Rugged Fiber Optic Downhole Sensor for Monitoring CO_2 in Brine

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Who we are

- A growing 45 year-old company of ~180 talented scientists, engineers and administrative personnel
- Headquartered in Andover, MA, with eight satellite locations in the U.S.
- Three wholly-owned subsidiaries, Q-Peak, Research Support Instruments, Faraday Technology, with complementary capabilities
- A technologically diverse research and development organization with revenues over $50M
- Employee-owned through an Employee Stock Ownership Trust

What we do

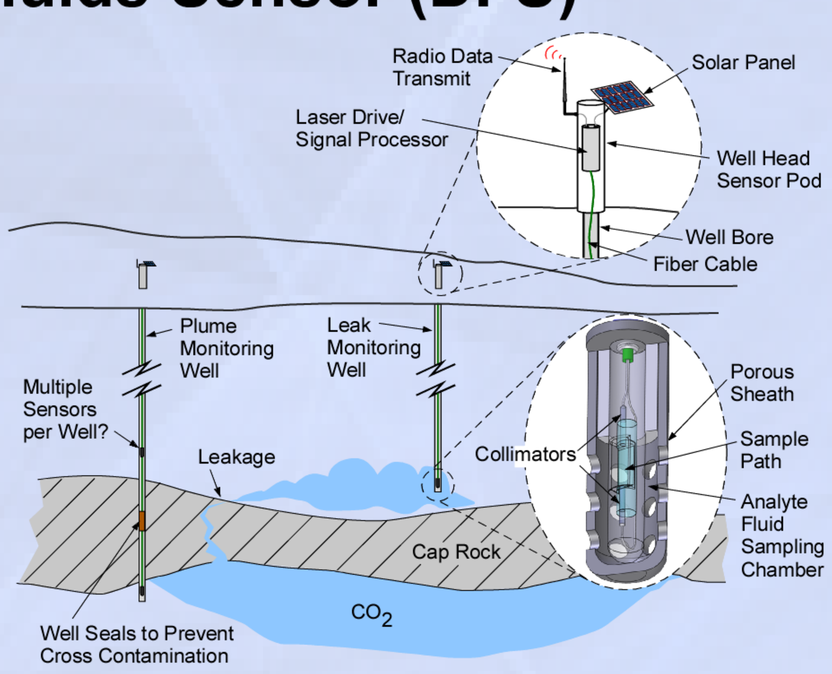
- Applied contract research and development for all major agencies of the U.S. government
- Technology development under contract to both industry and government
- Prototype product development for industry and commercial applications
- Components, systems, and instrumentation for industry and government sales
- Technology and product licensing

PSI Industrial Sensors

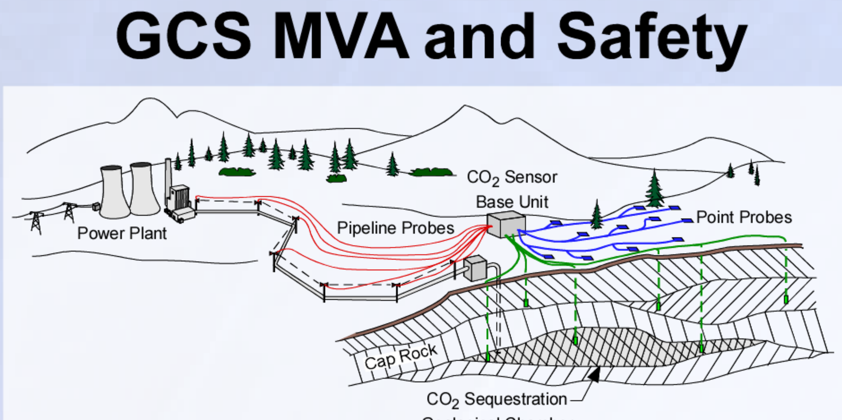
- Interdisciplinary combination of science and engineering skills with specific strengths in development and commercialization of photonic sensors and instrumentation
- Product development from concept to manufacturing prototype
- Go to market via direct sales, strategic partnerships, pilot scale manufacturing, and licensing
- Developing strong interactions with the oil & gas and broader energy industries since 1994

