A Highly Sensitive Real-Time Subsurface Sensor for CO_2 Leakage Monitoring

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U.S. Department of Energy

National Energy Technology Laboratory

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Presentation Outline

1. Project Overview and Bettergy Introduction
2. Background and Concept
3. Technical Status
4. Project Schedule
5. Summary

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1.1 Project Overview

- Goals and Objectives
  - Develop a highly stable and highly CO_2 sensitive material
  - Design and fabricate the sensor structure
  - Integrate the material into the as-fabricated sensor platform for CO_2 sensing
  - Demonstrate the sensor's capability of real-time detection of low concentration CO_2 flow

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1.2 The Company

Bettergy develops and commercializes innovative energy and environmental technologies, with expertise in nanopore engineered membranes and advanced battery technologies

- **Talented Team**
  - 16 employees and consultants, including 7 PhDs, with a broad range of expertise
- **Intellectual Property**
  - 6 issued U.S. Patents and 7 pending U.S Patent applications
- **$16M** in grants and contracts
  - From DOE, ARPA-E, DoD, NASA, NIH, NSF and NYSERDA
- **Commercialization Experience**
  - Spin out of a battery and membrane technology now in full-scale prototyping stage
- Numerous **academic collaborators**

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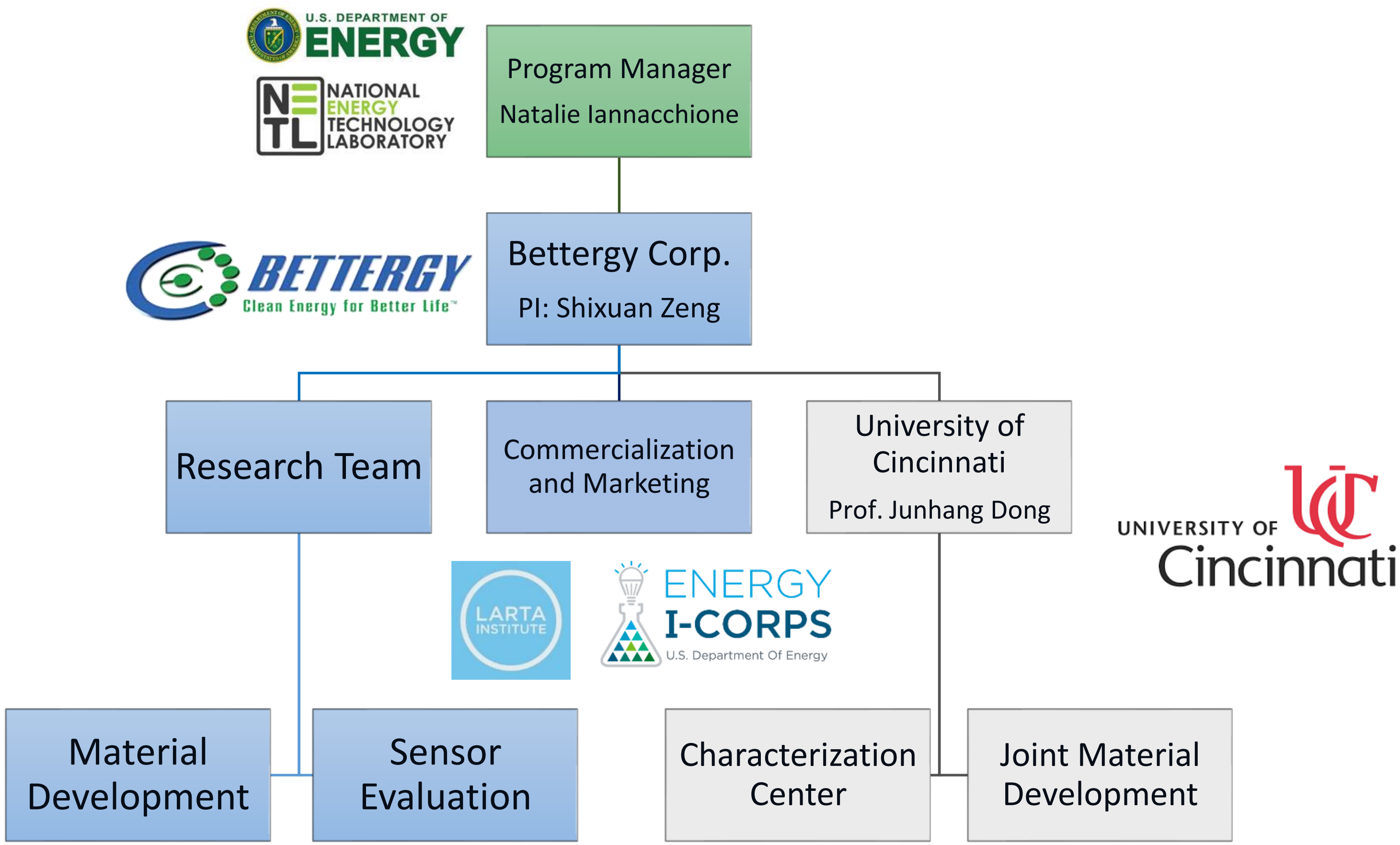
1.3 Project Organization Chart



