Borehole Based Monitoring of CO$_2$ Storage: Recent Developments in Fiber-Optic Sensing

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contributions from many project participants

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Photo: CO$_2$ Venting at 2006 Frio Pilot Test
Outline

• CO2 Monitoring – Brief Review
  – 1950-2000s:
    • Early Enhanced Oil Recovery (EOR) Tests
    • Development of reservoir monitoring
    • First CO₂ Sequestration Specific Tests

• Importance of monitoring wells
  • Look Forward: Large Scale Sequestration
  • Need for ‘adaptive’ monitoring well program

• Fiber optic technology for monitoring wells
  – Background
  – Field testing and applications (CO₂ monitoring)
    • Citronelle, Alabama, USA
      – Repeat with improvement
    • Otway, Australia
      – With surface cable testing
    • Ketzin, Germany
      – Multiple wells
    • Aquistore
1950s – 1960s

• Early EOR Tests: Laboratory and Field Studies
  – Torrey, 1951: Oil recovery by carbonic acid injection
  – Beeson and Ortloff, 1959, Laboratory investigation of the water-driven CO2 Process for Oil Recovery
  – Budde, 1959, Geoph. Prosp.: Detection of CO2 in ground water (mineral water) via atmospheric measurements: (uses heat conductivity variation of CO2 vs N2/O2)

Carbon Dioxide Solvent Flooding for Increased Oil Recovery

L. W. Holm  
Member AIME

The Pure Oil Co.  
Crystal Lake, Ill.

Abstract

Laboratory flooding experiments on linear flow systems indicated that high oil displacement, approaching that obtained from completely miscible solvents, can be attained by injecting a small slug of carbon dioxide into a reservoir and driving it with plain or carbonated water. Data are presented in this paper which show the flood. Oil recoveries of 6 to 15 per cent of the original oil in place were obtained during this blowdown period. This additional recovery was found to be a function of oil remaining after the flood, decreasing with decreasing oil saturation. It was also noted that highest oil recoveries by blowdown were obtained when carbonated water rather than plain water followed the CO2 slug.

Holm, 1959, SPE.
1970s

- **Large Scale CO2-EOR Field Tests - SACROC Field**
  - Crameik and Plassey, 1972, API: Carbon Dioxide Injection Project SACROC Unit, Texas
    - Plan 37 Mton injection over 9 years in 202 injection wells; 220 mile pipeline
  - Farr, 1978, SPE: “.. Seismic as a reservoir analysis technique”
    - Until recently ...pore fluid identification was considered ... beyond the resolving power of the seismic reflection method”
  - Richardson, 1979, JPT: Monitoring with Induction Logs: “using the technique on a CO2 pilot flood”

- **Early Climate Change Concern in U.S.**
  - National Academy Report 1977
1980-90s

• **Beginning of Subsurface Monitoring**
  – Goodrich, 1980, SPE/DOE: Review of past and ongoing CO2 injection field tests
    • 19 projects - abstract has no mention of monitoring
  – Svor and Globe, 1982, SPE: “..Quantitative Monitoring for CO2 Floods”
    • Pulsed Neutron logging for co2 saturation
  – Widmyer, 1987, JPT: **Use of Monitor Observation Wells** For fluid sampling

• **Maturing Monitoring Tools**
  – Lumley 2001, Geophysics: 100 total and 75 active reservoir monitoring projects (4D seismic)
1990s-2000s

• **Initial Sequestration Field Tests – All With Monitoring Program**
  
  – Industrial
    
    • Sleipner (4D marine seismic)
    • Weyburn-Midale (also EOR)
    • In Salah (success of InSAR)
    • Snohvit (2008 – marine seismic)

  – Research Pilots
    
    • Frio (crosswell, continuous fluid sampling)
    • **Nagaoka** (crosswell, multiple well logging)
    • Otway (multi-level continuous fluid sampling)
    • CO2Sink (Ketzin) (ERT, 4D seismic)

• US DOE Partnerships (e.g. Cranfield, Decatur, etc.)
  
