Rugged Fiber Optic Downhole Sensor for Monitoring CO_2 in Brine

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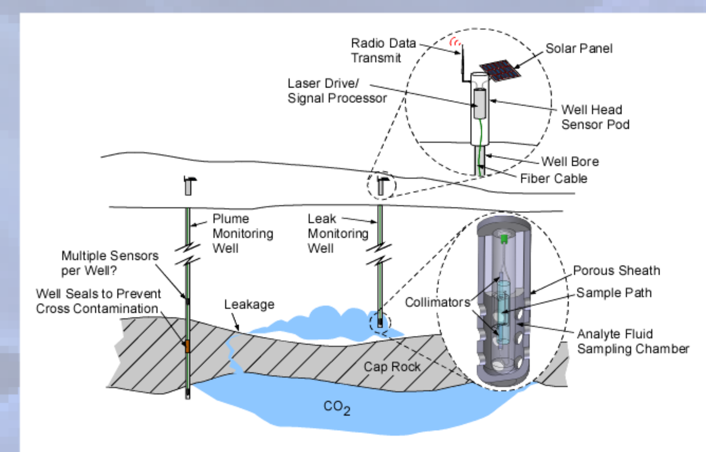
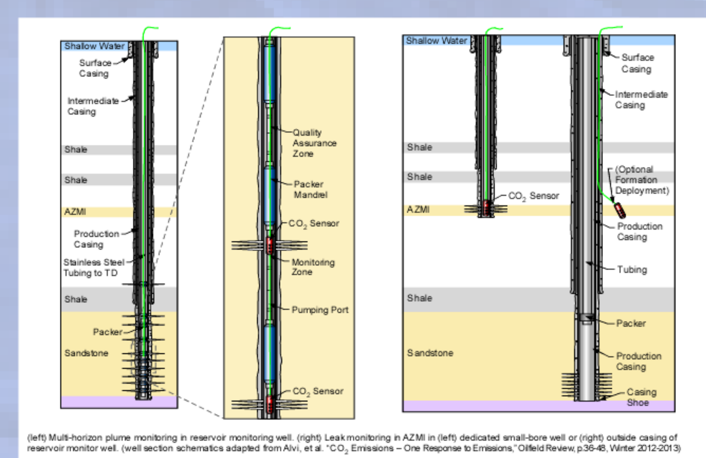
Abstract – Downhole Fluids Sensor (DFS)

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 sensor employs broad spectral tuning of a near-infrared laser to access vibrational absorption bands of supercritical and gaseous CO_2 in the presence of reservoir water. 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 from a benchtop proof-of-concept apparatus. 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.



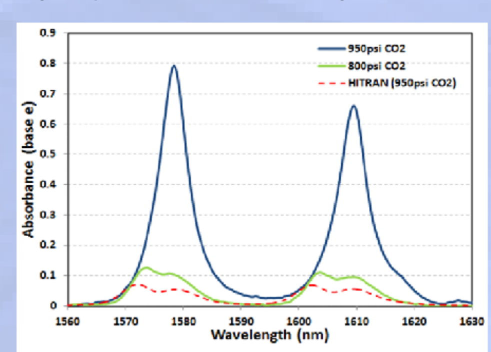
Concept of Operations

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

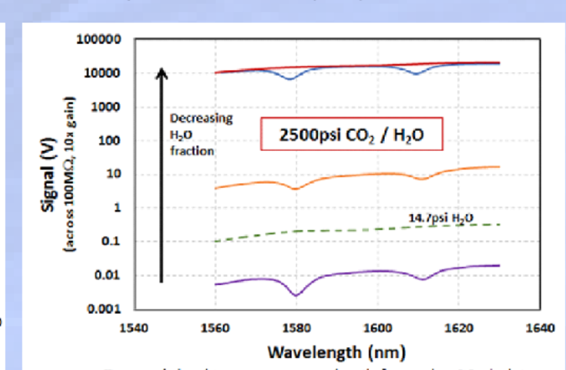


Measurement Principles

- **TDLAS** can be used to measure concentrations of CO_2 in any fluid phase. Carbon dioxide absorbs infrared light in specific wavelength bands. 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. However, at sequestration depth, high density water has an influence (see below) that must be accommodated. The figure below 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 10^6 in magnitude (below right). This limits the analysis path to ~1cm to still yield a suitable return power fraction (nW) to detect the dissolved CO_2 at 0.1% scale or lower.
- 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).

