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Downhole Smart Collar Technology for Wireless Real-Time Fluid Monitoring

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ABSTRACT

Carbon sequestration is a growing field that requires subsurface monitoring for potential leakage of the sequestered fluids through the casing annulus. Sandia National Laboratories (SNL) is developing a smart collar system for downhole fluid monitoring during carbon sequestration. This technology is part of a collaboration between SNL, University of Texas at Austin (UT Austin) (project lead), California Institute of Technology (Caltech), and Research Triangle Institute (RTI) to obtain real-time monitoring of the movement of fluids in the subsurface through direct formation measurements. Caltech and RTI are developing millimeter-scale radio frequency identification (RFID) sensors that can sense carbon dioxide, pH, and methane. These sensors will be impervious to cement, and as such, can be mixed with cement and poured into the casing annulus. The sensors are powered and communicate via standard RFID protocol at 902–928 MHz. SNL is developing a smart collar system that wirelessly gathers RFID sensor data from the sensors embedded in the cement annulus and relays that data to the surface via a wired pipe that utilizes inductive coupling at the collar to transfer data through each segment of pipe. This system cannot transfer a direct current signal to power the smart collar, and therefore, both power and communications will be implemented using alternating current and electromagnetic signals at different frequencies. The complete system will be evaluated at UT Austin's Devine Test Site, which is a highly characterized and hydraulically fractured site. This is the second year of the three-year effort, and a review of SNL's progress on the design and implementation of the smart collar system is provided.

1. Introduction

A critical component in combating anthropogenic climate change is leak resistant storage of captured atmospheric carbon dioxide (CO_2) and other greenhouse gasses. One method for achieving long-term storage is to inject the CO_2 into the subsurface via boreholes drilled to depths

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of 2000 to 4000 m as illustrated in Figure 1. A water-filled steel casing is used to prevent the rock from collapsing, and the CO_2 is injected through tubing within the casing. Sensors (instrumentation equipment) are located above and below the cap rock to monitor for CO_2 and ensure none of the sequestered CO_2 leaks back into the atmosphere. The instrumentation monitors for leaks between the cap rock, casing annulus, and casing. This activity continues for the duration of injection (up to 20 years) and for up to 20 years after the borehole is plugged.

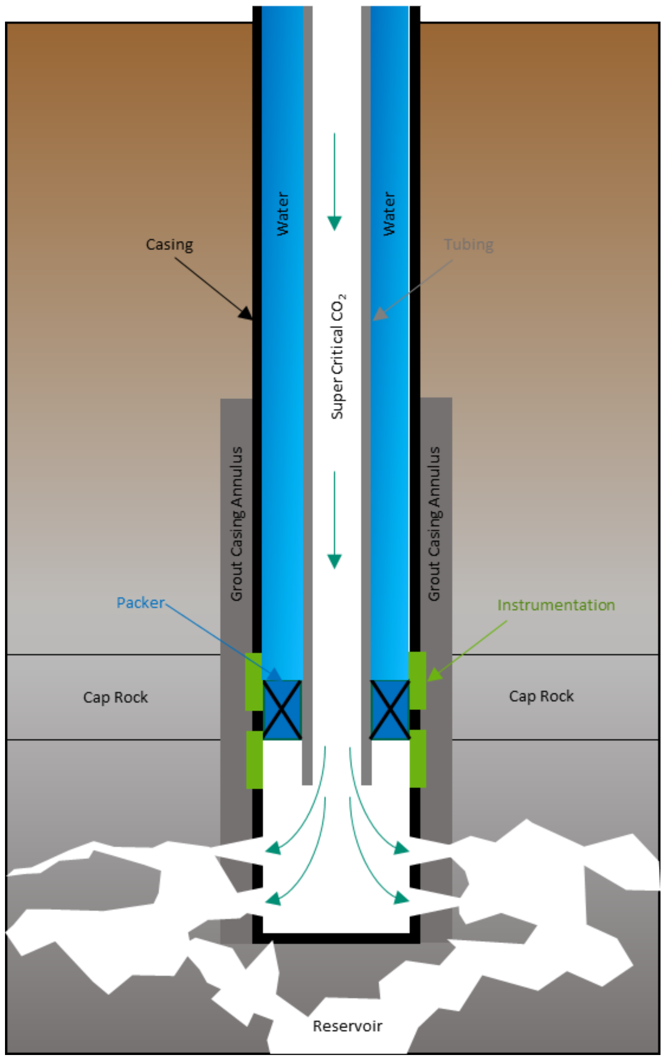

Figure 1: Illustration of CO_2 injection into the subsurface.