  – Wide range of monitoring tools tested
Early Success at Borehole Monitoring
McElroy Pilot Test 1995

Imaging CO₂ and Pressure Changes in McElroy
ΔVp (’93 to ’95) in CO₂ Pilot

Wang, et al, 1998;

Harris, et al, 1995

Well (Courtesy of Statoil)

>13 Mtons Injected

CO₂ plume in map view

Time-lapse seismic data

1994
2001
2008


Chadwick, et al, 2010
Issues with Seismic Imaging:
Quantitative interpretation without other data may be difficult:

How many layers at Sleipner?

No monitor well to aid interpretation!

Reservoir Model ($S_g$) & Seismic Data

D. Lumley, Leading Edge, 2010

Synthetic PSDM 4D seismic difference

Real PSTM 4D seismic difference

Arts and Vandeweijer, Leading Edge, 2011
Large Scale Storage – Multiple Injectors
Need to Optimize Utilization and Location of Monitoring Wells

~200 km

Large Scale Sequestration Model:
20 Injectors, 30 km apart, 5 Mton/year each for 50 years

Monitoring Well

Modified from:
Advances in Borehole Monitoring Methods are Needed for CCS Projects

Motivation: Deep monitoring wells are expensive to drill and complete and have limited space available for instrumentation

- Monitor CO$_2$ plume location
- Reservoir pressure and temperature
- Fluid sampling
- Leak detection
- CO$_2$ saturations

Goal: Develop a rugged, cost effective, multi-sensor monitoring platform designed for a single-well

- Distributed fiber optic sensor arrays
- Modular Borehole Monitoring (MBM)
Advanced Borehole Monitoring Tool:
Fiber Optic - Distributed Sensor Arrays

• Benefits:
  – Operate in harsh downhole environments
  – long potential life span, high data sampling rates,
  – high spatial resolution, adaptive to changing measurement technologies

Applications include:
• Distributed temperature sensing (DTS)
• Borehole strain measurements
• Direct chemical detection
• High density seismic arrays (DAS)
  – Leak detection
  – Compliance monitoring
• Heat-pulse monitoring
  – Leak Detection
  – CO₂ distribution behind casing
  – Flow monitoring and allocation

Subsea Fiber optic cable assembly

Citronelle Deployment
Distributed Temperature Sensing (DTS)

- DTS:
  - DTS used for past 20 years
  - Measurement of Raman backscattering, combined with Optical Time-Domain Reflectometry (OTDR), determines temperature along fiber length

- Specifications vary with stacking time and length:
  - ~10 km fiber: spatial resolution 25 cm, temperature resolution 0.01°C, measurement time 1 s

3 km DTS Temperature
DTS Heat-Pulse Monitoring

- **Heat Pulse:**
  - Copper heater elements (wire) integrated with DTS fiber in the same cable provide distributed pulse of heat
  - time-lapse measurement of temperature during/after heating

- **Fluid substitution in well or pore space changes thermal properties detected by heat pulse measurement**

Multiple heater elements and fibers are integrated into a 3/8” OD stainless steel control line.
Distributed Acousting Sensing (DAS)

- DAS acquisition allows seismic monitoring with fiber optic cable
- DAS has received great interest and development in recent years –
  - from Petroleum Technology (2012) to The Economist (2014)
  - Early adoption for CCS monitoring (2011)

**The Economist**

Acoustic sensing
The ear underground

How fibre-optic cables can work like microphones
Jan 4th 2014 | From the print edition

Field Trials of Distributed Acoustic Sensing for Geophysical Monitoring

S. Bourne, G. Ugueto, R. Lupton, G. Solano, Shell Upstream Americas; D. Hill, A. Lewis, QinetiQ OptaSense®

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SEG San Antonio 2011 Annual Meeting
DAS

• DAS acquisition
• Sensitivity currently less than standard geophone, but...
  – Spatial sampling and ease of deployment much greater
• Easy deployment of DAS with other lines
DAS Theory

- Light pulse is reflected throughout fiber’s length by Rayleigh scattering
- DAS system measures changes of the backscattered light
- An acoustic field around the fiber causes pressure/strain on the fiber, resulting in changes to the backscattered light
- The DAS measures these changes by generating a repeated light pulse at e.g. 100 µs and continuously processing the returned optical signal
- Up to 10 km in length, up to 10 kHz sample rate, and up to 1 m resolution

A 3 km single mode fiber becomes an acoustic array with up 3,000 sensors!

