Wireless Microsensors System for Monitoring Deep Subsurface Operations

DE-FE0031850

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management and Oil and Gas Research Project Review Meeting – Carbon Storage
August 2 - 11, 2021

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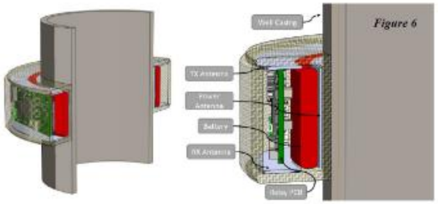

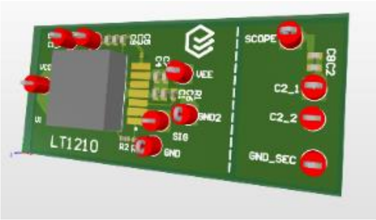

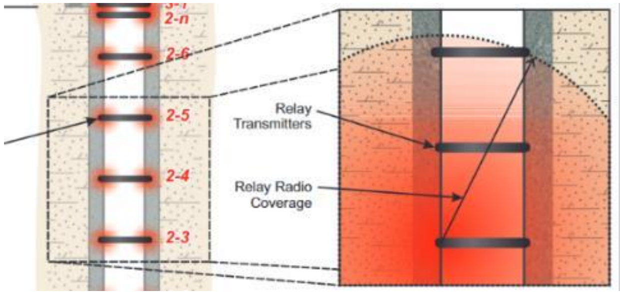

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Technical Status

- 3-year DOE-NETL project under *FOA1998 "Transformational Sensing Systems for Monitoring the Deep Subsurface" (started Feb. 2020)*
- Project Objective = Develop a technology for wireless downhole monitoring of subsurface operations via a three-prong approach:

Feb 2020-Dec 2021

1. Sensor System Development- design and fabricate a fully integrated wireless microsensor-based downhole sensing system to **measure temperature** as the primary indicator of CO_2 presence.

2. Field Deployment/Demonstration- demonstrate system operational feasibility by deploying & testing the sensor system in the casing annulus of two legacy oil & gas wells in Eastern Ohio.

3. Techno-Economic Analysis- establish the technical feasibility & practical utility of the sensing system for reservoir/above zone monitoring in a commercial-scale CO_2 storage complex with numerical multi-phase thermal reservoir simulations and a techno-economic evaluation that benchmarks the total costs, risks and unique benefits.

Result= real time, autonomous monitoring system for accurately tracking/modelling the subsurface movement of CO_2 plumes.

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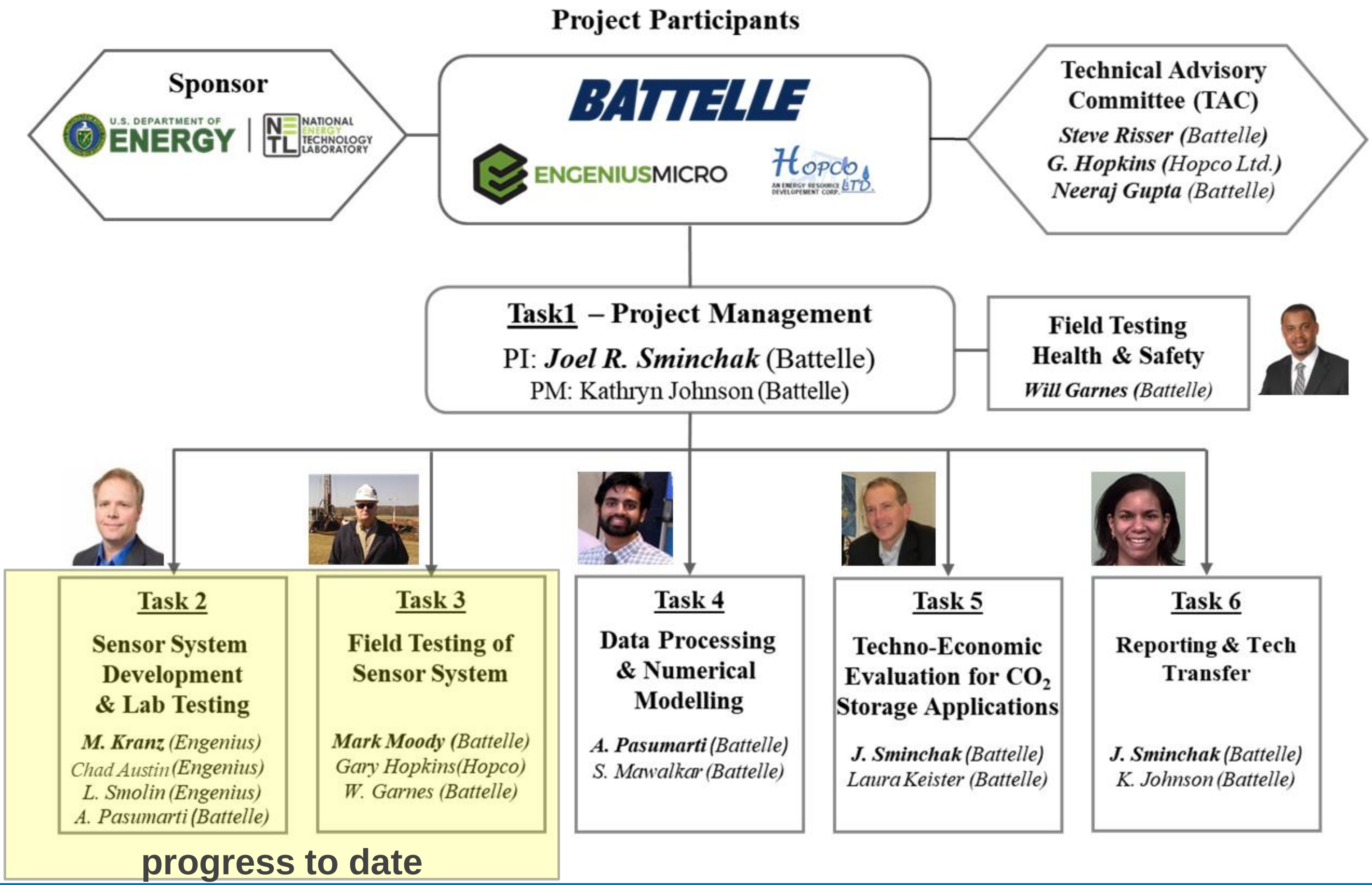
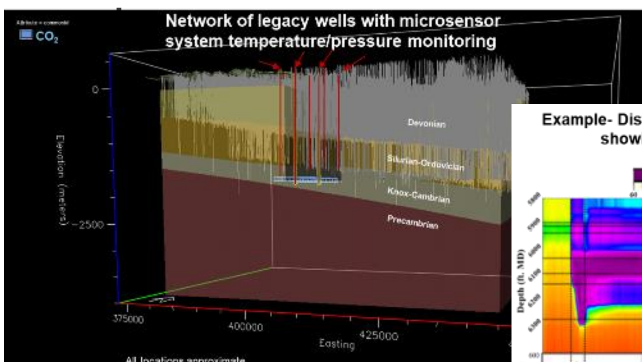
Technical Status

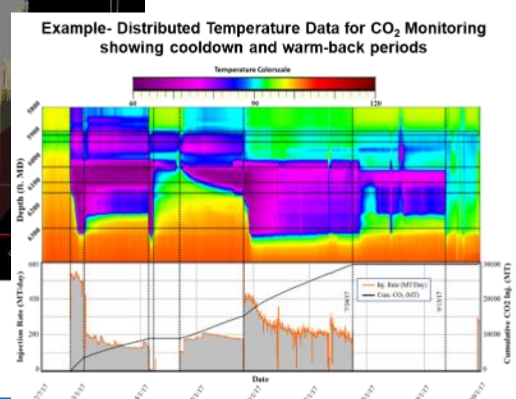
- The project is organized into 5 main technical tasks.
- Currently preparing for field testing task in Sept-Oct 2021.