1.4 Benefits of the Program

- Project Benefits
  - A "plug-and-play" sensor will assist the existing and future CO_2 injection process
  - Advancing carbon capture and storage (CCS) technology, helping to achieve "Carbon Free"
  - Significant impact on the market adoption of downhole monitoring sensors
- Program Objectives
  - Increasing private sector commercialization of our sensor technology
  - Stimulating technological innovation of subsurface sensors in the private sector
  - Improving the return on investment from DOE-sponsored SBIR project
  - Creating new, highly skilled jobs for the nation

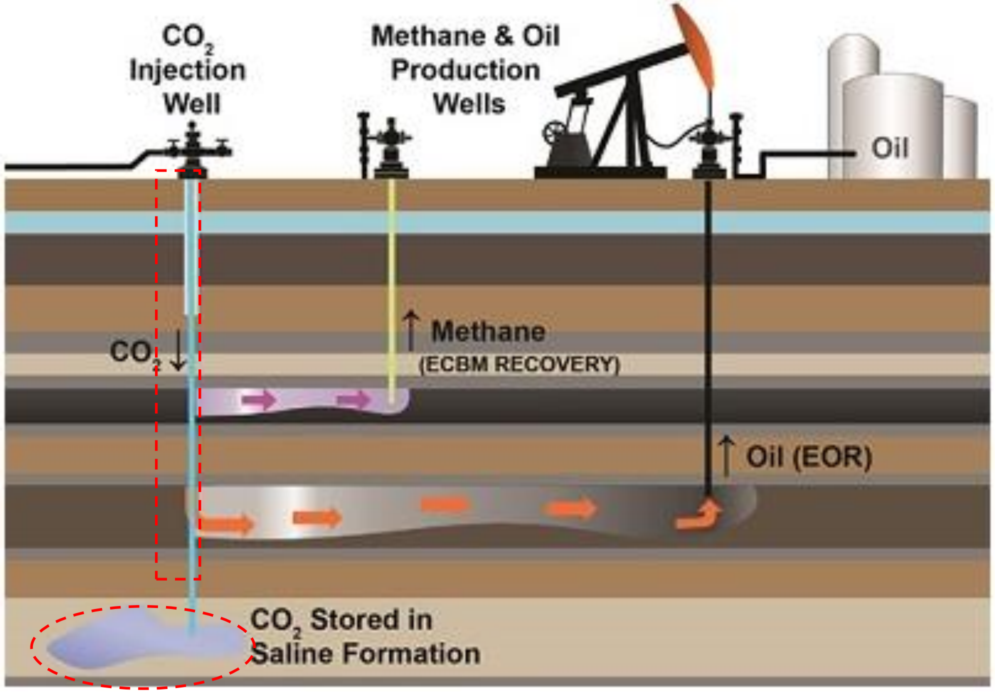
2.1 Background

➢ ***Subsurface CO_2 Monitoring --- Problems***

DOE SBIR Solicitation FY2021, Topic 24c.

- Innovative technologies to measure *plume location, pressure front and leakage conditions* are sought