From Hartog, et al, EAGE, 2013
Deployment: Modular Borehole Monitoring

• Motivation: Maximize efficient use of available boreholes for semi-permanent monitoring

• Measurements of Interest
  – Pressure*
  – Temperature
  – Fluid Sampling*
  – Wireline logs
  – Geophysical Monitoring
    • Seismic: active source and passive monitoring
    • Electrical

* Requires Packer for zonal isolation

The Previous Way:
6 Separate Lines
Modular Borehole Monitoring (MBM) Conceived at Otway Pilot (Australia) 2007

- Concept: A package of redeployable borehole monitoring instruments
- Example: Otway 2007
  - Dedicated Monitoring well
  - Fluid sampling was main monitoring success (not seismic)

- Geophone with clamp (VSP)
- 3c Geophone with clamp (Microseismic)
- Hydrophone (seismic)
- Pressure & Temperature
- Fluid Sampling: U-tube Inlet

Freifeld and Daley, LBNL & CO2CRC
Problem: Deploying many instruments and cables in small well was challenging.
Modular Borehole Monitoring (MBM)

- Tools Deployed with MBM
  - Discrete Pressure & Temperature (2 Quartz Gauges)
  - Distributed Temperature Sensing (DTS) with Heater (Heat-Pulse)
  - Fluid Sampling (U-tube)
  - Seismic monitoring
    - 18 clamping geophones
  - Distributed Acoustic Sensing (DAS)

The MBM Improvement:
Flatpack and Geophone Cable
SECARB Anthropogenic Test

- Integrated Capture, Transmission, Storage
  - CO₂ Capture began June 2011
  - Transportation via 19 km pipeline
  - Saline Storage at Citronelle Oil Field began August 2012
SECARB Anthropogenic Test
Citronelle, Alabama

• First integrated CO₂ capture, transportation and storage project on a coal-fired power station using advanced amines

• Southern Co. and MHI have captured over 200,000 metric tonnes of CO₂ to date

• Denbury Resources has transported, injected and stored over 100,000 tonnes

• Injecting CO₂ into the Paluxy Formation, which has excellent storage capacity of regional significance
Citronelle Storage

Elements of the MVA Program

- Shallow MVA
  - Groundwater sampling (USDW Monitoring)
  - Soil Flux
  - PFT Surveys

- Deep MVA
  - Reservoir Fluid sampling
  - Crosswell Seismic
  - Mechanical Integrity Test (MIT)
  - CO₂ Volume, Pressure, and Composition analysis
  - Injection, Temperature, and Spinner logs
  - Pulse Neutron Capture logs
  - Vertical Seismic Profile

- MVA Experimental tools

Courtesy of ARI
R&D Effort Focused on the MBM System in Observation Well

- Observation well (D9-8#2):
  - ~250 m east of the CO₂ injection well
  - Perforated at a depth of ~2.8 km in Paluxy Formation
Deployment of MBM

- Tubing Deployed (allows wireline access)
- 4-element flatpack and sealed geophone cable
- 18-level Geophone array
  - Hydraulic clamps for Geophones
  - Clamp in tubing/casing annulus
- Dual mandrel hydraulic packer
  - Non-rotating overshot connection for coupling to 450’ bottom assembly
  - Avoids splices at packer
MBM System Sensor Configuration

• Fiber optic cable for distributed temperature and acoustic measurements
  - Heat-pulse monitoring for CO$_2$ leak detection
• Tubing deployed geophone array (6,000-6,850 ft)
• Two in-zone quartz pressure/temperature gauges (~9400 - 9500 ft)
• U-tube for high frequency, in-zone fluid sampling (tube-in-tube design)
• 2 7/8” production tubing open for logging

Geophone pod and clamping assembly and yellow flat pack containing fiber cable
MBM Design: Flat-Pack and Geophone

Flatpack replaces 7 lines

DTS, Heater, DAS
Hybrid 6-copper, 4-fiber-optic cable

Components
A: 6 x 20 AWG 7/32 Tin Coated Copper, O.D.: 0.96 mm (0.037") Nominal
B: Colored T-01 (FEP), O.D.: 1.73 mm (0.068") Nominal.