It is challenging to monitor fluids at significant depths without creating a leakage pathway back to the surface for over 40 years of operation. Current technologies for communicating with downhole instrumentation, such as fiber optics, electrical wire, wireless radio frequency (RF) transmission, and acoustics, are not ideally suited for this application. Individually, these solutions can be prone to damage during installation, create a leak pathway to the surface, and experience long-term degradation, and/or high propagation loss. A collaboration between University of Texas at Austin (UT Austin), Sandia National Laboratories (SNL), California Institute of Technology (Caltech), and Research Triangle Institute (RTI) seeks to demonstrate a subsurface system that can detect fluids in the casing annulus using a combination of wired pipe and wireless sensors embedded in the casing annulus cement.

2. Design Goals

The project goal is to advance a fully integrated system for validating the detection of fluid in a casing annulus to a Technology Readiness Level 5. The system will utilize a combination of technologies for validating the concept, including wired pipe for communications/power, wireless radio frequency identification (RFID) sensors to detect fluids in the cement, and a custom smart collar to relay the RFID data to the surface (Figure 2). UT Austin is the project lead for this effort and will provide testing at a highly instrumented field test site. SNL's role is to develop the smart collar for collecting data from the RFID sensors and relaying it to the surface. Caltech is developing the RFID sensors for detecting CO_2, pH, CH_4, and temperature in the casing annulus. Finally, RTI is designing the RFID specialized polymer coating, enabling sensor survival in the sequestration environment.

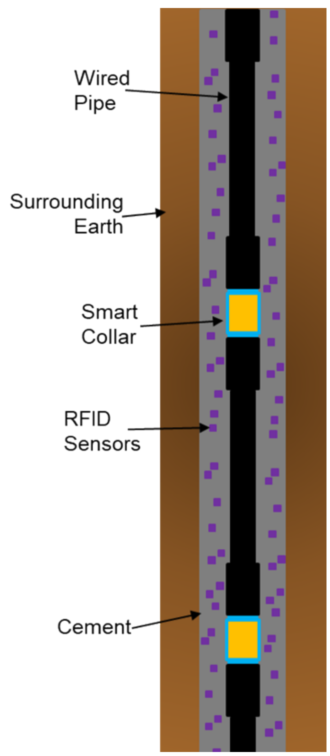

Figure 2: Illustration of the subsurface installation with wired pipe, smart collar, and RFID sensors.

Caltech is utilizing its expertise in RFID sensor technology to develop new millimeter-scale sensors capable of measuring CO_2, pH, CH_4, and temperature (see example in Figure 3). These sensors will be mixed and injected with the drilling mud, which segregates the sensors on the formation surface. RTI is developing a polymer coating (Figure 3) that will be applied to the sensors to protect them while still enabling detection of the fluids of interest. This coating will allow the sensors to withstand drilling mud, the pumping mechanism, and the subsurface environment.