Abstract – Downhole Fluids Sensor (DFS)

PSI is developing a sensor, based on **tunable diode laser absorption spectroscopy (TDLAS)**, for continuous and autonomous in situ measurement of fluids within and around sequestration reservoirs for CO_2 content. The fluid interrogation is accomplished via a passive optical sensor head at depth that is coupled to the laser at the surface (well head) via an optical fiber. A field test prototype design is presented, along with initial laboratory results. The sensor supports geological carbon sequestration (GCS) monitoring, verification, and accountability (MVA) needs for detecting and characterizing leakage from GCS sites at all depths. A suite of downhole sensors can also help advance the science of GCS fluid transport modeling by monitoring CO_2 plume progress cost effectively with speed, sensitivity, and chemical selectivity to supplement current techniques of seismic mapping and pulsed neutron decay.

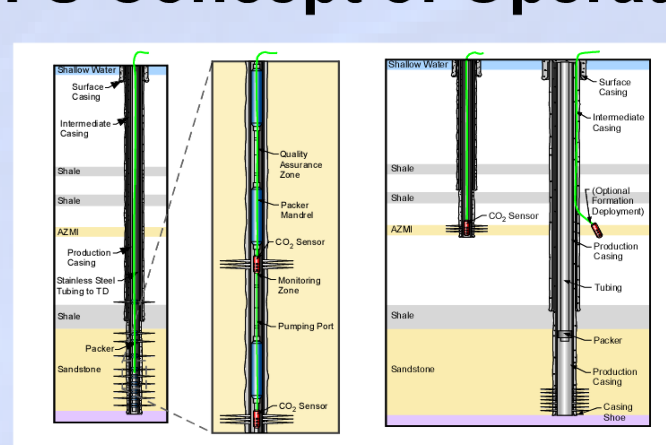


Laser-based Sensors for GCS MVA and Safety



- Open-path CO_2 gas sensors (red) (and below)
- Handheld / mobile leak survey tools (and below)
- Shallow in-ground CO_2 gas point sensors (blue)
- Well-depth supercritical CO_2 sensors (green) (this project)

DFS Concept of Operations

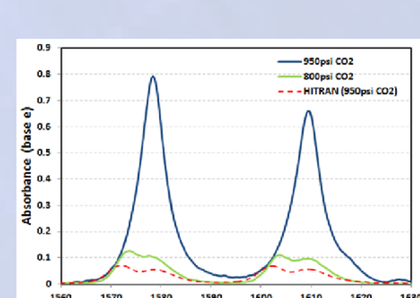


(left) Multi-horizon plume monitoring in reservoir monitoring well. (right) Leak monitoring in AZMI in (left) dedicated small-bore well or (right) outside casing of reservoir monitor well. (well section schematics adapted from Alvi, et al. "CO_2 Emissions – One Response to Emissions," Oilfield Review, p.36-48, Winter 2012-2013)

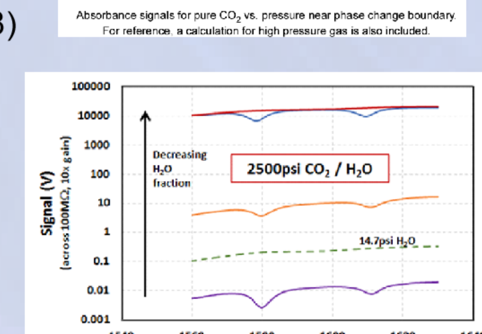
- Deployed in reservoir monitor well at potentially multiple depths with single cable
- Deployed in porous "leak-monitoring" layer (above-zone monitoring interval (AZMI))