Geophone clamp hydraulic line

Hybrid copper fiber-optic cable
Geophone TEC
Tube-in-tube U-tube sampler
Coax P/T monitoring cable

Welded Geophone Line
Citronelle DAS VSP (Vertical Seismic Profile):

- June 2012 and August 2013
- Citronelle Offers an Opportunity to Compare Seismic Methods to Monitor CO₂
- Seismic monitoring at Citronelle:
  - Cross-well seismic surveys
  - Geophone VSP surveys using
    - 80-160 level 3C arrays in the injector and D9-8#2
    - 18 geophone MBM array
  - DAS and MBM Geophone:
    - Source: vibroseis truck
    - ~60 shot points
    - 4–64 sweeps per location
    - Sweep: 16 s, 10–160 Hz
2012 DAS Testing
3 km, Tubing Deployed

- DAS VSP ‘piggy-back’ on standard acquisition
- Initial data quality insufficient to observe P-wave below ~1600 m, triggering needed improvement
- Benefit: 3000 sensors versus 18


Processed by D. Miller, Silixa
Improvement: Acquisition of more source sweeps and improved triggering increased DAS data signal to noise ratio, producing data comparable to more sensitive geophones.

*Approximately 9 dB difference in sensitivity – can be overcome with extra source effort.*

Single Channel Comparison:
DAS 64 sweeps comparable to Geophone 24 sweeps

SP 2003; iDAS setting D30; channel at 6450 ft

Courtesy D. Miller, Silixa
DAS Advantage in Number of Sensors

- Comparison of data acquired from one source point: 18 geophones vs 3000 DAS channels

7” Casing
2 7/8” TRS-8 Tubing
Flatpack
Geophone TEC cable
Clamp Hydraulic line spliced from flat pack
18 Geophones
Breakout of flatpack end: 9377’
Packer 9426’-9432’
Ni Plated overshot
P/T Gauge
Perforated Chrome Tbg
U-tube fluid sample inlet
Fiber/Heater cable
P/T Gauge

Courtesy D. Miller, Silixa
2013 Citronelle DAS vs MBM Geophone Comparison

- Comparison of Spectral Response
  - DAS matches geophone

[Graph showing spectral response comparison between DAS and geophone]

Courtesy D. Miller, Silixa
Fiber Optic Temperature at Citronelle

- Heat Pulse with Distributed Temperature Sensing (DTS)

Diagram:
- 7” Casing
- 2 7/8” TRS-8 Tubing
- Flatpack
- Geophone TEC cable
- Clamp Hydraulic line spliced from flat pack
- 18 Geophones
- Breakout from flatpack
- Packer
- Ni Plated overshot
- P/T Gauge
- Perforated Chrome Tbg
- U-tube fluid sample inlet
- Fiber/Heater cable
- P/T Gauge

Dimensions:
- ~9400 ft
- ~9850 ft
Monitoring with DTS Using Heat Pulse (Static Wellbore Conditions)

- Initial completion of well included use of MBM for diagnostic testing

- Heating 6 Watt/meter

- Heat Pulse located perforation w.r.t packer

- Information used in regulatory assessment of completion

- Heated Temperature (Red)
- Ambient Temperature (Blue)

- Colder Kill Fluid

- End of Flatpack

- Below Perforations
Well Diagnostics Using Heat Pulse Monitoring
Flowing Annulus – Thermal Change (Green)

- Packer
- Perforations
- Lower Flow
- Higher Flow
Citronelle Heat-Pulse Diagnostic Test

- Location of the packer is determined ±1 ft.*
- Perforation flow zone interpreted from distinct cooling noted from a 10±1.5 m zone.*
- The thermal profiles indicate flow both above and below the packer
  - strong likelihood that the packer has been set within the perforated interval

* Depth measured from bottom of fiber
Citronelle/MBM Summary

• SECARB’s Anthropogenic Pilot is an operational integrated CCS project
• A modular borehole monitoring (MBM) system was designed, built and deployed for Citronelle
• The MBM system includes:
  – P/T gauges, U-tube fluid sampling, hydraulic clamping geophones,
  – Fiber optic temperature (with heat pulse) and seismic (DAS)

• MBM system is operational and was useful in understanding well completion

• Following initial proof-of-concept testing MBM DAS VSP acquisition was improved and is very promising
  – Sensitivity within ~9 dB of clamped geophones
DAS Testing at Otway: 2012

Stage 2: Well CRC-2

- ~1400 m, Tubing Deployed Fiber plus Surface cable
- DTS (with heat pulse)
- DAS

Otway DAS included borehole (VSP) and surface cable

Otway DAS VSP

Raw Stacked Data

Data Compared to previous wireline geophone VSP
Increase Source Effort (stack 41 vs 5-10)

Otway Tubing DAS VSP vs Clamped Wireline Geophone Signal/Noise

How Much Extra Source Effort?