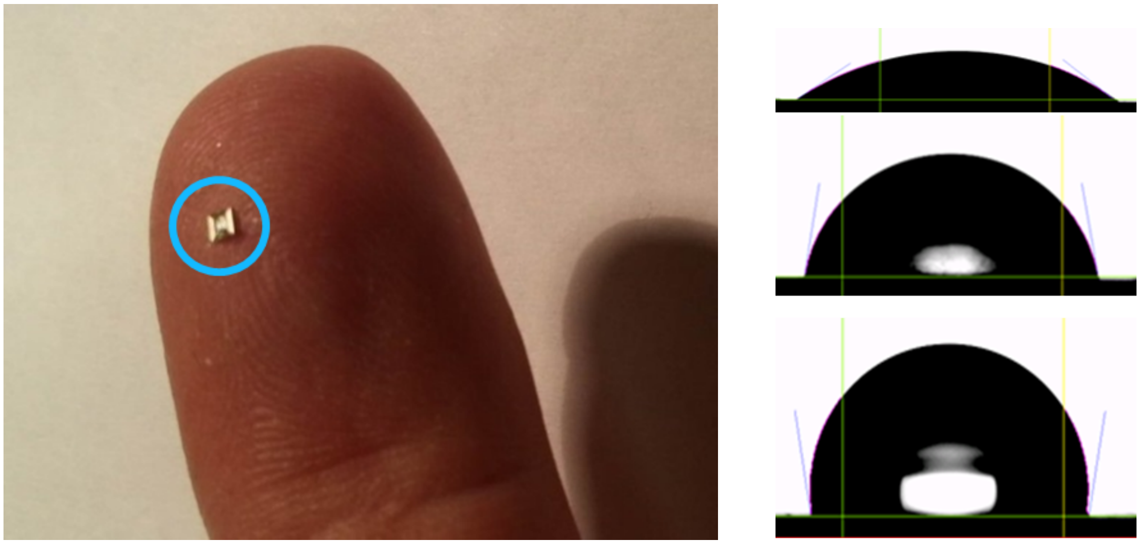

Figure 3: Picture of the millimeter-scale RFID sensor from Caltech (left) and polymer coating on the sensor from RTI (right).

The focus of this paper is the smart collar technology being developed by SNL. For this demonstration, wired pipe will be used for bi-directional communications and powering the instrumentation electronics. The smart collar will wirelessly power the RFID sensors embedded in the casing annulus by transmitting high RF energy through the annulus cement to power the micron-size circuit on the RFID sensor. Simultaneously, bi-directional communications will be utilized to capture the sensor data, and the onboard smart collar microcontroller will relay the information back to a computer at the ground surface.

2.1 Smart Collar Design

The smart collar is a unit placed between sections of wired pipe used to collect and relay status data from the casing annulus to the surface. The electronics contained within the smart collar will be protected by a watertight enclosure as it is anticipated there will be high pressure fluids both within the center of the collar and in the annular space. Power for the onboard electronics will be stored within a bank of supercapacitors so the device will last several decades, something that current battery technology cannot achieve.

The electronic system design shown in Figure 4 uses off-the-shelf wired pipe to propagate an RF and alternating current (AC) signal from the surface to the smart collar. At the ground surface, a computer will transmit commands and receive the subsurface data. An Ethernet Over Coax (EoC) module will be used to convert data from a computer's ethernet port to a two-wire coaxial typology. This data signal will then be combined with a 1.5 W AC power signal and injected into the wired pipe, and a smart collar placed between segments of wired pipe will split the RF and AC signals. The AC signal will be rectified and charge a bank of supercapacitors. Once sufficient energy has been stored, it will be regulated and used by the necessary components. The RF signal will be converted back to ethernet and processed by the on-board microcontroller. When the microcontroller determines there is enough energy stored in the bank, the RFID reader and amplifier will quickly power the embedded RFID sensors and collect data from the environment. After data retrieval, the reader and amplifier will be put into sleep mode to conserve power, and the onboard microcontroller will then reverse the ethernet/coax/ethernet data link with the surface computer to send the gathered information.

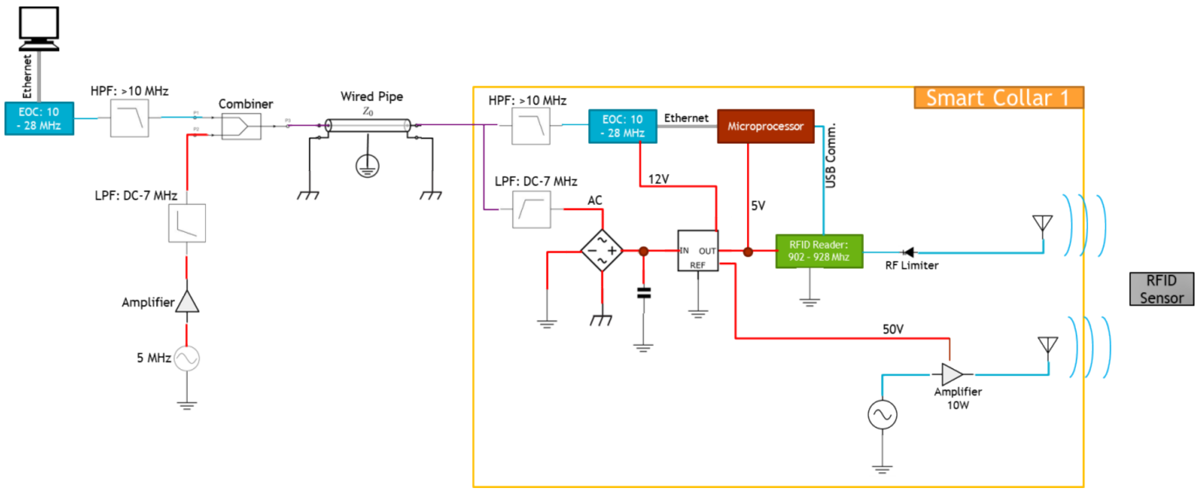

Figure 4: General schematic of the computer on the surface, communication/power through the wired pipe, and the smart collar system.