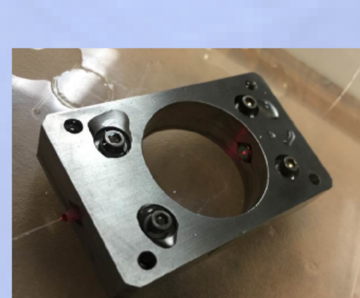


Absorbance signals for pure CO_2 vs. pressure near phase change boundary. For reference: a calculation for high pressure gas is also included.

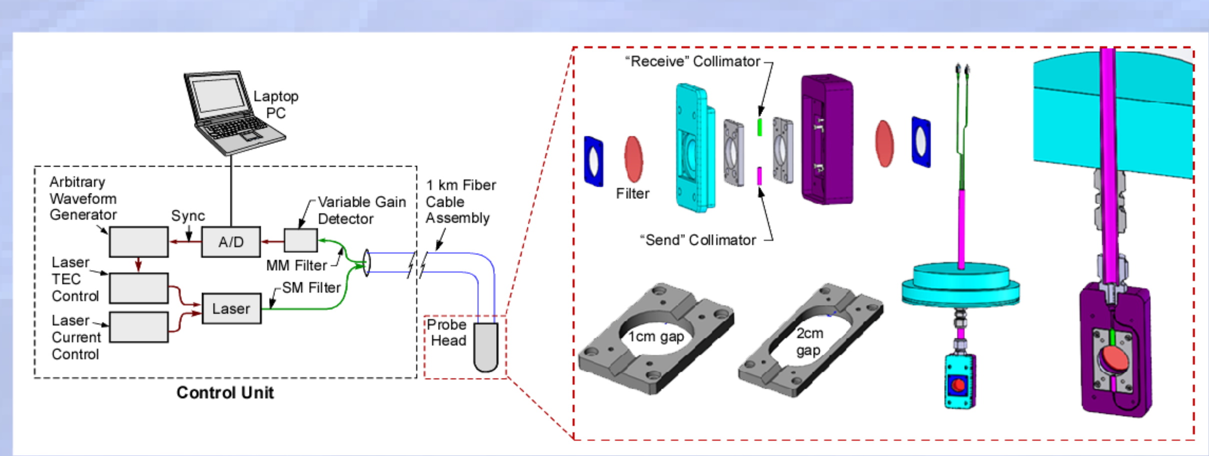


Temporal signal traces versus wavelength for varying CO_2 / mixtures.

Engineering Alpha Prototype (AP) Design



- Passive optical probe head with porous outer sheath
- ~1cm fiber-optically coupled path with machined (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



Physical Sciences Inc.

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- 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 of nearly $50M
- Employee-owned through an Employee Stock Ownership Trust

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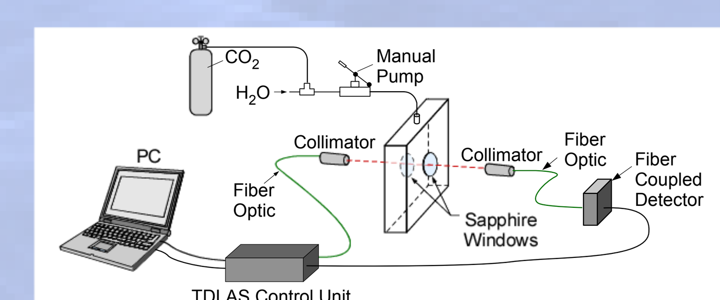
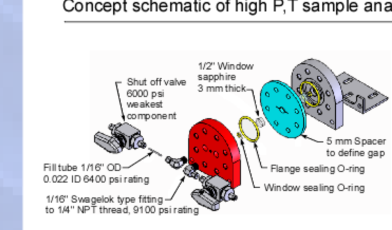
- Interdisciplinary combination of science and engineering skills with specific strengths in development and commercialization of photonic sensors and instrumentation
- Product development from concept to manufacturing prototype
- Go to market via direct sales, strategic partnerships, pilot scale manufacturing,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