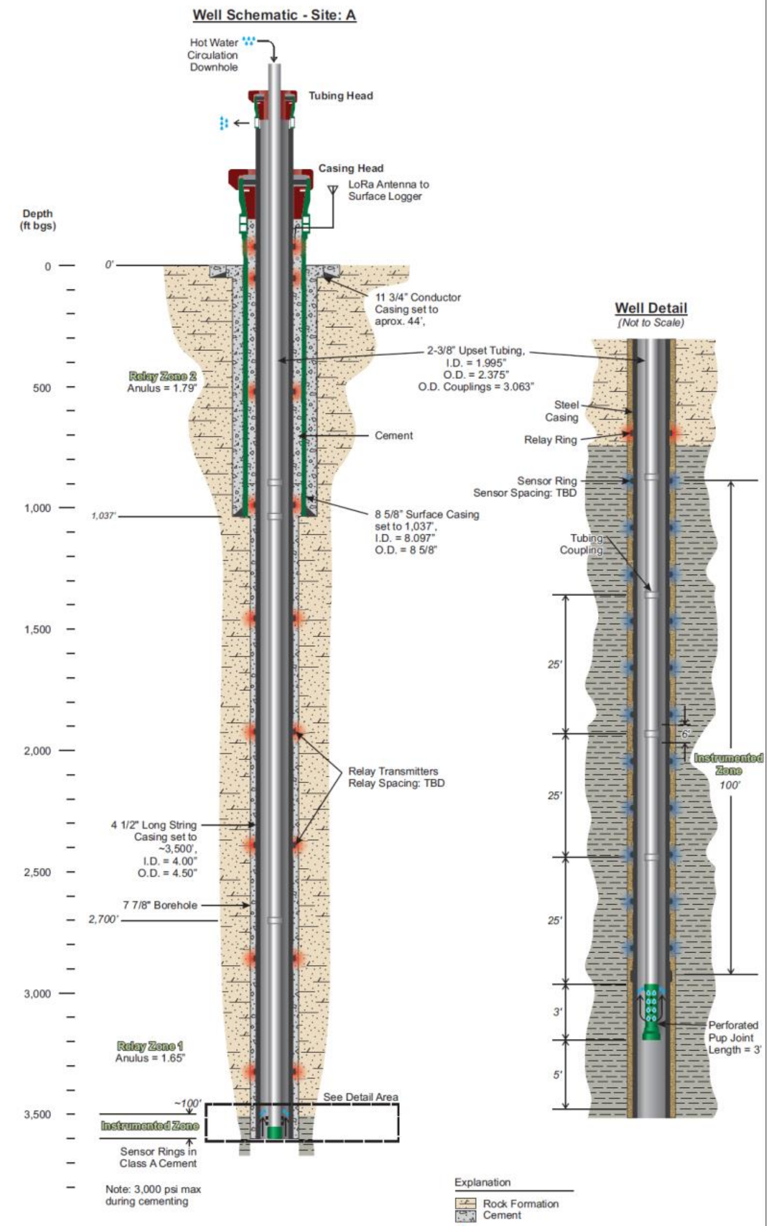


Technical Status

- Objective = Develop a sensors system for emplacement in CO_2 and/or O&G wells to monitor temperature as proxy for CO_2.
- ‘Sensor ring’ concept was adopted to facilitate development of sensors, central data collection & transmitter, wireless charging, energy harvesting, data relay system to surface, encapsulation, retrievable wireless battery charging







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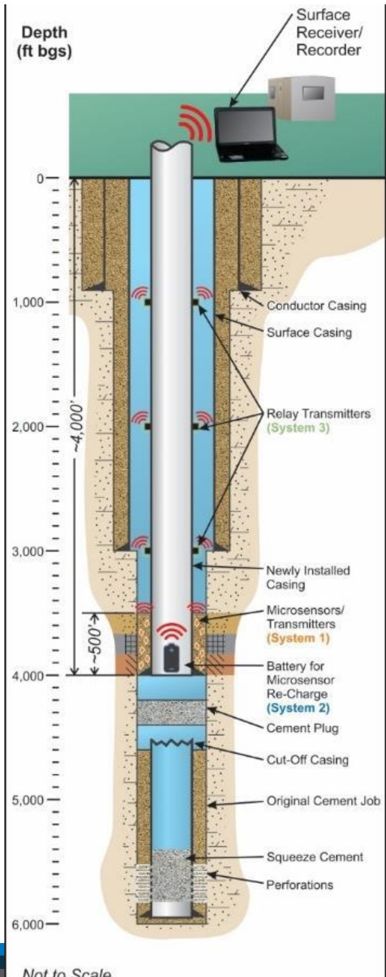
Technical Status: Sensor Design

- Challenges to long-term wireless monitoring CO_2 Storage.



- **Environmental survivability.**
  - ❖ Significantly moisture-laden downhole environment.
  - ❖ Pressures/Temperatures encountered during cementing.
  - ❖ Dimensional restrictions.
- **Wireless data telemetry through wellbores.**
  - ❖ Can you push data through wellbore materials?
  - ❖ Can you achieve a meaningful range between relays?
- **Wireless power transfer and energy harvesting.**
  - ❖ Can we transfer a meaningful amount of energy sufficient for all functionalities for 10-30 years?
  - ❖ Is the recharging process fast and effective enough?

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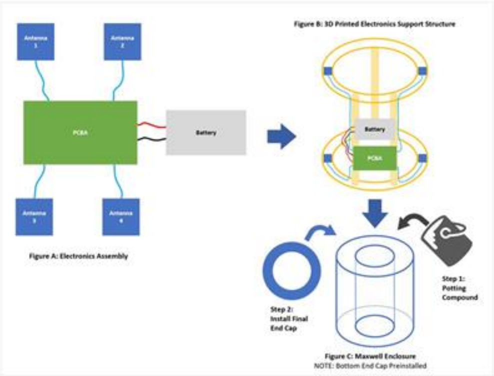
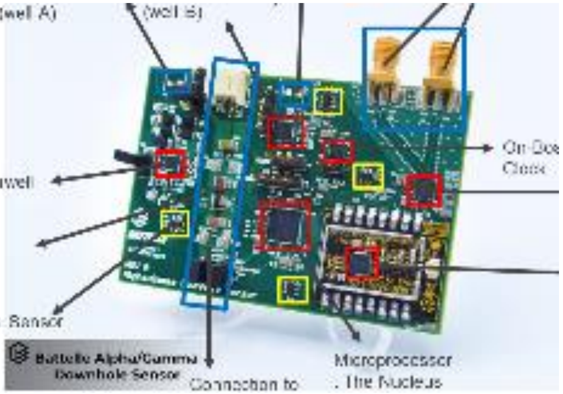
Technical Status: Sensor Design

- Sensor design completed.

Product	Description
Surface Logger	Receives the data from the wellhead and uploads it into the cloud, from where it may be accessed remotely.
Relay Ring (sonic energy charged)	Communicates with the single nearest rings immediately above and below it.
Sensor Ring (magnetic induction charged)	Communicates with the Battery Module via coil and not LoRa antennas. Otherwise structurally identical to the relay ring.
Wireless Battery Charging Assembly (for sensor rings)	Two-sectioned product. Top section is the battery antenna module, which drives the coiled section below. Entire assembly can be fished out of the well to replace (or recharge) the batteries at the surface, and lowered back in.
Sonic Charging Tool	Essentially a re-purposed Cement Bond Logging (CBL) tool. Sonic Tool is lowered via wireline and dwells around the vicinity of each ring for under an hour.
Encapsulation	Integrated centralizer to protect sensor electronic components running in well and during cementing