The initial design of the smart collar housing is shown in Figure 5. Steel will be used for the structure to ensure it can handle the weight of the wired pipe string. It will consist of a box and pin so that it can be placed between wired pipe segments, enabling RF coupling through the wired pipe and allowing multiple smart collars to be used along the length of the borehole. Thus, multiple points along the length of the borehole can be monitored for fluids in the casing annulus.

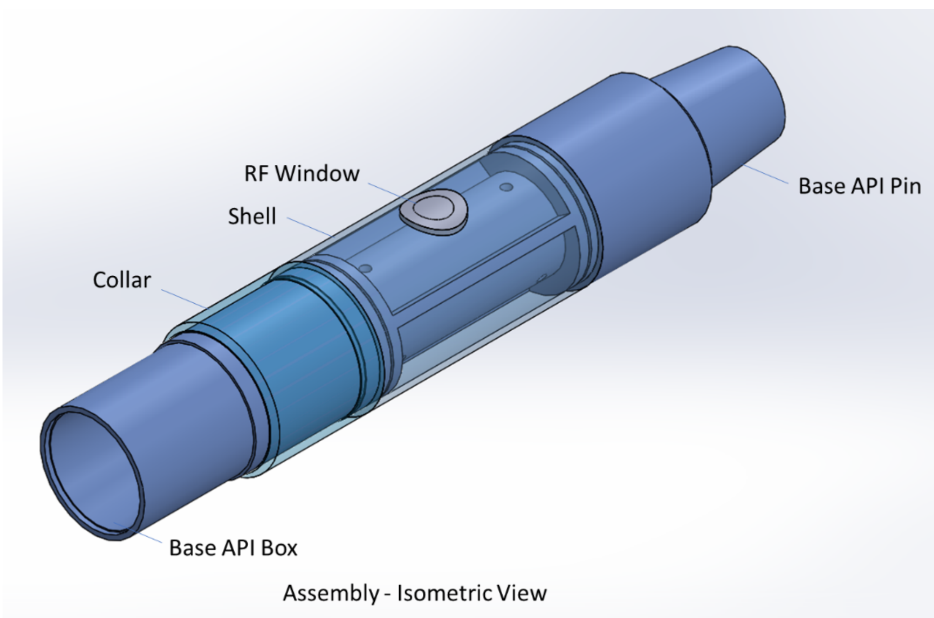

Figure 5: Smart collar housing, design to support the load of the wired pipe, and design to have no leakage pathways. The RF window is a non-conductive solid that seals against fluids but enables communications between the antenna and RFID sensors.

The volume between the base and shell will be used to keep the electronics safe from the surrounding subsurface environment. An RF window will be placed on the shell to allow communications between the antenna and RFID sensors while sealing against pressurized fluids, preventing them from penetrating the electronics bay. An evaluation of nonconductive tungsten carbide supported polycrystalline diamond and alumina are being conducted the RF window.

2.1.1 Subsurface Communications and Power

Off-the-shelf wired pipe will be used for communications and power for the smart collars. Typically, wired pipe is used for drilling applications, but for this effort it will be used as a casing. The wired pipe has been characterized and observed to operate from 3.5–28 MHz with 5–20 dB of attenuation across five segments of pipe. Each pipe has a length of 9.8 m (32 ft). Gain and reflection data as a function of frequency is shown in Figure 6.