Measurement Principles

- **TDLAS** can be used to measure concentrations of CO_2 in any fluid phase. Carbon dioxide absorbs infrared light in specific wavelength bands (ro-vibrational transitions). A modulated laser diode current results in intensity and wavelength modulation. The diode wavelength modulation is generally centered on a CO_2 absorption feature that is away from the absorption bands of interfering molecules. The figure right left illustrates absorbance (A) spectra for pure high pressure gaseous and liquid CO_2 for a 50mm optical path (A_{CO2} = 0.8) through the fluid at the wavelength region of interest for this work.
  [Optical transmission $T = I/I_0 = e^{-A}$]
- In the presence of water (a very strong broadband absorber at these wavelengths) increasing H_2O will induce an additional attenuation up to 6 dB in magnitude (right bottom). This is still a suitable return power fraction (nW) to detect the dissolved CO_2 at 0.1% scale or lower.



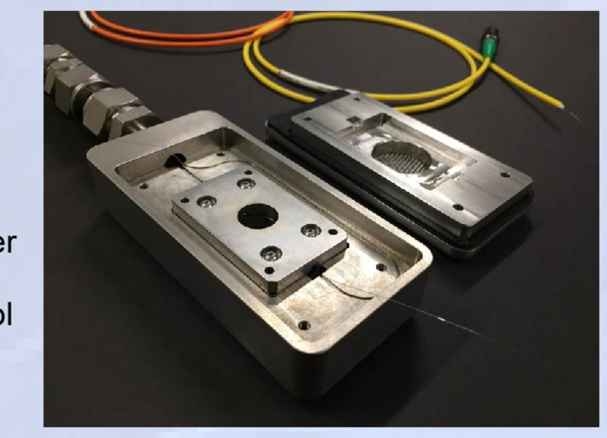
Absorbance signals for pure CO_2 vs. pressure near phase change boundary. For reference, a calculation for high pressure gas is also included.



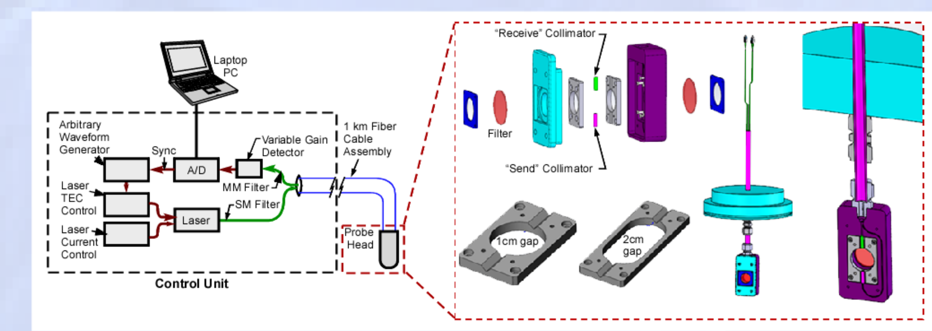
Temporal signal traces versus wavelength for varying CO_2 / mixtures.

Engineering Alpha Prototype (AP) Design

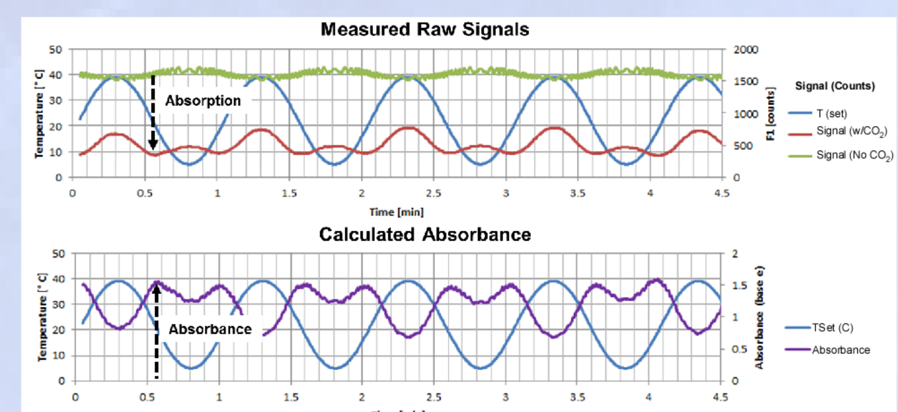
- Passive optical probe head with porous outer sheath
- Few cm fiber-optically coupled path (fixed alignment)
- Rugged fiber cable with delivery and return fiber
- Electronics at surface in shoe box-sized Control Unit connected to PC for R&D or telemetry hardware for autonomous operation
- **Strategy:** The very broad spectral width of the liquid CO_2 feature (~6nm FWHM) motivates **a novel laser tuning approach that ideally has ~12nm of wavelength tuning (standard TDLAS approach = 0.25nm)**