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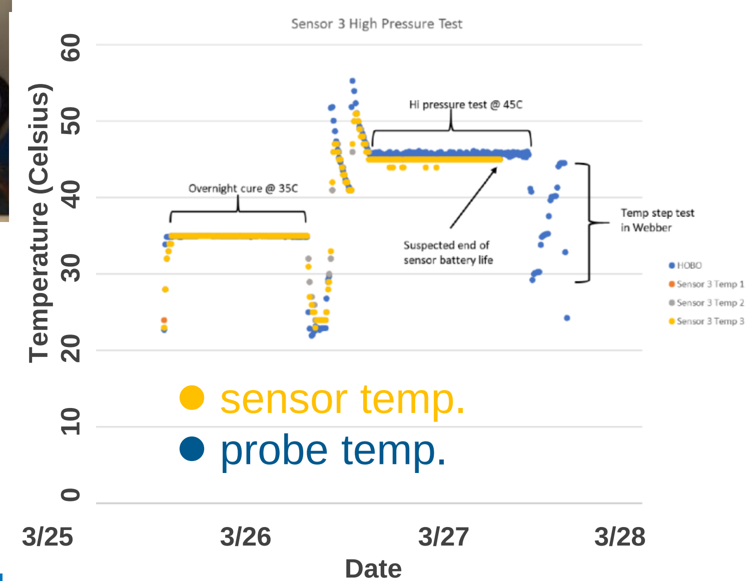
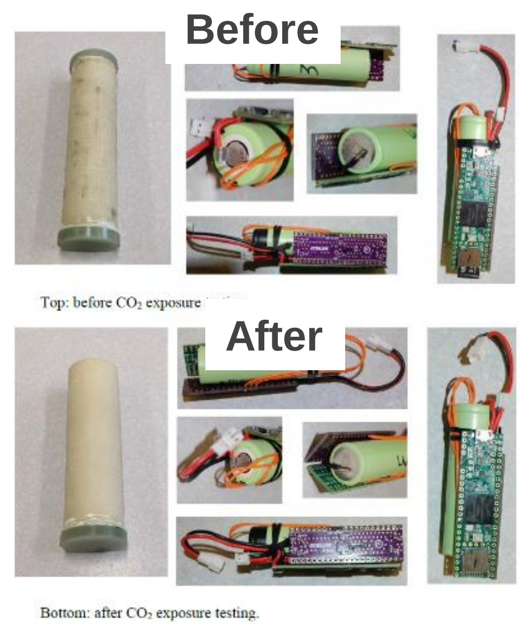
Technical Status: Lab Exposure Tests

- A sensor prototype & housing was exposed to supercritical CO_2 in a pressure test cell at temperatures ranging from 20 °C to 50 °C and pressures up to 1,400 psi for 24 hrs.
- The temperature sensor calibrated to measured conditions in the test cell. The resin housing enclosure also protected the electronic components and showed no signs of corrosion.





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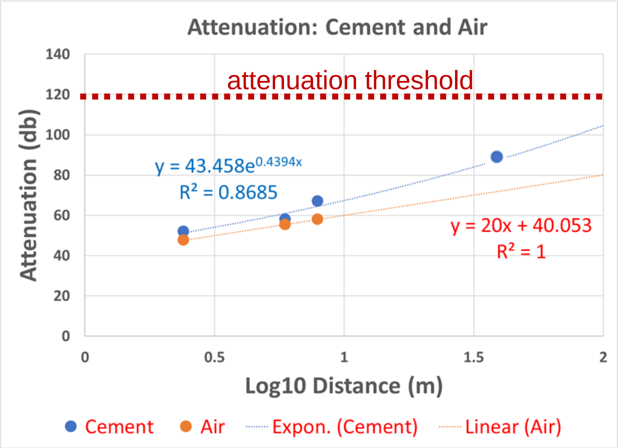
Technical Status: Bench-Scale Tests

- Data relay ring communication testing was completed in a series of test pipes constructed in lengths of 3’, 9’, 27’, and 120’
- 4 ½” steel tubing centered in 8” outer PVC pipe with resulting annulus filled with oilfield cement to simulate the downhole environment. (Copper foil added to approximate environment in upper well where production casing resides inside surface casing).
- Results demonstrate signal communication through cemented pipe >120 ft with acceptable RSSI attenuation.



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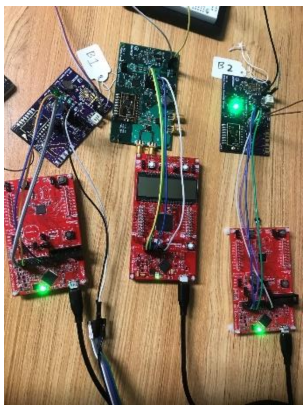
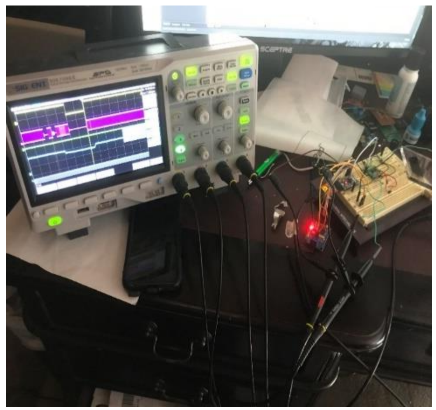
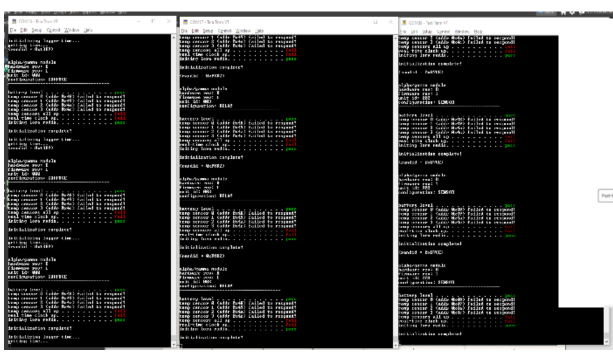
Technical Status: Functional Demos

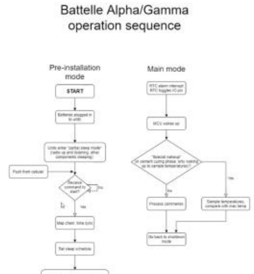
- A series of functional demonstrations were completed to confirm operation of the temperature sensors, wireless charging, sonic energy harvesting, data handling, and surface logging.

Temperature Sensor Data Handling









Sonic Harvesting & Wireless Charging

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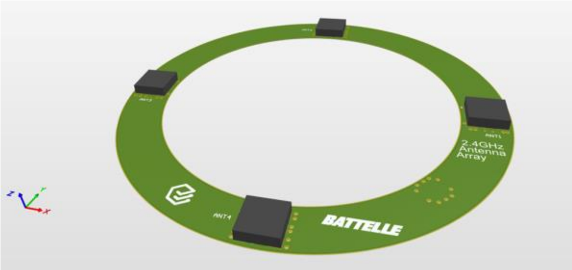
Technical Status: Sensor Fabrication

- Fabrication of sensor components in progress.
- Components were customized to fit in existing well (7” surface casing and 4 ½” deep casing).
- A total of 100 sensor rings will be fabricated.
- Procurement of oil & gas field services and materials in progress (service rig, cementing, wireline logging, casing, water hauling, excavation)



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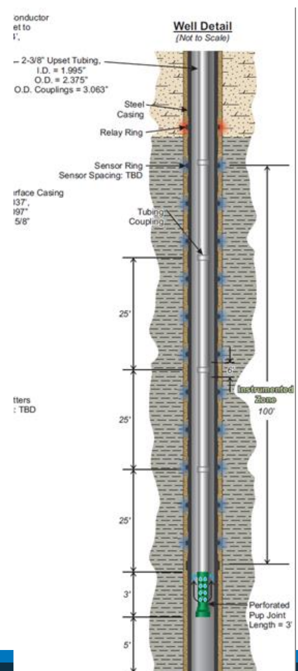
Technical Status: Field Test Planning

Well A Wireless Data Telemetry

- Sensors and Relays are all rings
- All rings have batteries that depend on sonic based battery charging
- Hot water circulation within 4 ½" csing to induce a temperature gradient to test sensors.

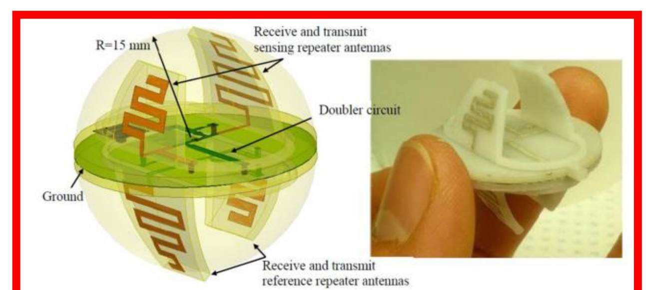
Cemented 4 ½" Casing within 7" casing



Well B + Wireless Power Transfer

- Adds to system A.
- Includes a custom battery-module located inside wellbore.
- This module will:
  - Power the sensors
  - Act as a "bridging relay" from the sensors to the first ring-relay.