- Bettergy proposed a real-time CO_2 leakage sensor for CCS applications



- ➢ Injection well integrity
- ➢ CO_2 plume migration
- ➢ Reservoir leakage

https://www.netl.doe.gov/coal/carbon-storage/faqs/carbon-storage-faqs

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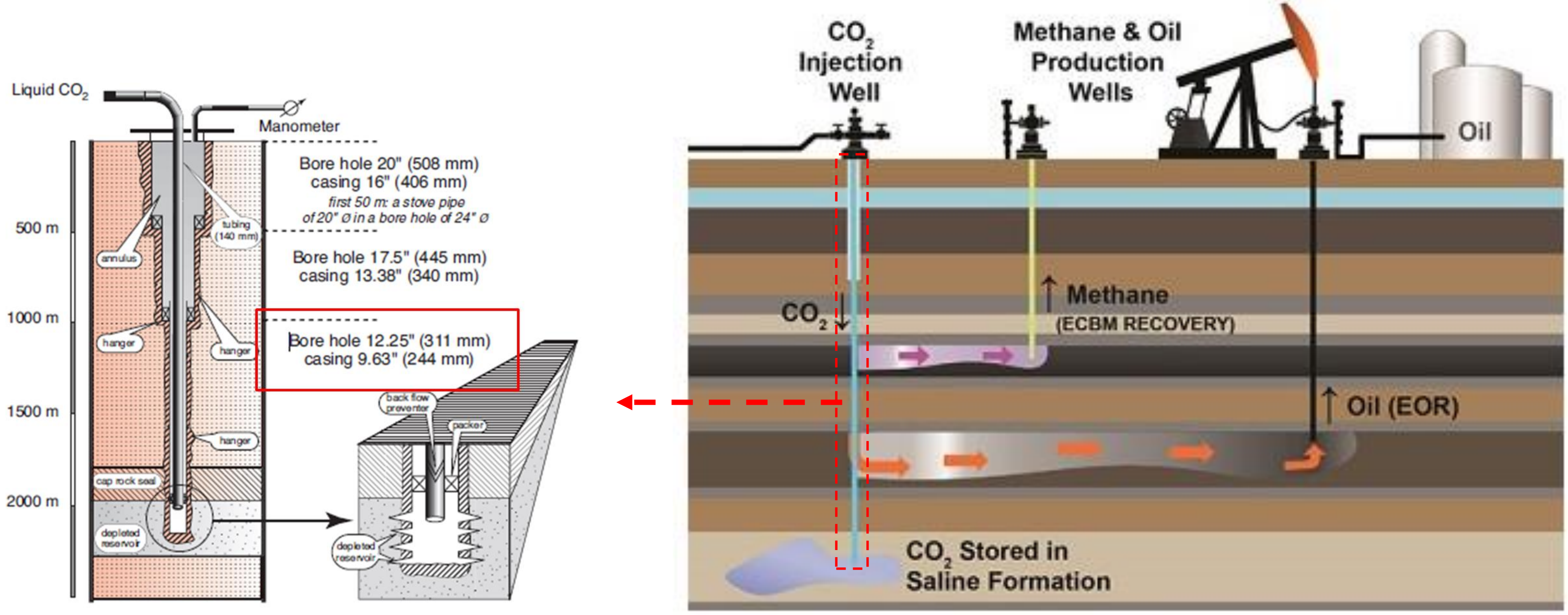
2.1 Background

➢ ***Injection Well Leakage Detection***



*** The space between CO_2 injection casing and bore hole wall is **<u>very limited</u>** (~35 mm), making it very challenging for sensor implementation.

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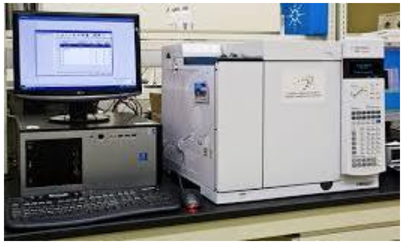
1. DOE Project Report: DE-FE0004001
2. https://www.netl.doe.gov/coal/carbon-storage/faqs/carbon-storage-faqs

2.1 Background

➢ ***State-of-the-art Subsurface CO_2 Sensing and Challenges***

Leakage Detection Techniques	Challenges
Laser-based Optical Sensor[1]	Signal accuracy; complicated packaging; stability issue; cost
Shallow 2D Seismic Sensor[2]	Dissolved CO_2 or low-saturation CO_2 detection near well; sensitivity; cost
Soil gas monitoring[3]	Localized leakage detection; analysis and sampling time; use of tracers; cost
Groundwater monitoring[4]	Analysis and sampling time; potential use of tracers; cost
Reservoir Fluid Monitoring[5]	Analysis and sampling time; labor-intensive; cost



1. DE-FOA-0001258, Richard Wainner
2. Rutters, H. et al., 2013.
3. Oldenburg and Unger, 2003; Klusman, 2011, Shevalier et al., 2005.
Annunziatellis et al. 2009, Schuster et al. 2009
4. Freifeld and Trautz 2006