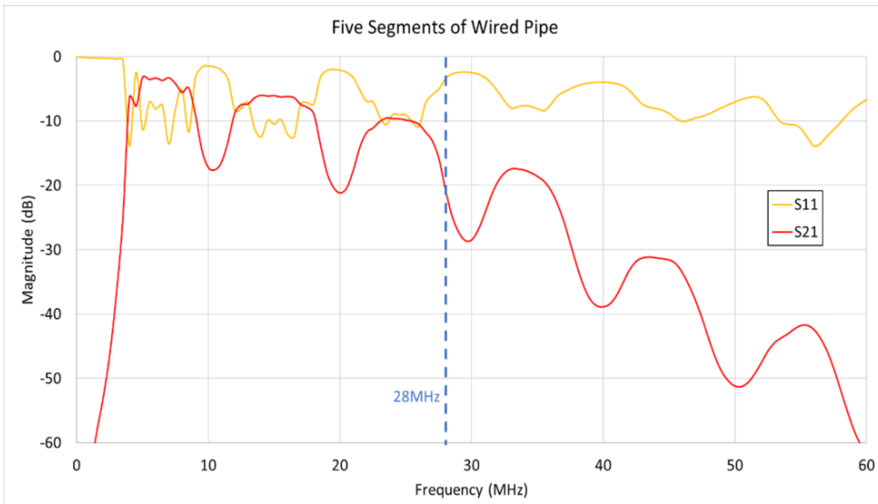

Figure 6: Insertion loss and port 1 reflection for the wired pipe.

Figure 7: Testing communications with the ethernet-to-coax module through the wired pipe.

A pair of off-the-shelf EoC modules appropriate for this application were selected based on the wired pipe’s performance. The EoC modules can operate between DC-28 MHz but are flexible enough to allow selection of the ideal operating frequency within that band. They can also operate with more than 60 dB of attenuation between them. The EoC modules were tested on the wired pipe, and data rates of over 80 Mbits/s across five segments of wired pipe were observed (Figure 7).

A variable attenuator was used to replicate the wired pipe and simplify the evaluation process. Both communications and power were evaluated through the attenuator via the laboratory tabletop setup shown in Figure 8. A Tabor A10160 amplifier was used to transmit an AC power signal (S-parameters and output power shown in Figure 9) by amplifying a 4 MHz signal to produce 1.6 dBm of power. Simultaneous transmission of both power and data (via the EoC modules) was tested and a data throughput of 60 Mbits/s was observed; after the attenuation, a 30 Vpp (peak-to-peak voltage) signal was also observed; and finally, upon rectification and conditioning this translated to an open circuit voltage of 16 V_{DC} and a short circuit current of 250 mA. Observations show that it takes 7 minutes to charge a 20 F, 2.7 V supercapacitor. The next step will be to evaluate the electronics on the wired pipe to confirm proper operation.

Figure 8: Bench top setup for testing communications and power transfer simultaneously. Variable attenuator represents the wired pipe.

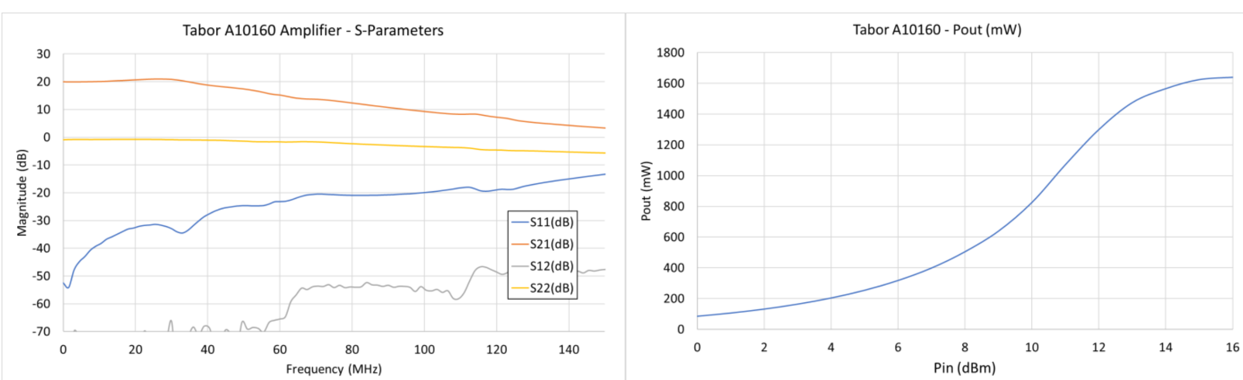

Figure 9: S-parameters and output power for Tabor A10160 Amplifier.

2.1.2 RFID Communications and Power

Communication and power transfer to the RFID sensors embedded within the annulus cement will use two distinct RF frequencies; power will be transmitted at 903 MHz, and communications will be transmitted at 920MHz. Initially, a single frequency was investigated for both power and communications by boosting the output RFID reader signal with an amplifier and then allowing the reflected sensor signal to bypass the amplifier via RF circulators (see Figure 10). However, after further study, it was determined that the reflected energy from the cement caused too much interference with the reflected data from the RFID sensors. This low signal-to-noise ratio prevented single frequency communication within the desired environment. Future testing will examine the two discrete frequency approach.