Downhole Fluids Sensor (DFS) Alpha Prototype sensor head



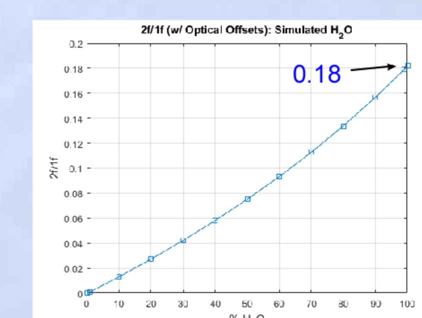
Early Benchtop Test Results - Direct CO_2 Absorbance

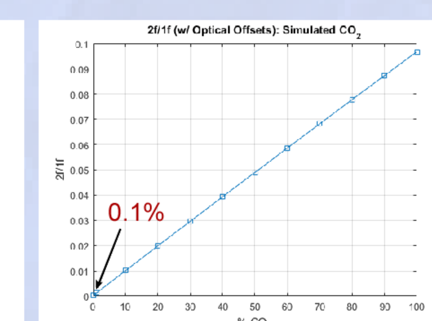


- 500 laser wavelength steps per period at ~5Hz = 100sec sweeps
- Compare signals through empty 5cm cell (green) and with 1000psi CO_2 (red).
- Absorbance = 1.5 for pure CO_2 (→ A=0.3 for 1cm path)
- **Potential detection limit: 0.1% CO_2 (A=3x10^{-4} for 1cm path)**

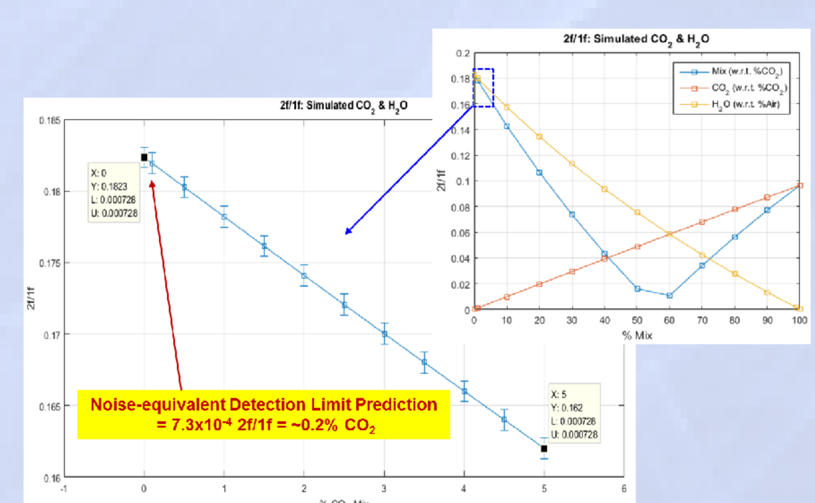
Lock-in Detection Simulation (CO_2 & H_2O Contributions)