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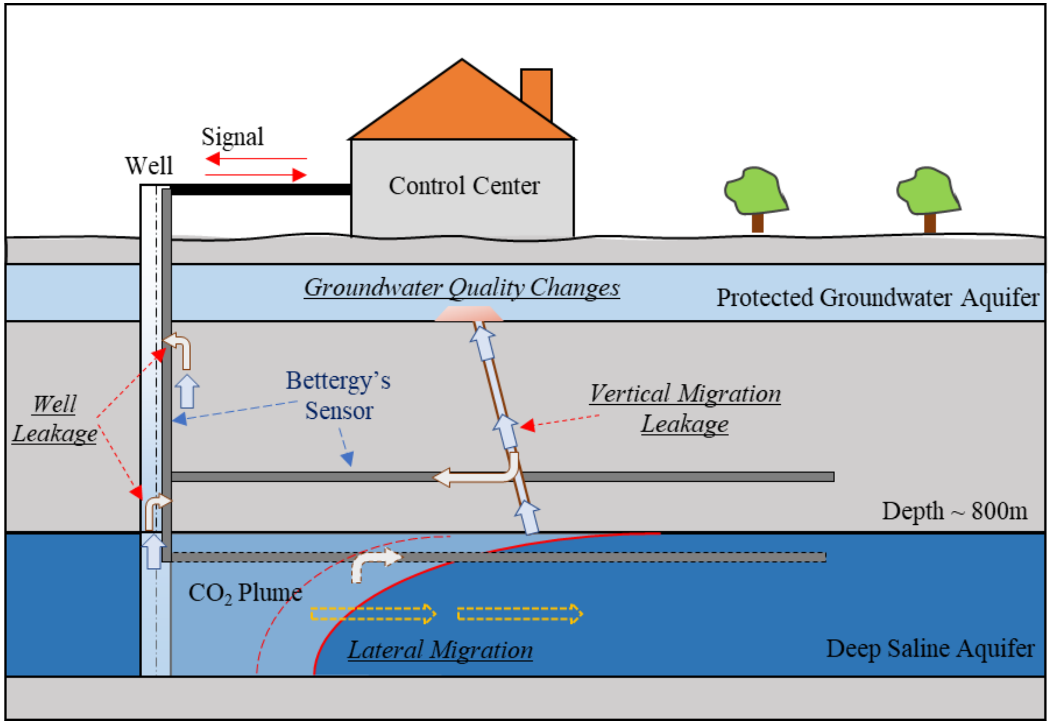
2.2 Sensor Concept

➢ *Proposed Subsurface CO_2 Leakage Sensor*



*** System level projection for our proposed sensor in underground CO_2 leakage detection and/or plume migration monitoring.

Sensor requirements (Pain points)

- ➢ Physically and chemically robust
- ➢ Small in size
- ➢ Highly sensitive to CO_2
- ➢ In-situ, real-time signal response
- ➢ Subsurface environment
- ➢ Low manufacturing cost, low O&M cost

! Coaxial cable sensor is the solution !

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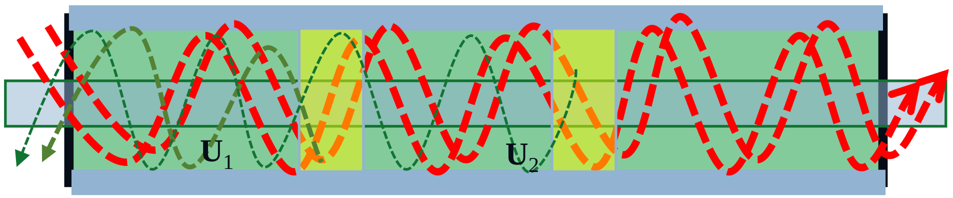
2.2 Sensor Concept

What is a coaxial cable sensor?

A Typical Coaxial Cable



By analyzing Reflected, Transmitted or Interfered signals[1], the coaxial cable sensor can detect:

Physical parameters: e.g. temperature[2], torsion.

Chemical changes: e.g. gas, liquid.

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1. J. Huang, Sensors, (2013)
2. A. Trontz, Sensors, (2015)

2.2 Sensor Concept

➢ *Previous work on coaxial cable sensor*

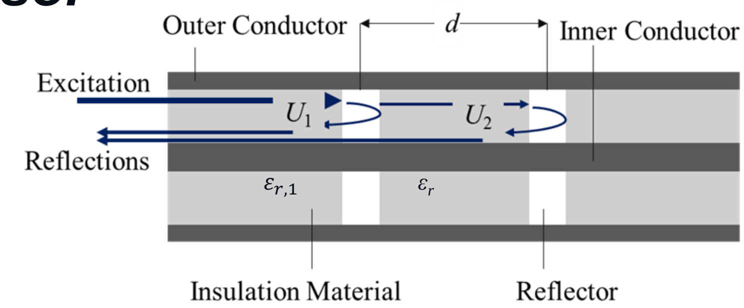
Resonant frequency: $$f_N = \frac{Nc}{2d\sqrt{\varepsilon_r}} \ (N=1,2,3\ldots)$$

