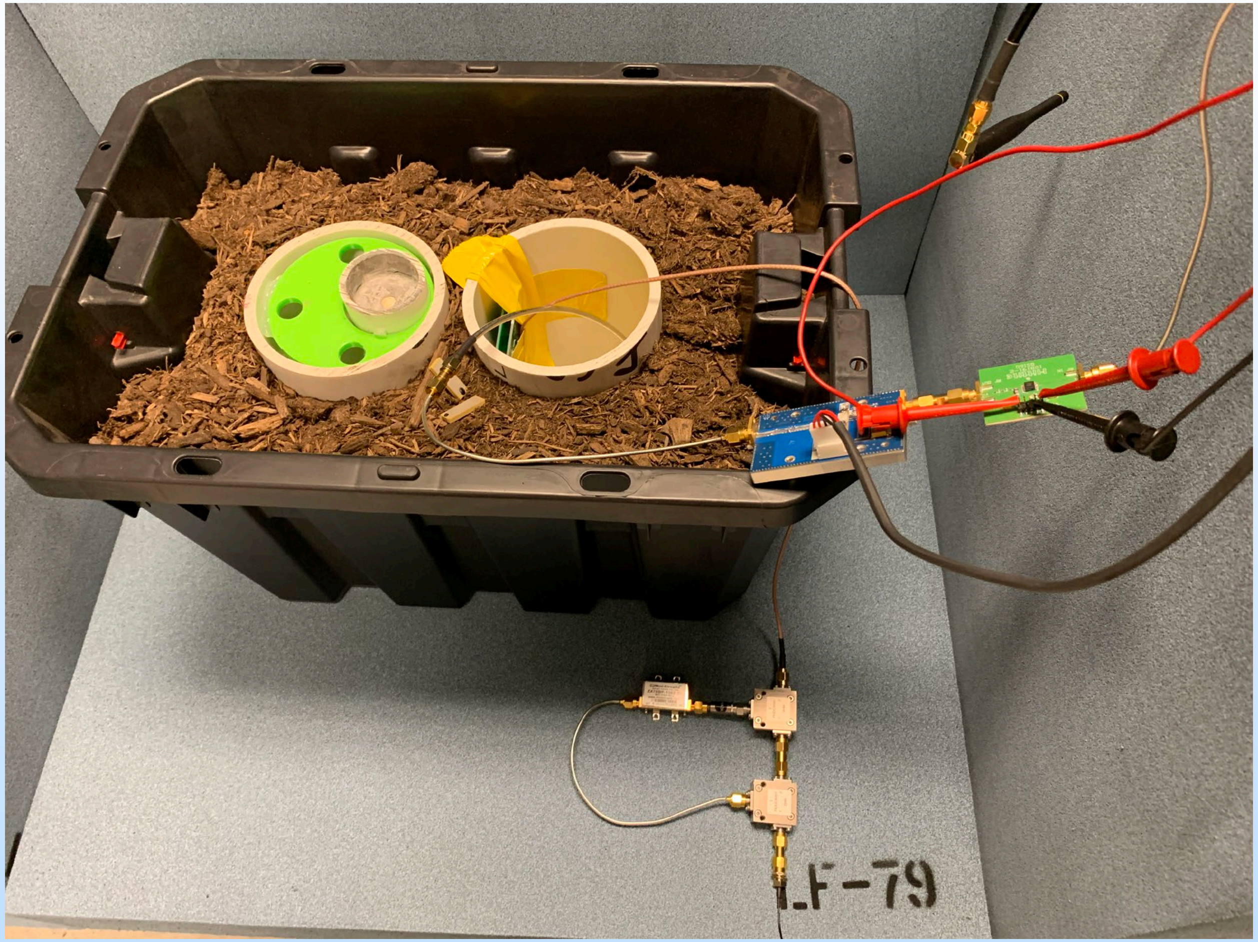


Devine Simulation- Lab RF Testing Setup

- Preparing setup to mimic Devine Test Site
- 4 inch pipe for Smart Collar and parallel pipe
- 9 watt RF Power
- 1 watt RF communications
- 20 dB anechoic chamber



Acknowledgment - Thank you!

Funding for this project provided by DOE Fossil and NETL. 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 and the support and guidance of our program manager Bill Aljoe