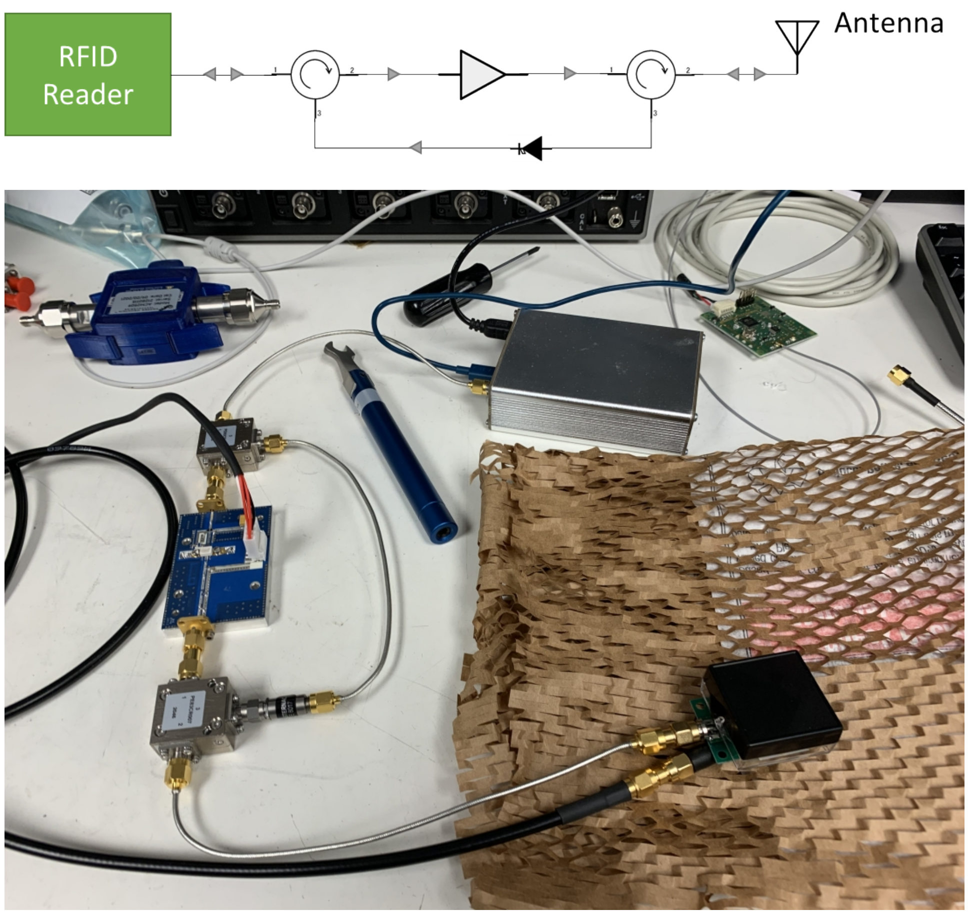

Figure 10: Evaluating power amplifier/circulator with RFID reader for long range communications. Schematic (Top) and real hardware (bottom).

The Cree CMPA0527005F amplifier, which can produce 20 dB of gain and output up to 9.3 W of power, will be used to power the RFID sensors. SNL tested the amplifier and measured about 5 W of output power at 40–50 V bias (Figure 11). However, the full power range could not be measured due to limitations of the signal generator used during the evaluation. We expect that 5–10 W of power will be required to compensate for the attenuation from the cement surrounding the RFID sensors. Note that Federal Communications Commission regulations restrict emission at the 902–928 MHz range to 1 W, and thus, all evaluations of this technology are taking place within an anechoic chamber to suppress the signal emitted into free space.