Benchtop Feasibility Lab Tests

- Sapphire-windowed optically-accessible sample chamber
- Singlemode "send" and multimode "catch" optical fibers
- Remote (at surface) fiber-coupled detector module with wide dynamic range amplifier
- In-line manual pump to 3500psi
- H_2O / CO_2 mixtures generated by injecting water first then pressurizing with CO_2. CO_2 diffuses in or is elevated with partial sample removal and successive dilution with CO_2.



Concept schematic of high P,T sample analysis chamber and experimental setup.


CAD solid model of high pressure downhole fluids sensor test facility.

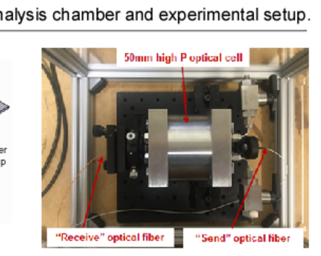
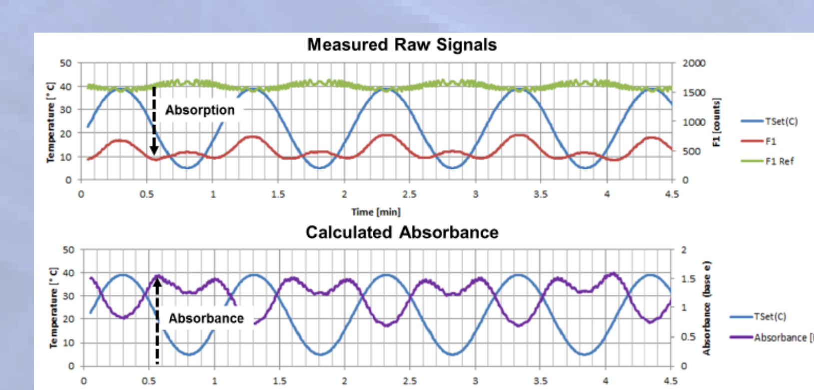


Photo of assembled optical cell with fiber collimators aligned through it.

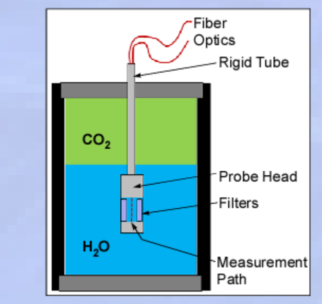
Benchtop Test Results

- 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)
- **Calculated detection limit: 0.1% CO_2 (A=3x10^{-4} for 1cm path)**



Alpha Prototype (AP) Lab Tests

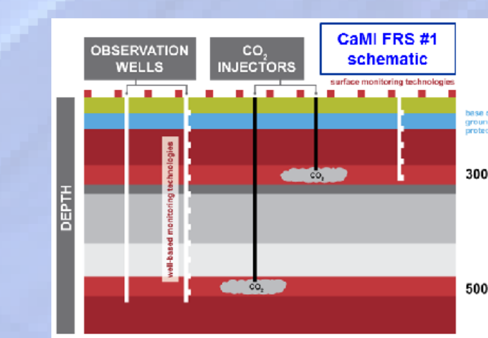
- AP DFS unit to be fabricated & tested in August 2016 at Schlumberger-Doll Research labs
- Simple pressure vessel (below) employed to access pure H_2O (brine), pure CO_2, and CO_2–saturated H_2O conditions
  - To 130atm and 75°C
- AP head is baseline design for Beta (field test) Prototype, to incorporate km-scale rugged fiber cable and embedded automatic gain detection system