1. Temperature sensor[1]
2. Torsion sensor
3. Pressure sensor
4. Liquid level sensor

Existing physical sensors

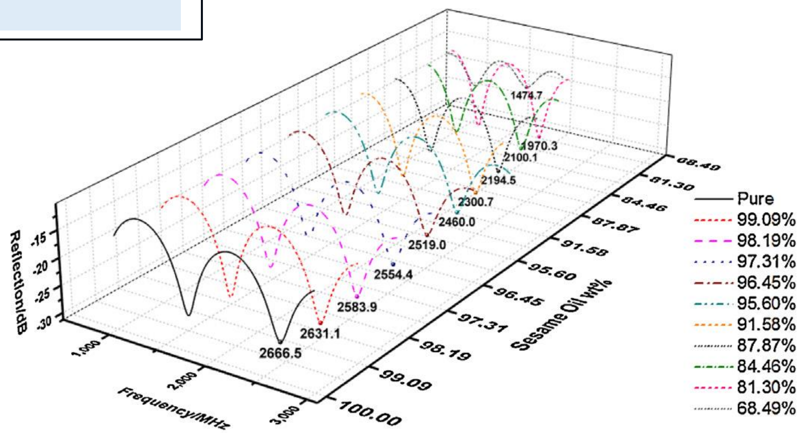
Material property change will introduce resonant frequency shift[2,3]

New materials for building chemical sensors



A Coaxial Cable Fabry-Perot Interferometric (CC-FPI) Sensor

- Example of the microwave interference spectrums detected by CC-FPI upon the liquid analyte composition changes[1].
- Resonant frequency shift.



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1. A. Trontz, Sensors, (2015)
2. S. Zeng, Sensor and Actuator A: Physical, (2017)
3. S. Zeng, MJNN (2018)

2.2 Sensor Concept

➢ ***Proposed work***

We propose to develop a highly CO_2 sensitive material and integrate it with a CC-FPI sensor for real-time detecting low concentration CO_2.

Sensor requirements for subsurface CO_2 leakage detection:

- ✓ Physically and chemically robust
- ✓ Small in size
- ✓ In-situ, real-time signal response
- ✓ Scalable
- ✓ Low manufacturing cost, low O&M cost
- ➢ Highly sensitive to CO_2 (this work)

Based on our previous work, we can conclude that this CC-FPI:

- has demonstrated chemical sensing capability
- is highly robust against harsh conditions
- has high resolution for low concentration analyte detection
- has the potential in scaling-up applications
- is made of low-cost, off-the-shelf commodities
- is easy to manufacture

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3. Technical Status

➢ Expected Outcomes

1. A novel CO_2 adsorbent will be developed with high CO_2 adsorption capacity, fast diffusion rate, high stability and low cost.
   - ➢ Potential CO_2 adsorbent with higher carbon removal efficiency
   - ➢ Special CO_2 affinity will advance carbon separation processes
   - ➢ Understanding fundamental gas diffusion mechanism in the material
2. A novel coaxial cable sensor for real-time detecting low concentration CO_2 will be demonstrated.
   - ➢ A future sensor platform technology for chemical detection
   - ➢ Specially designed for harsh environment applications
   - ➢ Combine sensor device development with fundamental material research

3. Technical Status

➢ Tasks and Accomplishments

Task I. Material Synthesis and Characterization

- ✓ Explore and optimize the material synthesis procedure
- ✓ Characterization and material performance results will be delivered

Task II. Sensor Fabrication

- ✓ Explore sensor functionality with different structures
- ✓ Fabricate sensor with different materials

Task III. Sensor Evaluation

- ✓ Evaluate the as-fabricated sensor with a lab apparatus
- Current Work ➢ Sensor's sensitivity, response time and detection limit will be tested
- • Use sensor data to guide material development

Task IV. Preliminary System Design and Cost Analysis

- ✓ Sensor system design based on practical applications
- • Preliminary technical economic analysis (TEA) will be provided