Future development path for "Sensor-balls"



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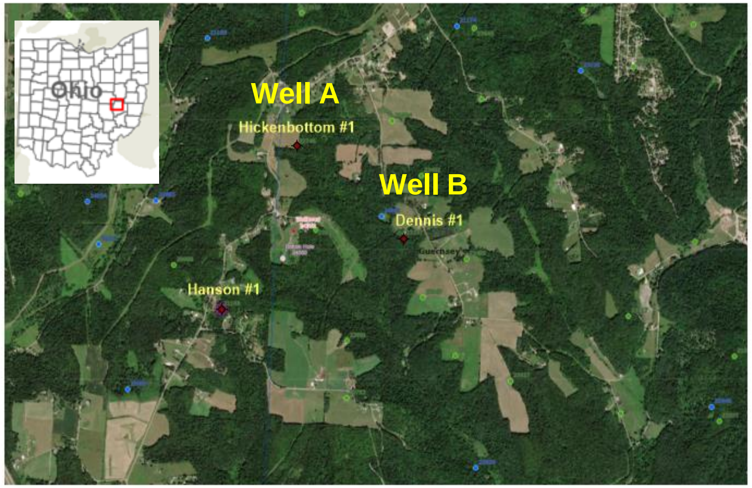
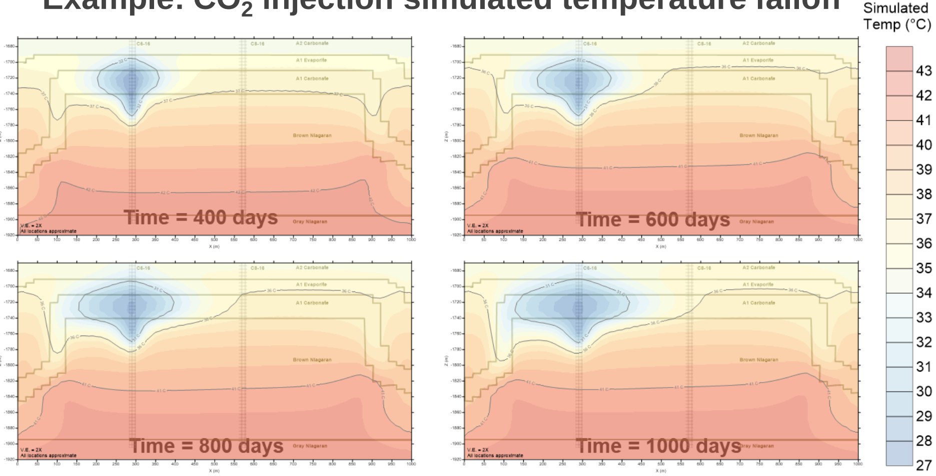
Technical Status: Field Test Planning

- Field testing plan:
  - ***#1 Health & Safety!!!! (mostly routine O&G workover effort)***
  - plug back 2 existing O&G wells in Guernsey County, Ohio.
  - install sensor system on casing ~3600 ft, cement well to surface.
  - Well A: 2500 ft deep test zone, circulate **hot** water as poxy for CO_2 to demonstrate sensor function, monitor temperature falloff.
  - Well B: 3800 ft deep test zone, battery module wireless charging, longer term test 2-3 weeks, measure ambient temperatures.



Example: CO_2 injection simulated temperature falloff



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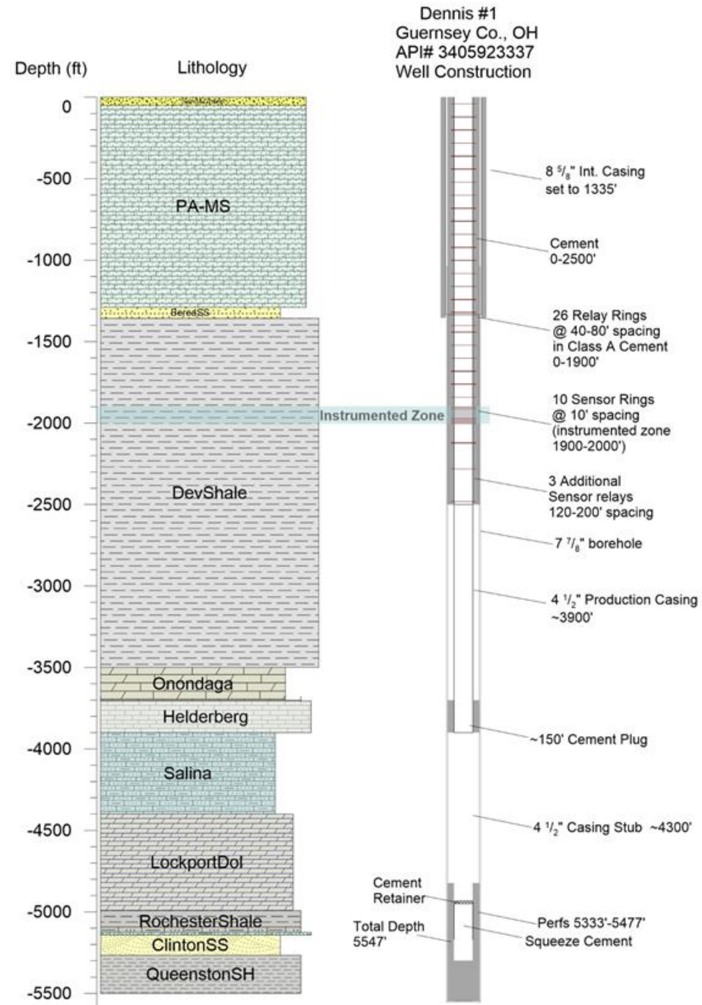
Field Testing of Sensor System

- Plug-back design completed
- Site access agreement completed with Hopco Ltd. for 3 wells:
  - Dennis #1, Guernsey Co.
  - Hickenbottom #1, Guernsey Co.
  - Hanson #1, Guernsey Co. (Backup well)
- Field testing Sept-Oct 2021.

Dennis #1

Hickenbottom #1



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Site Prep, Plug-back, Sensor Install

- Site preparations include grading wellpads and access roads, installing culverts, spreading stone, etc.
- Existing perforations in Clinton SS (5,300-5,500 ft.) will be squeezed off with cement.
- 4 ½ inch casing will be shot-off at +/- 4,500 ft.
- Composite centralizers containing sensor rings will be installed on 4 ½" casing and the casing will be run in well and cemented to surface in 2 stages.
- Well A sensors will be installed from ~2,500 ft. to surface.
- Well B sensors will be installed from ~3,600 ft. to surface.