Test / Purpose	Probe Head	Filter	P (atm)	T (C)	Salinity (M)	Expected Saturated Conc (mol/kg)
Verify fluid exchange rate through filters. Compare long & short path.	Short	Coarse	100	23	0	~1.6
	Long	None	100	23	0	~1.6
	Long	Coarse	100	23	0	~1.6
	Long	Fine	100	23	0	~1.6
Conc / Signal vs P	Long	None	10	23	0	~0.5
	Long	None	30	23	0	~1.0
Conc / Signal vs T (depth)	Long	None	100	23 → 50	0	~1.6 →~1.2
Conc / signal vs salinity	Long	None	100	23	0.5	~1.3
	Long	None	100	23	5.0	~0.5
Solution → Pure CO_2	Long	Coarse	100	23	5.0	~0.5 →100%
	Short	Coarse	100	23	5.0	~0.5 →100%

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



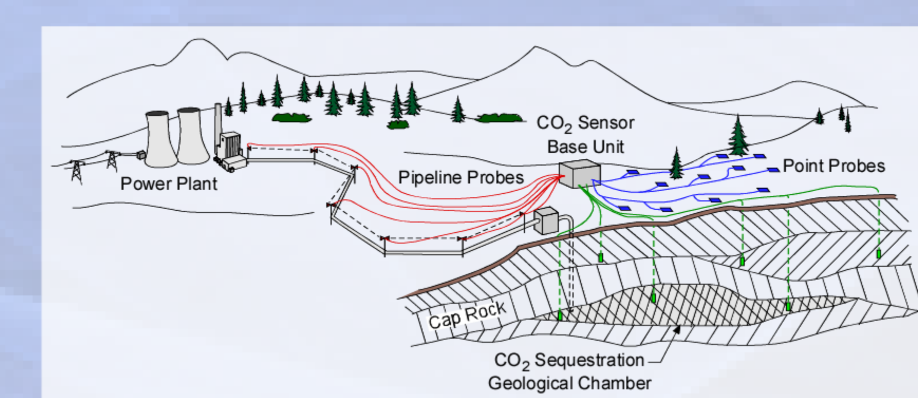
Extension Applications

- 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 dual (and ultrawide) wavelength modulation
- Passive (mechanical) fiber alignment scheme tested and yields good coupling, even to 50°C
- Detection limits for a 1cm path estimated at ~0.1% CO_2
- Engineering Alpha prototype (AP) is designed and under fabrication
  - Internal components (fiber assemblies, alignment plates) completed and under test
  - Passive (mechanical) fiber alignment scheme tested and yields good coupling, even to 50°C
  - Immersed probe head to be lab tested August 2016

Laser-based Sensors for GCS MVA and Safety



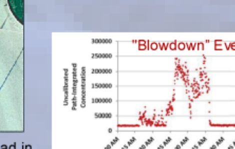
- Open-path CO_2 gas sensors (red) (and below)
- Handheld / mobile leak survey tools (and below)
- Shallow in-ground CO_2 gas point sensors (blue)
- Well-depth supercritical CO_2 sensors (green) (this project)

Open-path Sensor (OPS)

- Alarm-type system with 100-m path length
- Solar powered, with continuous monitoring via radio modem
- Intended for use along pipelines and wellhead infrastructure


Aerial view of OPS installation at IBDS injection wellhead in Decatur, Illinois at Illinois Basin Decatur Project (IBDP)


IBDP Injection Wellhead



RMLD / RCLD

- Compact, portable, personnel-wearable laser module with hand-held transceiver. Initially developed for natural gas leak survey (photo left)
- Battery powered with optional data logging via RS-232 port.
- The Remote Carbon Dioxide Leak Detection (RCLD) (photo right) was laboratory tested to show its response to CO_2 plumes and field tested to illustrate its effectiveness around a CCS site using various objects as targets


Hand-held natural gas leak standoff survey tool – Remote Methane Leak Detector (RMLD™) Manufactured by *Heath Consultants Inc.*


An RMLD was modified to detect carbon dioxide levels by replacing the laser module, and the infrared detector with devices operating at 2.0 µm.

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