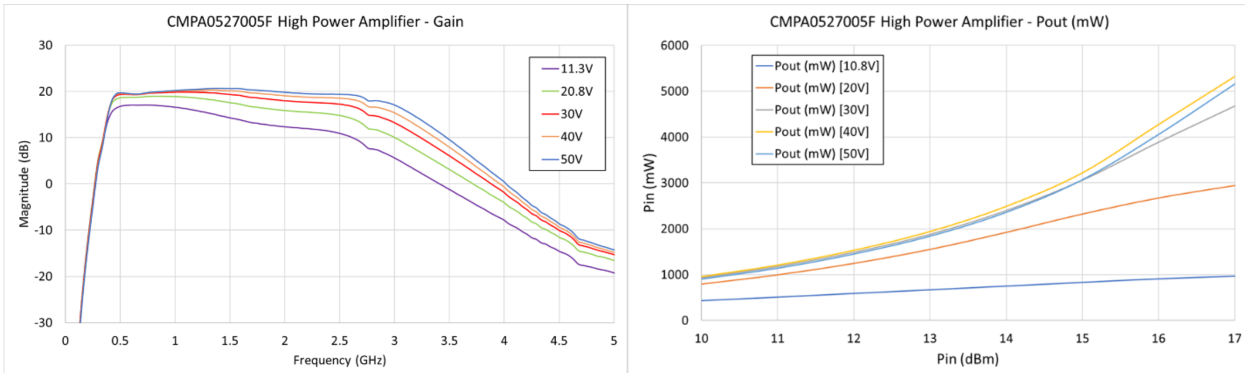

Figure 11: Gain profile and output power of the Cree high power amplifier. Full output power profile could not be measured due to limitation of equipment output power. Amplifier is specified for 10 W output at 50 V setting.

The cement that will be used in the casing annulus was characterized using the open-probe technique to determine its dielectric constant and loss tangent (Figure 12). There is no coaxial cable connected to the probe in Figure 12; the image simply illustrates the method of making contact between the probe and cement. A vector network analyzer was used to capture S11 (reflection from the probe) and back calculate the dielectric constant and loss tangent.

Figure 12: Characterizing the dielectric constant and loss tangent of cement that will be used in the casing annulus.

Five class H cement samples were tested in a dry state, and the results are shown in Figure 13. At 1 GHz, a 0.04–0.05 loss tangent and a 7–7.4 dielectric constant was observed. There is an outlier for one of the samples, likely due to an air bubble on the surface that degraded the measurement.

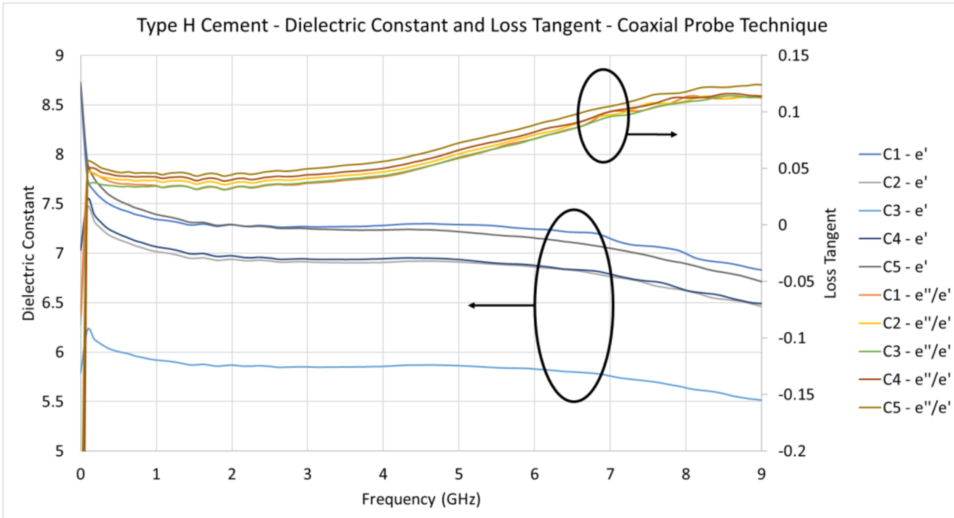

Figure 13: Measured dielectric constant and loss tangent of dry cement samples.

In a real-world carbon sequestration environment, the samples will be saturated with brine, so the test was repeated at three different brine levels, 0.1%, 2%, and 10% (Table 1). At higher brine concentrations, the dielectric constant and loss tangent increases. These results will be used by electromagnetic (EM) simulation software to calculate the loss in relation to the thickness of the cement and the amount of power needed from the Cree amplifier. The simulation software will also inform the quantity of energy reflected and whether a custom antenna will be required to improve the RF injection efficiency.

Table 1: Dielectric Constant and Loss Tangent of cement at various brine levels.