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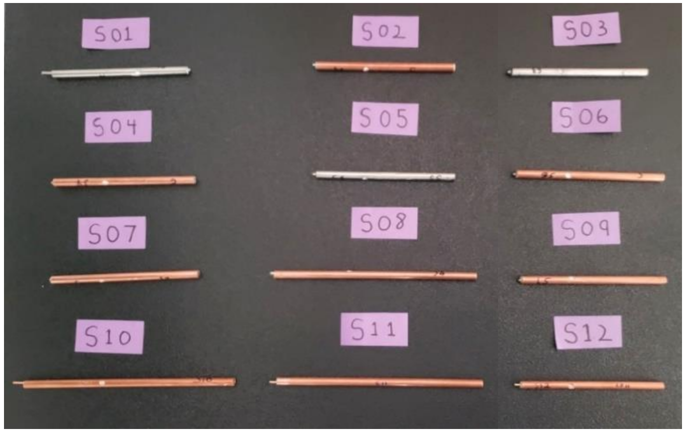
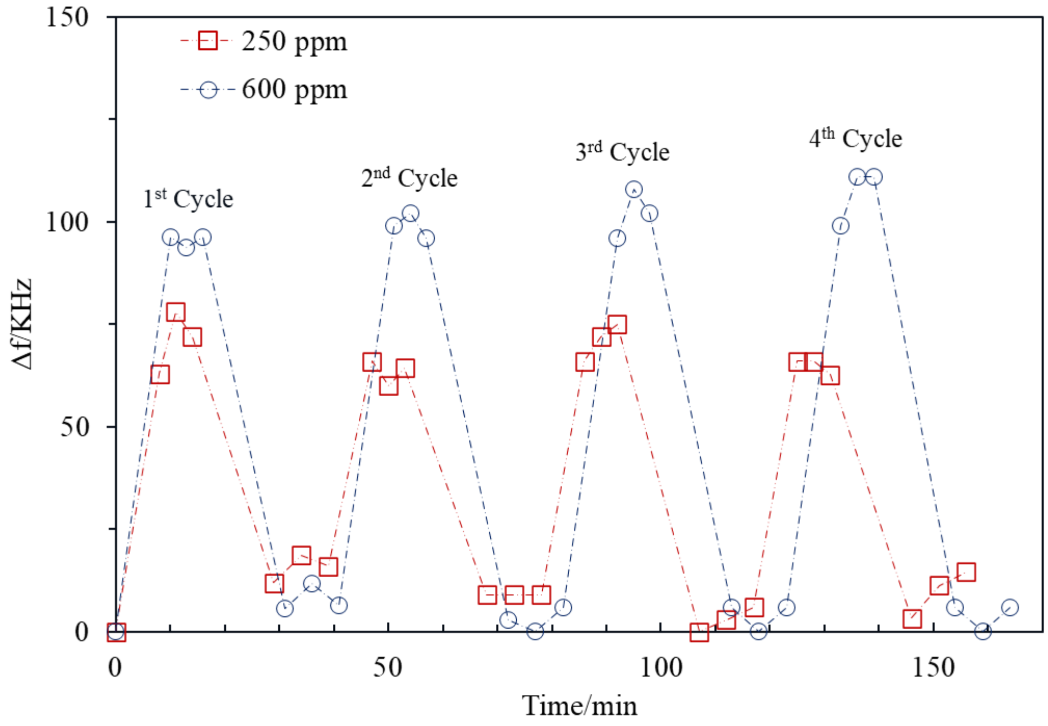
3. Technical Status

➢ Selected Results

Bettergy's CC-FPI CO_2 sensors



35 sensors fabricated, more on the way...



S11 cycling tests, C_{CO_2} = 250 ppm and 600 ppm, 4 cycles with air regeneration