Wireless Micro Sensor Project Field Work Schedule

Assume September 1st start date

Dennis #1 Well

Task	Vendor	Start	Finish	Days	Comments
Complete Field Work	**All**	**9/1/2021**	**10/9/2021**	**39**	**Field work period of performance**
Prepare Access Road and Location	Wolf Run	9/1/2021	9/4/2021	4	Mob in and prepare road and location
Deliver purchased casing	Berry Well Service	9/2/2021	9/2/2021	1	Deliver purchased casing to the centralizer installation location (Cambridge, OH?)
Install composite centralizers	Maxwell & Engenius	9/3/2021	9/6/2021	4	Install composite casing centrlaizers on purchased 4 1/2" casing
Escort Equipment / Reclaim	Wolf Run	9/3/2021	10/9/2021	37	As needed
MIRU Service Rig	Berry Well Service	9/3/2021	10/7/2021	35	MIRU to RDMO
Spot tanks and haul water	Dow Cameron	9/3/2021	9/4/2021	2	1 @500 Bbl, 1 @ 150 Bbl open top, haul water as needed
Plug Clinton formation	Berry Well Service	9/6/2021	9/7/2021	2	Run 2-3/8" tubing to top Clinton perforation, set cement plug, pull tubing
Squeeze Clinton Perfs	Petroset	9/6/2021	9/6/2021	1	Spot 400 ft. cement plug through tubing
Deliver casing w/centrlaizers	Berry Well Service	9/7/2021	9/7/2021	1	
Run CBL / Shoot off 4-1/2" casing	Appalachian Well Surveys	9/7/2021	9/7/2021	1	Run CBL to determine TOC, Shoot 4-1/2" casing, Pull one jt. Casing
Set casing stub plug	Petroset	9/7/2021	9/7/2021	1	Set 100 ft. casing stub plug in 7-7/8" hole w/30 sacks Class A cement
Circulate hole with gel	Petroset	9/7/2021	9/7/2021	1	Mix gel and circualte hole
Pull 4-1/2" casing	Berry Well Service	9/7/2021	9/8/2021	2	Load +/- 3800 ft. of casing on float trailer for centralizer installation
Log open hole	Appalachian Well Surveys	9/9/2021	9/9/2021	1	Calculate hole volume from claiper log for cement fill
Run 4-1/2" casing in well	Berry Well Service	9/11/2021	9/11/2021	1	Run casing to +/- 3800 ft. Run DV tool at +/- 2000 ft. Run sensors to +/- 2,500 ft.
Cement 4-1/2" casing	Petroset	9/10/2021	9/11/2021	2	Cement from 3800 ft. to surface in 2 stages. Circulate 8 hours between stages.
WOC - 72 hours	N/A	9/11/2021	9/13/2021	3	Wait on Cement
Drill out cement and stage tool	Berry Well Service	9/14/2021	9/16/2021	3	Drill out and chase to bottom and curculate clean. POOH with tubing
Run Radial CBL	Appalachian Well Surveys	9/17/2021	9/17/2021	1	Check for cement fill-up and bond quality
Run 2-3/8" tubing in well	Berry Well Service	9/18/2021	9/18/2021	1	Run tubing to +/- 2550 ft.
RDMO Service Rig	Berry Well Service	9/20/2021	9/20/2021	1	Move to Hickenbottom well
Test sensor and relay system	Battelle & Engenius	9/20/2021	9/23/2021	4	
Circulate hot water in well	Fishburn Services	9/24/2021	9/24/2021	1	Monitor sensors and relays to confirm bottom hole temperature change
Analyze system performance	Battelle & Engenius	9/24/2021	9/28/2021	5	
MIRU Service Rig	Berry Well Service	10/6/2021	10/6/2021	1	
Haul water and tanks off location	Dow Cameron	10/6/2021	10/8/2021	3	Empty and clean out tanks - dispose of waste water
Pull tubing	Berry Well Service	10/6/2021	10/6/2021	1	
RDMO Service Rig	Berry Well Service	10/7/2021	10/7/2021	1	Move back to Hickenbottom well
Reclaim location and lease road	Wolf Run	10/7/2021	10/9/2021	3	

Hickenbottom #1 Well

Task	Vendor	Start	Finish	Days	Comments
Complete Field Work	**All**	**9/15/2021**	**10/16/2021**	**31**	**Field work period of performance**
Deliver casing for centralizer install	Berry Well Service	9/8/2021	9/8/2021	1	Deliver pulled casing to centralizer installation location (Cambridge, OH?)
Install composite centralizers	Maxwell & Engenius	9/9/2021	9/12/2021	4	Install composite casing centrlaizers on 4-1/2" casing from pulled Dennis well
Prepare Access Road and Location	Wolf Run	9/15/2021	9/17/2021	2	Mob in and prepare road and location
Escort Equipment / Reclaim	Wolf Run	9/20/2021	10/16/2021	27	As needed
MIRU Service Rig	Berry Well Service	9/20/2021	10/15/2021	26	MIRU to RDMO
Spot tanks and haul water	Dow Cameron	9/20/2021	9/21/2021	2	1 @500 Bbl, 1 @ 150 Bbl open top, haul water as needed
Plug Clinton formation	Berry Well Service	9/21/2021	9/22/2021	2	Run 2-3/8" tubing to top Clinton perforation, set cement plug, pull tubing
Squeeze Clinton Perfs	Petroset	9/21/2021	9/21/2021	1	Spot 400 ft. cement plug through tubing
Run CBL / Shoot off 4-1/2" casing	Appalachian Well Surveys	9/22/2021	9/22/2021	1	Run CBL to determine TOC, Shoot 4-1/2" casing
Set casing stub plug	Petroset	9/22/2021	9/22/2021	1	Set 100 ft. casing stub plug in 7-7/8" hole w/30 sacks Class A cement
Circulate hole with gel	Petroset	9/22/2021	9/22/2021	1	Mix gel and circualte hole
Pull 4-1/2" casing	Berry Well Service	9/22/2021	9/23/2021	2	Load casing on float trailer for delivery to buyer (Ken Miller Supply, Wooster, OH?)
Deliver casing to buyer	Berry Well Service	9/24/2021	9/24/2021	1	Ken Miller Supply in Wooster, OH?
Deliver casing w/centrlaizers	Berry Well Service	9/24/2021	9/24/2021	1	
Log open hole	Appalachian Well Surveys	9/24/2021	9/24/2021	1	Calculate hole volume from claiper log for cement fill
Run 4-1/2" casing in well	Berry Well Service	9/24/2021	9/25/2021	2	Run casing to +/- 3800 ft. Run DV tool at +/- 2000 ft. Run sensors to +/- 2,500 ft.
Cement 4-1/2" casing	Petroset	9/25/2021	9/26/2021	2	Cement from 3800 ft. to surface in 2 stages. Circulate 8 hours between stages.
WOC - 72 hours	N/A	9/27/2021	9/29/2021	3	Wait on Cement
Assemble induction coils	Engennius	9/27/2021	9/30/2021	4	Wind coil wire around tubing joins and prepare wire connectors
Drill out cement and stage tool	Berry Well Service	9/30/2021	10/2/2021	3	Drill out and chase to bottom and curculate clean. POOH with tubing
Run Radial CBL	Appalachian Well Surveys	10/4/2021	10/4/2021	1	Check for cement fill-up and bond quality
Run Retrievable Battery Pack	Berry Well Service	10/5/2021	10/5/2021	1	Run 4 jts. 2-3/8" tubing/induction coils on sand line and set on casing profile
RDMO Service Rig	Berry Well Service	10/6/2021	10/6/2021	1	Move back to Dennis #1 well
Analyze system performance	Battelle & Engenius	10/6/2021	10/12/2021	7	
Recharge sensor/transmitter batteries	Appalachian Well Surveys	10/12/2021	10/13/2021	2	Use sonic tool or CBL to recharge select sesnsor and transmitter batteries
MIRU Service Rig	Berry Well Service	10/14/2021	10/14/2021	1	
Retrieve Battery Pack	Berry Well Service	10/15/2021	10/15/2021	1	Retrieve battery pack on sand line.
Haul water and tanks off location	Dow Cameron	10/14/2021	10/16/2021	3	Empty and clean out tanks - dispose of waste water
RDMO Service Rig	Berry Well Service	10/15/2021	10/15/2021	1	Release service rig
Reclaim location and lease road	Wolf Run	10/14/2021	10/16/2021	3	

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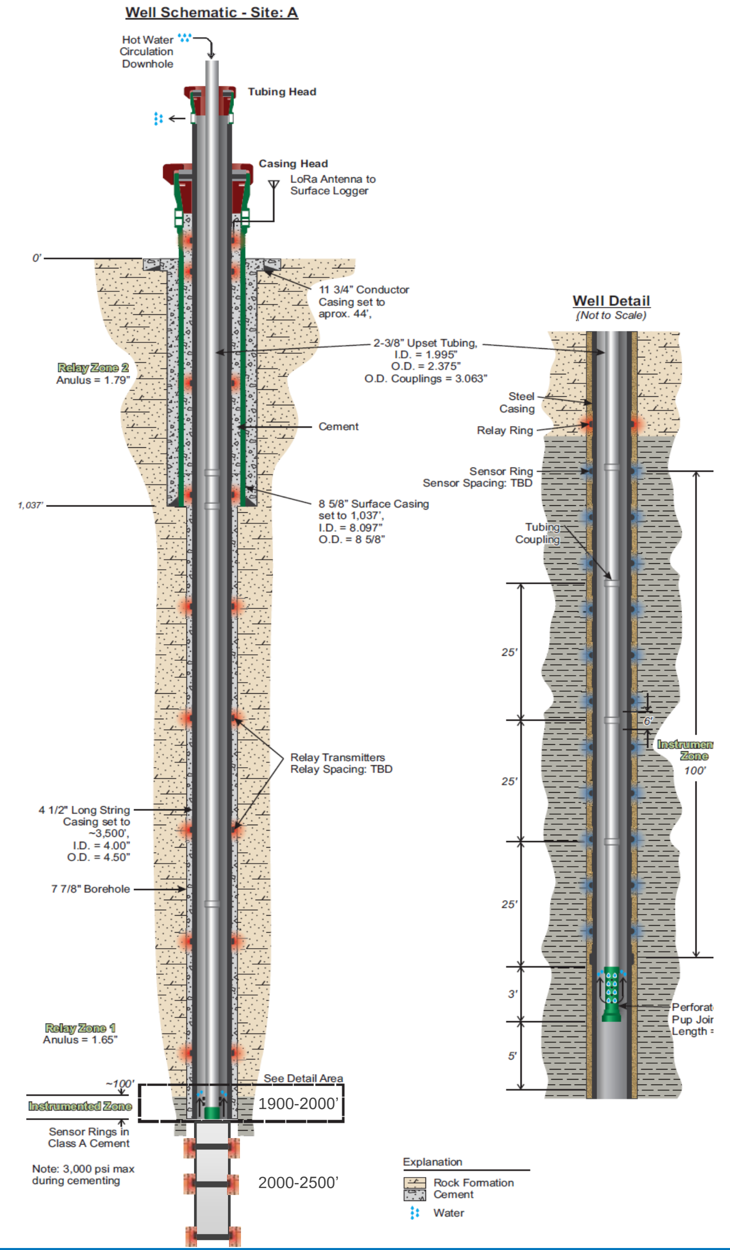
Well A Testing