Brine Level	0%	0.1%	2%	10%
Dielectric Constant	7.2	9.5	10	14
Loss Tangent	0.045	0.08	0.16	0.23

3.1 Field Experiment

Currently, smart collar development is in its second year of the projected three-year effort. A working prototype that can be linked with the wired pipe is expected by the end of year two, and a field test of the complete system is anticipated by the end of year three. The field test will be conducted at UT Austin's highly instrumented field test site. As part of the demonstration, the full system will be permanently emplaced into a borehole at the test site. This will include the wired pipe, smart collar, and RFID sensors. PVC pipe emplaced next to the length of wired pipe will both position the RFID sensors relative to the smart collar and allow a detection fluid to be injected directly into the sensor (see Figure 14). This will allow us to demonstrate the technology without producing large quantities of RFID sensors and smart collars and also eliminate the need for a fracture to inject the detection fluid.

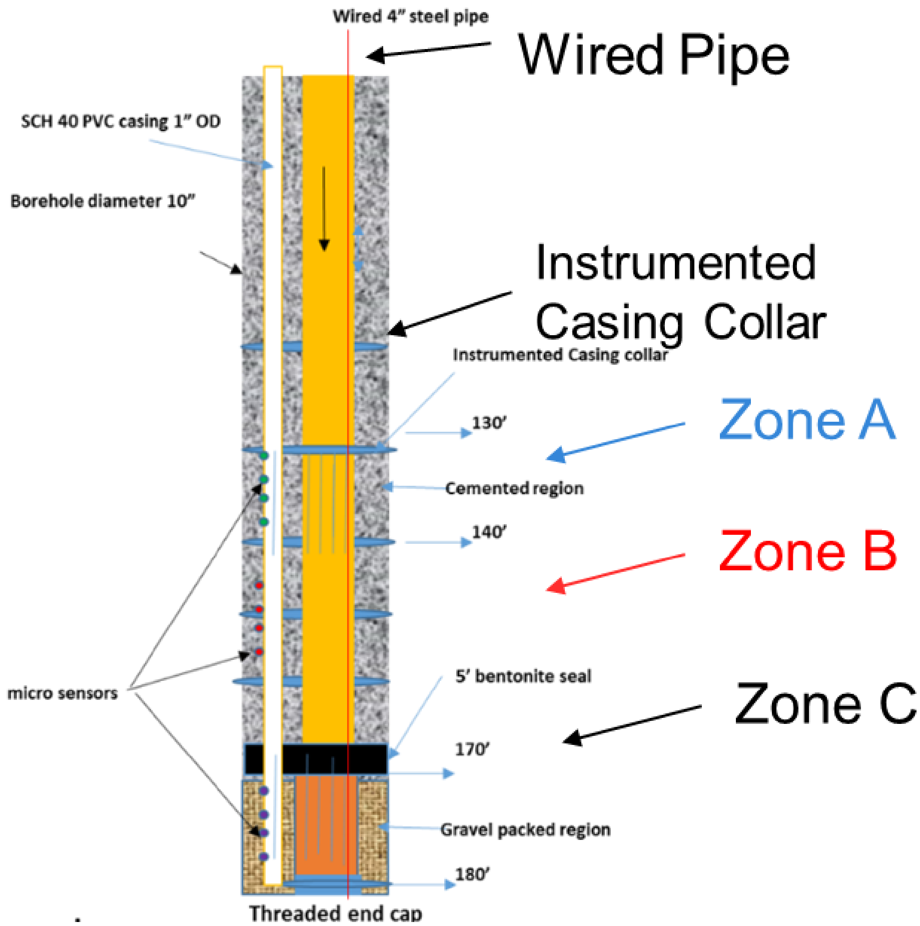

Figure 14: Proposed subsurface experiment at UT's highly characterized test site.

4.1 Conclusion

SNL is on schedule to build a working smart collar prototype by the end of 2022. The project has demonstrated high speed communications through a set of wired pipes, tested simultaneous communications and power in the laboratory, and completed preliminary work to test methods for communicating with RFID sensors embedded in cement. In addition, the initial design of a ruggedized housing and RF characterization of the casing annulus cement are underway. Next steps include simulating the cement in an EM simulator, validating communications with the RFID sensors through cement, and building a full prototype in preparation for emplacement at the field test site.

This technology is the first step to enabling subsurface monitoring of environments that can reliably store (sequester) CO_2 within the earth for more than 40 years. Wired pipe (in this case drill string) is much more expensive than standard casing, and this use case could necessitate the production of wired casing to reduce costs. Another option would be to develop a hybrid communication system with the wired pipe and other methods of communication to balance cost, reliability, and efficiency, while preventing leakage pathways.

Acknowledgement

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.

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