- 2f/1f ratio is independent of total light returned
  - 2f is proportional to analyte-induced absorption (either CO_2 or H_2O)
  - Both 2f and 1f are proportional to total laser light returned
- Across the wavelength range being scanned, the water absorption feature has a curvature that also (like CO_2) generates a 2f signal contribution, along with the very strong total (dc) signal attenuation
- **Goal:** Detect 3x10^{-4} scale (0.1%) CO_2 signature in the presence of 0.18 H_2O signature





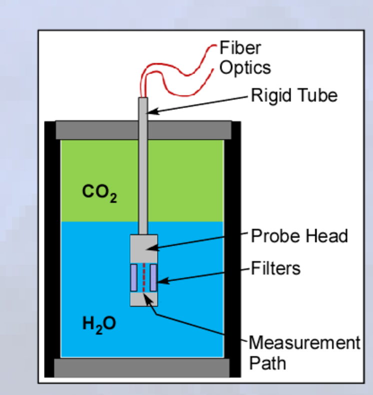
Software Lock-in Simulation with AP-Measured Noise Levels Added



- Measure ~15hrs data in water with 0.5" path AP DFS probe
- RMS drift/noise contribution to 2f/1f = 7.3x10^{-4}
  – Equivalent to ~0.2% CO_2

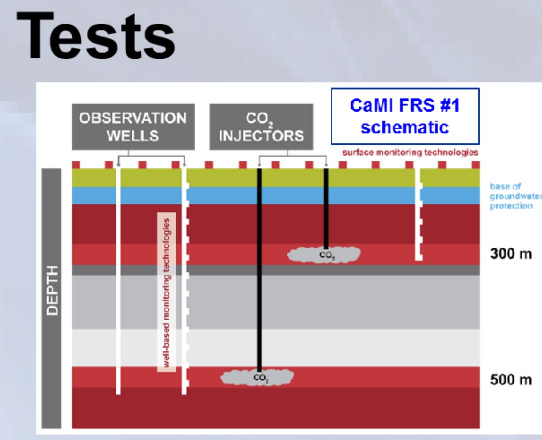
Alpha Prototype (AP) Lab Tests

- AP DFS unit to be tested at Schlumberger-Doll Research labs
- Simple pressure vessel (right) employed to access pure H_2O (brine), pure CO_2, and CO_2– saturated H_2O conditions
  - To 130atm and 75°C
  - Verify CO_2 detection limit
- AP head is baseline design for Beta (field test) Prototype, to incorporate km-scale rugged fiber cable and embedded automatic gain detection system



Beta Prototype (BP) Field Tests

- Carbon Management Canada (CRC) – Containment and Monitoring Institute (CaMI)
  - Priddis well (near Calgary) is a closed foot system with coiled tubing integrated to inject CO_2 at the bottom, to relevant pressures (>3000psi)
  - FRS#1 site (more remote) has medium depth injection wells and nearby monitoring wells
- 2-3 days of field testing, focused on deployability, functionality, and performance



Extension Applications

- Enhanced oil recovery (EOR) – plume monitoring, multi-horizon on/off production and phase control, broadband NIR optical fluid analysis…
- Enhanced (natural) gas recovery (EGR) and CO_2-based hydraulic fracturing – plume, leak, and production path monitoring
- Logging while drilling
- Monitoring natural CO_2 reservoirs
- Factory supercritical CO_2 applications (solvent, refrigerant, reagent…)
  - CO_2 as extracting solvent (coffee decaffeination, botanical oils…)
  - Rapid CO_2 expansion for microparticulation (pharma & more)

Conclusions

- Supercritical CO_2 spectral signatures observed with telecom diode laser with ultrawide wavelength modulation
- Passive (mechanical) fiber alignment scheme tested and yields good coupling, even to 50°C
- Detection limits for a 0.5 inch path estimated at ~0.2% CO_2
- Engineering Alpha prototype (AP) is designed and fabricated
  - Explore broadly tunable laser for ~2x sensitivity gain.(~0.1% CO_2)
  - Immersed probe head to be lab tested Fall 2017

Acknowledgments

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Disclaimer

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