- Demonstrate long-range wireless telemetry through cement, 40-80 ft relay spacing.
- Circulate hot water through tubing to record increase in bottom hole temperature and monitor temperature fall-off.



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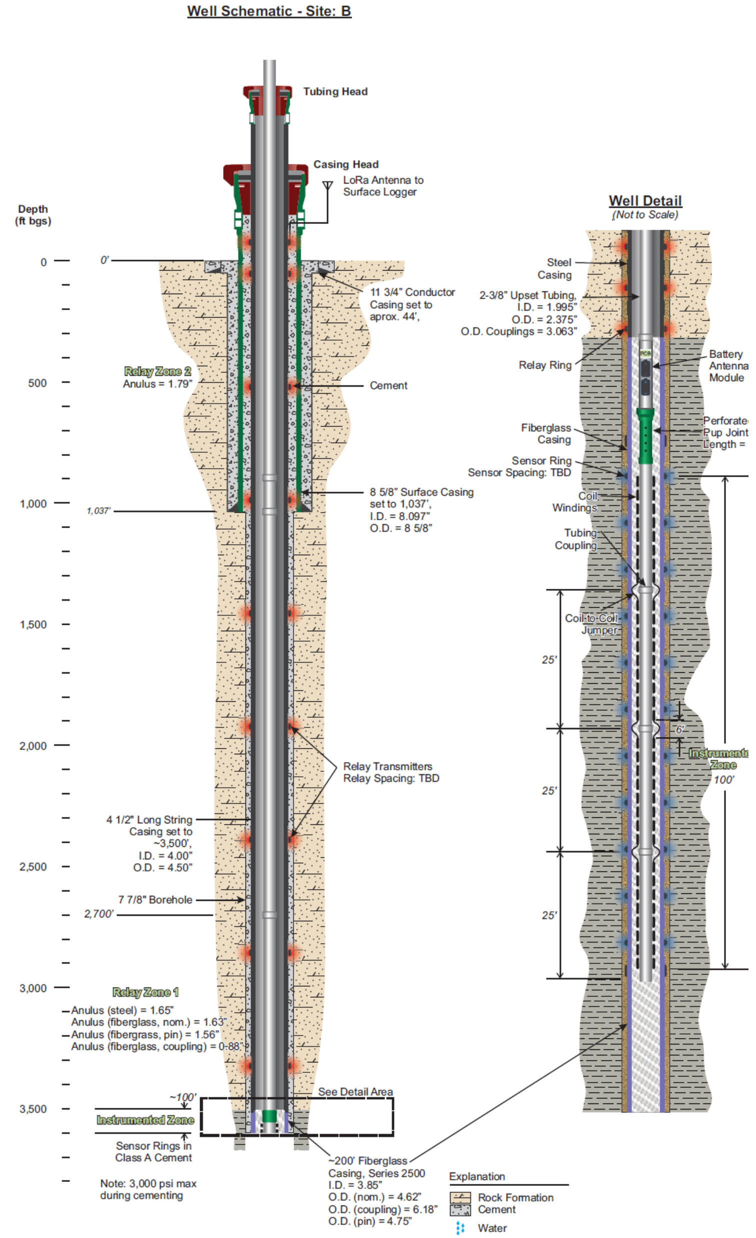
Well B Testing

- Demonstrate repeatability and reliability of the deployment of the wireless system to 3,600 ft depth.
- Extend relay spacing to 120 ft.
- Demonstrate that sonic charging of electronic devices in the annulus is possible.
- Longer term monitoring 2-3 weeks or greater.



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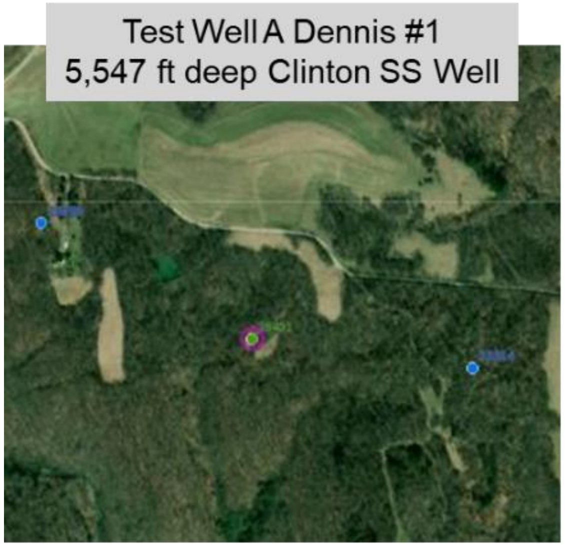
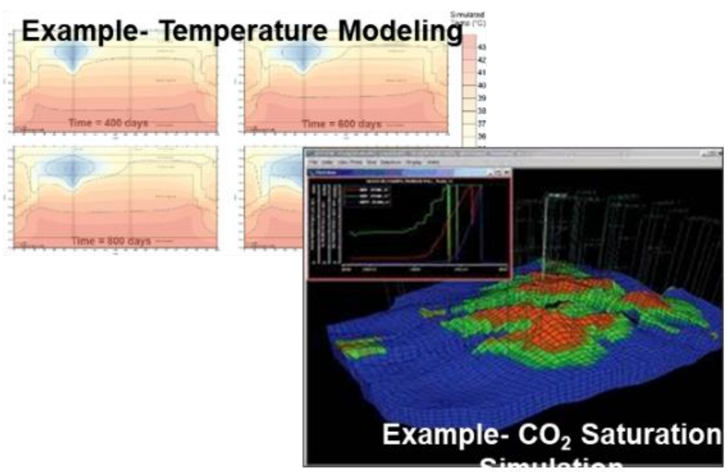
Health & Safety

- Health & Safety plan completed for field testing.
- Relatively routine well work.
- Main hazards = heavy machinery, rotating parts, high pressure oil/gas/water, cement materials.