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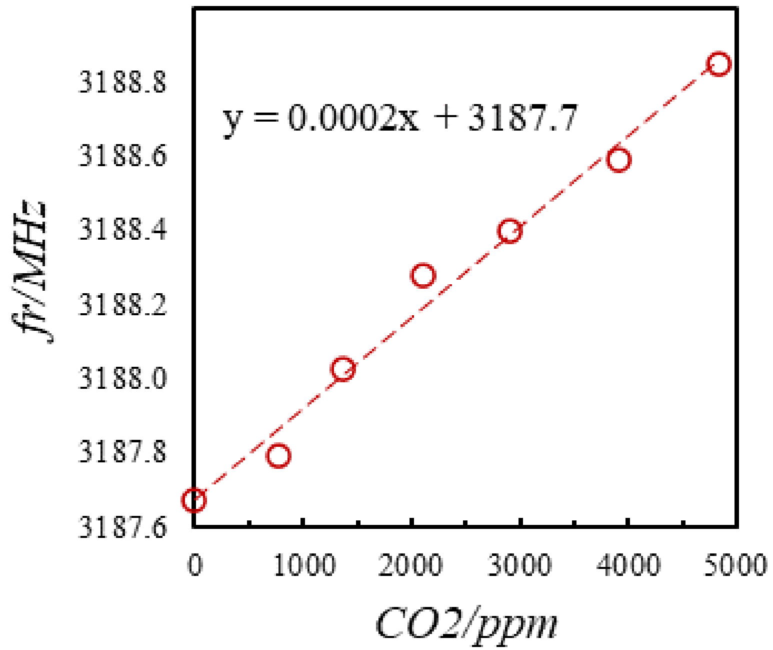
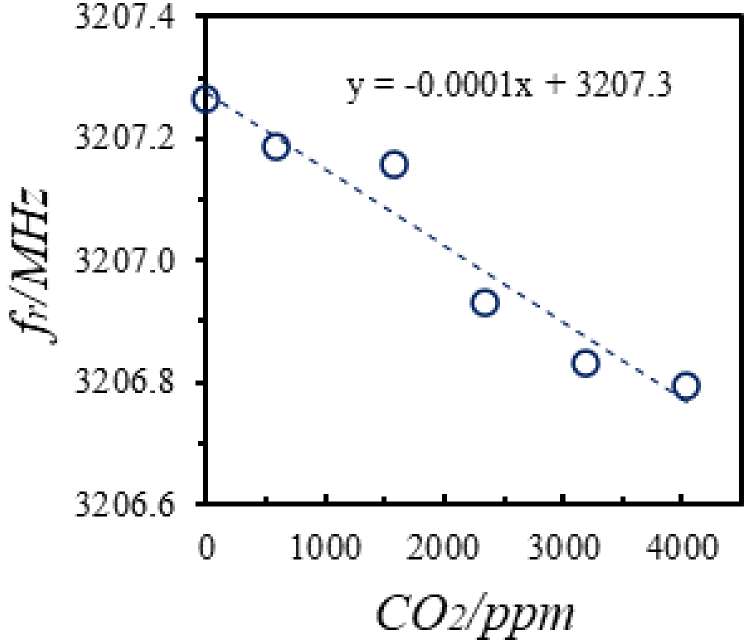
3. Technical Status

➢ Selected Results

Sensor #11



Sensor #13



Signal response of sensors made of different adsorbent material --- new fundamental study.

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3. Technical Status

➢ Challenges and strategies

Research Challenges	Mitigation Strategies
Material synthesis issues	Modify synthesis conditions such as temperature, time or composition.
Sensor assembling issues	Design and fabricate new sensor structure that works the best.
Sensor test issues	Modify sensor testing conditions, adjust testing instrument methods, using advanced control systems from the vendor.
Environment factors impact	Calibration, multiple experiments.

4. Project Schedule

➢ Project Timeline

Task\Month	1	2	3	4	5	6	7	8	9
Task I. Material Synthesis and Characterization	X	X	X	X	X	X			
Task II. Sensor fabrication			X	X	X	X	X	X	X
Task III. Sensor evaluation				X	X	X	X	X	X
Task IV. Preliminary System Design and Cost Analysis								X	X
Final Report									X

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4. Project Schedule

➢ Milestones and plans (next quarter)

Milestone I. CO_2 sensitive material development, <u>*Aug. 2021*</u>

- ➢ Material properties are optimized for this sensing application.

Milestone II. More Sensors fabricated, <u>*Sep. 2021*</u>

- ➢ The as-fabricated sensor shows well-defined signals.

Milestone III. CO_2 detection tests, <u>*Oct. 2021*</u>

- ➢ Sensor parameters such as sensitivity, response time, detection limit will be monitored and further optimized.

Milestone IV. Sensor's economic feasibility demonstrated, <u>*Nov.2021-Jan. 2022*</u>

- ➢ TEA analysis, market research (interviews, future customers).

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5. Summary

This program aims at developing a cost-effective sensor technology that can real-time monitor CO_2 leakages for CCS applications.

- A novel CO_2 sensitive material was developed
- A new sensor configuration for harsh environment chemical sensing was proposed and fabricated
- The sensor was demonstrated for real-time, low concentration CO_2 detection
- The sensor's reusability was demonstrated with multiple sensing cycles

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Thank you!