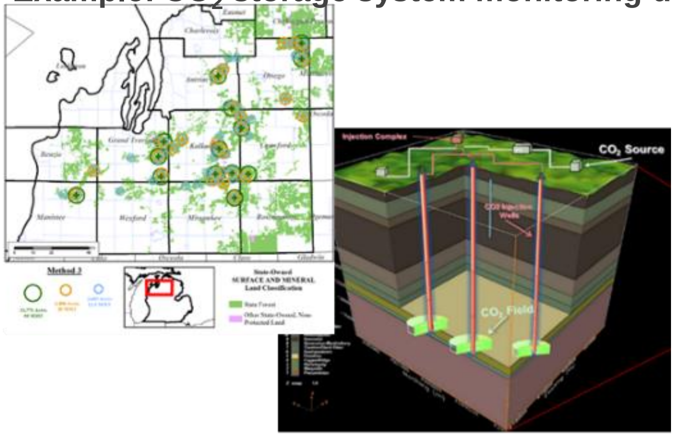


Data Processing/Modeling & Techno-Economic Evaluation

- Data Processing and Numerical Modelling
  - Data processing and QA/QC
  - Numerical modeling of field microsensor data
  - Verify CO_2 plume w/temperature
- Techno-Economic Evaluation for CO_2 Storage Applications
  - Assessment of monitoring integration with existing technologies
  - Benchmarking analysis of microsensor system applications



Example: CO_2 storage system monitoring design



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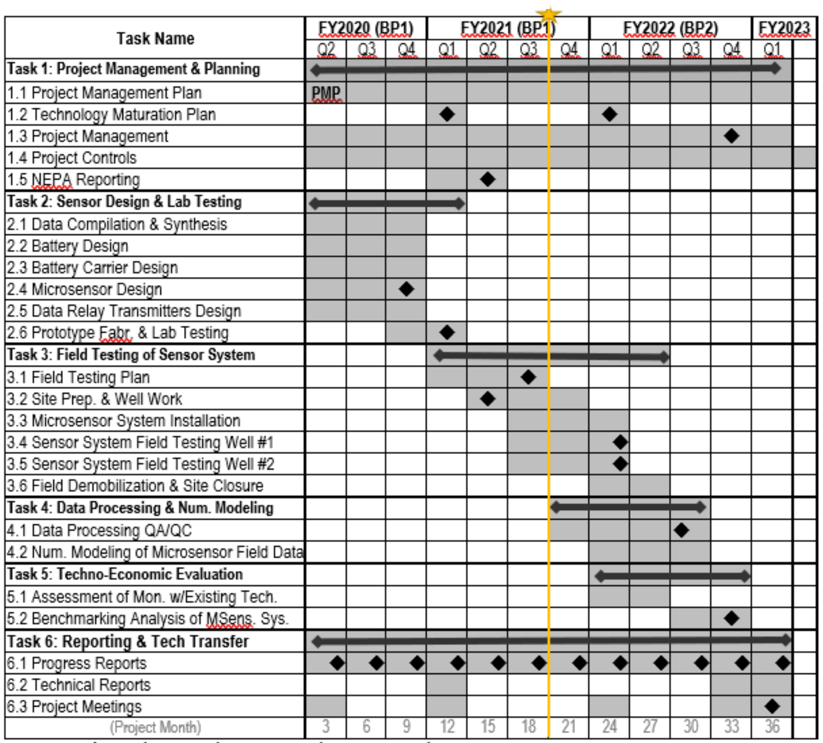
Accomplishments to Date

- Sensor design and lab testing completed for wellbore telemetry, temperature monitoring, wireless charging, energy harvesting, data transfer, and field tests.
- Field testing planned for September-October 2021 in 2 existing oil wells in Guernsey Co., Ohio.

Schedule



◆ = Deliverable/Milestone F = Final PMP = Project Management Plan

Milestones

Task/ subtask	Milestone Title & Description	Scheduled Completion date	Verification method
1.1	Update project Management Plan	**February 12, 2020**	Electronic Document Submission
2.5, 2.6	Microsensor System Design	**December 2020**	Sensor Design Memo
2	**Decision Point to Move to Field Testing**	**February 2021**	**DOE-NETL Approval**
2.6	**Complete Field Test Unit Construction**	**March 2021**	**Sensor System Lab Test Memo**
3.0	**Confirm wells for field testing**	**January 2021**	**Final NEPA Env. Quest.**
3.1	**Prepare Field Testing Plan (sensor system deployment plan complete)**	**May 2021**	**Field Testing Plan Submitted Electronically**
3	**Decision Point on Final Field Sites**	**February 2021**	**DOE-NETL Approval**
3.6	Sensor Data Collection (initial sensor data successfully collected)	February 2022	Field Testing Summary Report Submitted Electronically
4.3	Sensor Data Validation (data validated by numerical simulations)	June 2022	Field Data Submitted Electronically to EDX
5.1	Technology Development Plan (techno-economic assessment and methods)	October 2022	Technology Development Plan Submitted Electronically
6.3	Complete Project and Final Report (final DOE submittal)	January 2023	Final Report Submitted Electronically

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Lessons Learned

- There are many challenges to wireless sensors in deep wellbores (depth, cement, casing, pressure, temperature, fluids, install).
- These challenges have resulted in a more developmental process exploring items like data transmission lengths, effect of well materials on data signals, energy harvesting options, wireless charging, and data handling using a sensor ring and relay ring approach.
- A sensor ring approach was adopted to allow for functional technology field testing and accommodate legacy well specifications.
- The project team successfully demonstrated sensor system operation at supercritical conditions lab testing, 120 ft cemented casing data transmission test on surface, and functional bench-scale demos.
- Next step is field testing in two oil wells at depths of 2500 ft and 3600 ft scheduled for September-October 2021.

Project Summary

- Three-prong project approach: 1) develop a wireless downhole sensor system to monitor for CO_2 storage, 2) field test the sensor system in two legacy oil & gas wells, and 3) validate the technology and demonstrate its applicability to monitoring CO_2 in the subsurface.
- Key advancements in generated through this research: distributed wireless microsensor system, wireless telemetry system to transmit data to surface, customized deployment options, and an approach to processing and integrating sensor data to understand CO_2 distribution and track CO_2 plume movement in the subsurface.
- Path Forward
  - Sensor System Component Fabrication of sensor rings, relays, battery module
  - Sensor System Field Testing (September-October 2021)
    - Plug back wells, install sensor system, cement to surface
    - Collect, analyze data for well A and well B deployments
  - Field Test Data Analysis, Modeling, & Techno-Economic Evaluation
    - Model CO_2 temperature indicator for CO_2 storage
    - Techno- economic deployment options for legacy O&G wells, CO_2 wells

Appendix Material

- As follows

Benefit to the Program

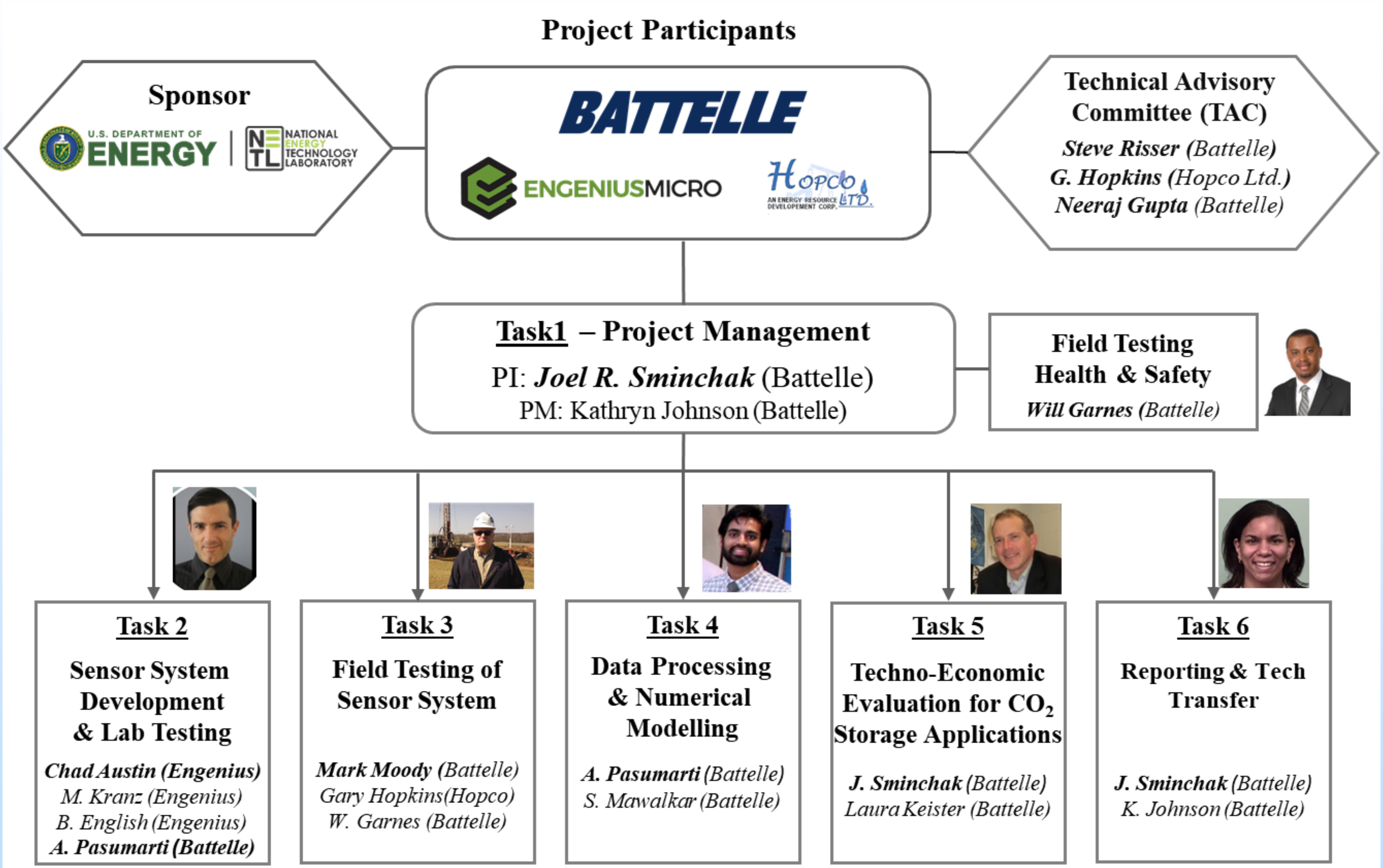
- Project addresses FOA1998 Area of Interest 1: *Transformational Sensing System for Monitoring the Deep Subsurface:*
- **Wireless microsensors system for CO_2 storage applications**.
- System deployment options for legacy oil & gas wells.
- Network of real-time monitoring points for CO_2 storage zones without the expense of new wells.
- Real time, autonomous monitoring data for accurately tracking/modelling the subsurface movement of CO_2 plumes.
- The sensor system benefits operators, regulators, and stakeholders associated with diverse CO_2 storage applications:
  - Commercial-scale deep saline CO_2 storage sites,
  - CO_2-EOR operations/optimization,
  - 45Q monitoring/reporting/verification requirements, and
  - USEPA Class 6 UIC requirements for geologic CO_2 storage.