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

LARTA INSTITUTE

ENERGY I-CORPS U.S. Department Of Energy

UNIVERSITY OF Cincinnati

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5. Schuster, U., Hannides, A., Mintrop, L., and Körtzinger, A., 2009, Sensors and instruments for oceanic dissolved carbon measurements, *Ocean Sci*., v. 5, p. 547–558, available at https://doi.org/10.5194/os-5-547-2009.
6. Freifeld, B.M. and Trautz, R.C., 2006, Real-time quadrupole mass spectrometer analysis of gas in borehole fluid samples acquired using the U-tube sampling methodology. *Geofluids*, v. 6, p. 217-224, available at https://doi.org/10.1111/j.1468-8123.2006.00138.x
7. Trontz, A, Cheng, B, Zeng, S, Xiao, H, Dong, J., 2015, Development of Metal-Ceramic Coaxial Cable Fabry-Pérot Interferometric Sensors for High Temperature Monitoring. *Sensors*. V. 15, P. 24914-24925, available at https://doi.org/10.3390/s151024914
8. Huang, J, Wang, T, Hua, L, Fan, J, Xiao, H, Luo, M., 2013, A Coaxial Cable Fabry-Perot Interferometer for Sensing Applications. *Sensors*. v. 13, p. 15252-15260, available at https://doi.org/10.3390/s131115252
9. Zeng, S., Trontz, A., Zhu, W., Xiao, H., Dong, J., 2017, A metal-ceramic coaxial cable Fabry-Pérot microwave interferometer for monitoring fluid dielectric constant, Sensors and Actuators A: Physical, v. 257, p. 1-7,available at https://doi.org/10.1016/j.sna.2017.02.004.
10. Zeng, S., Trontz, A., Cao, Z., Xiao, H. and Dong, J.. 2018 Characterizing the gas adsorption dependent dielectric constant for silicalite nanoparticles at microwave frequencies by a coaxial cable Fabry-Pérot interferometric sensing method. Madridge J Nano Tech. v. 3, p. 100-107.
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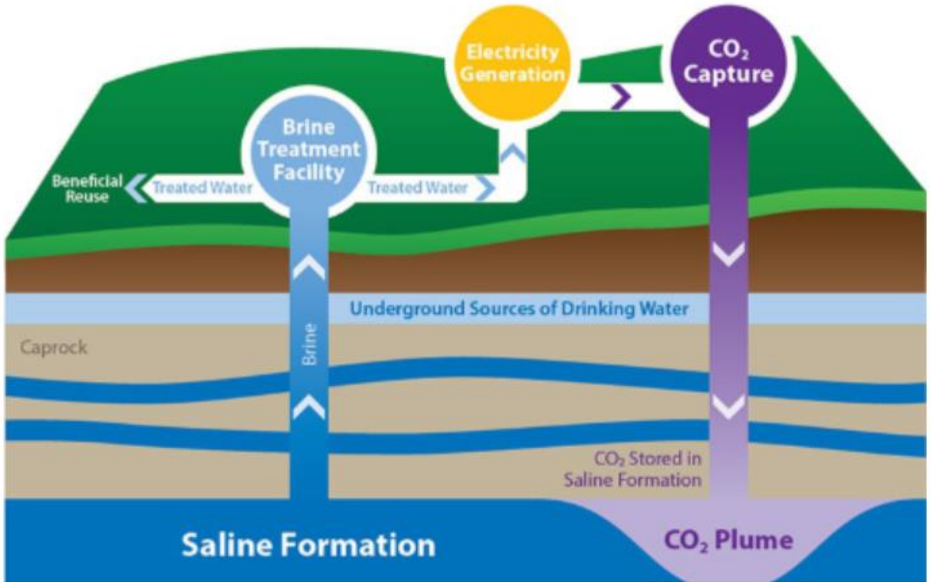
Appendix: Background

Carbon capture and storage (CCS) is the separation and capture of carbon dioxide (CO_2) from the emissions of industrial processes prior to release into the atmosphere and the storage of the captured CO_2 in deep underground geologic formations.



Major CCS Methods

- Saline formations
- Oil and natural gas reservoirs
- Unmineable coal seams
- Organic-rich shales
- Basalt formations

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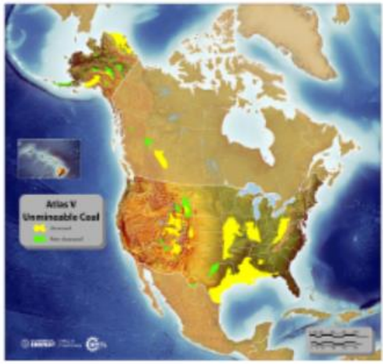
https://www.netl.doe.gov/coal/carbon-storage/faqs/carbon-storage-faqs

Appendix: Background



- Oil/natural gas extraction leaves a permeable and porous volume for CO_2 storage.
- These “reservoirs” are ideal geologic storage sites as they have conditions suitable for CO_2 storage.
- Injecting CO_2 can push fluids towards producing wells --- Enhanced Oil Recovery (EOR), Enhanced Coal Bed Methane (ECBM) recovery

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https://www.netl.doe.gov/coal/carbon-storage/faqs/carbon-storage-faqs