Project Overview- Goals and Objectives

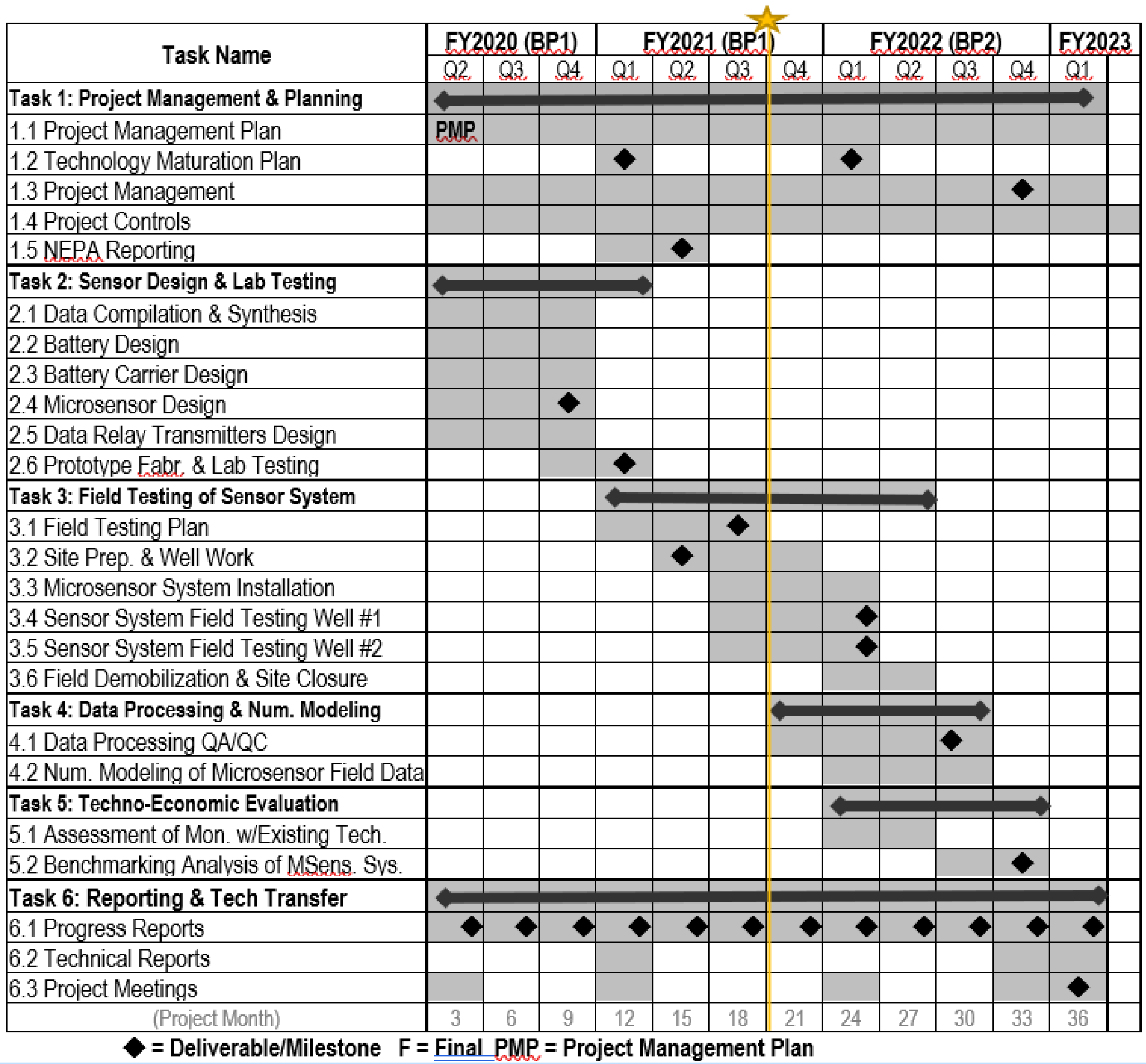
The goal of this project is to develop a technology for wireless downhole monitoring subsurface operations via a three-prong approach:

1. **Sensor System Development**- design and fabricate a fully integrated wireless microsensor-based downhole sensing system to measure temperature as the primary indicator of CO_2 presence.
2. **Field Deployment/Demonstration**- demonstrate system operational feasibility by deploying & testing the system in the casing annulus of two legacy 5000-6000 ft boreholes.
3. **Techno-Economic Analysis**- establish the technical feasibility and practical utility of the sensing system for reservoir and above zone monitoring in a commercial-scale CO_2 storage complex by:
   - integrating this data into a numerical multi-phase thermal reservoir simulator that can predict the location and movement of fluid flow in the subsurface, and
   - a techno-economic evaluation that benchmarks the total costs, risks and unique benefits.

Project Organization Chart



Gantt Chart


Task Name
FY2020 (BP1)
FY2021 (BP1)
FY2022 (BP2)
FY2023
Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1
Task 1: Project Management & Planning
1.1 Project Management Plan
PMP
1.2 Technology Maturation Plan
1.3 Project Management
1.4 Project Controls
1.5 NEPA Reporting
Task 2: Sensor Design & Lab Testing
2.1 Data Compilation & Synthesis
2.2 Battery Design
2.3 Battery Carrier Design
2.4 Microsensor Design
2.5 Data Relay Transmitters Design
2.6 Prototype Fabr. & Lab Testing
Task 3: Field Testing of Sensor System
3.1 Field Testing Plan
3.2 Site Prep. & Well Work
3.3 Microsensor System Installation
3.4 Sensor System Field Testing Well #1
3.5 Sensor System Field Testing Well #2
3.6 Field Demobilization & Site Closure
Task 4: Data Processing & Num. Modeling
4.1 Data Processing QA/QC
4.2 Num. Modeling of Microsensor Field Data
Task 5: Techno-Economic Evaluation
5.1 Assessment of Mon. w/Existing Tech.
5.2 Benchmarking Analysis of MSens. Sys.
Task 6: Reporting & Tech Transfer
6.1 Progress Reports
6.2 Technical Reports
6.3 Project Meetings
(Project Month)
3 6 9 12 15 18 21 24 27 30 33 36
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