2012 Otway test says 40 dB

2013 testing at Citronelle indicates ~9 dB

Otway is not simultaneous acquisition -> Citronelle better comparison

Note: Stack of 100 = 20 dB

Parallel Surface Cables (Loop)
Very Similar Response

Cross correlation of all channels:
Time shifts < +/- 1 ms
Correlation Coefficient: ~0.8-0.95

DAS as Surface Seismic Cable:
Stacking Different Fiber Lengths

Directionality of DAS limits reflection signal: can improve by stacking, but Surface waves dominate signal compared to vertical geophones.

Otway DAS: Surface Wave Analysis

Result: Useful data for near surface properties (spectral analysis of surface waves – SASW)

Otway Test Summary

• DAS VSP data ~40dB below high quality geophones
  – Note: great improvement seen at second Citronelle test
• Simultaneous borehole and surface data on one cable
• DAS Surface wave data analysis is good quality
Ketzin Project

- CO2 Storage Pilot operated by the German Research Centre for Geosciences (GFZ); Injection at ~700 m
- Injection well and 3 observation wells
- DAS acquisition in 2012 (2 wells) and 2013 (4 wells)
- Weight Drop Source (240 kg)
Ketzin: 2012 DAS survey – 2 Wells

- Two Wells Simultaneous
- Fiber Behind Casing
- Surface connecting fiber added for VSP
Good Quality Data: Various Waves Observed

(A) Extensional signal propagating in undamped casing above 269m (5.5 km/sec)
(B) Direct compressional formation arrival (3 km/sec)
(C) Tubewave propagating in fluid annulus above 460m (1.35 km/sec)
(D) Reflected formation arrival from reflector at 540m
(E) Downgoing formation shear (1.67 km/sec)

Courtesy D. Miller, Silixa
Fiber deployed behind casing, but not cemented at all depths
DAS records waves related to well casing completion

Weak signal at ~650m in both geophone and DAS data – no cement

Courtesy J. Gotz, GFZ
Aquistore DAS 3D-VSP

2 Example Shots

- ~3 km Fiber Behind Casing, cemented, explosive shot
- Initial recording May 2013 of >200 shots
- Second recording Nov 2013 > 600 shots; being processed analyzed
May 2013 DAS VSP

• Currently: Processing of individual shots

Shot Points: 69 71 113 114 136

Observation Well

750 m
May 2013 Aquistore: Shot #136 (730m offset)
VSP Reflection Image

Possible Reservoir Reflection At ~3.2 km
New Data: Aquistore Nov 2013
DAS and Geophone 3D-VSP

MaxiWave 60-level

60-level MaxiWave
1470 to 2355 m
15m spacing + telemetry pod

Staging collar 2068 m

1x SM and 2x MM fibers
broken at ~2867m

OBS well completed in 2012

Source: www.aquistore.ca

Compare:
DAS and Geophones;
Vibroseis and explosive;
Single mode and Multi-mode

Results Soon!!
Summary 1

- CO₂ monitoring needs improved borehole methods
- DAS and Heat-Pulse DTS are new, useful fiber-optic applications
- Modular borehole deployments make sense for CCS monitoring
- DAS testing conducted within CO₂ monitoring R&D
- Citronelle site
  - Tubing deployed, 2.9 km, with short 260 m geophone string
  - Initial test had relatively low sensitivity
  - Repeat test greatly improved, about 9 dB below geophones, good potential for monitoring
- Otway site,
  - Tubing-deployed, 1.5 km, poor in comparison with previous geophone survey
  - Larger source effort needed, but promising result
  - Surface cable gives useful data
Summary 2

• Ketzin site,
  – casing deployed, ~750 m
  – Multiple wells recorded simultaneously on single cable loop
  – good overall data quality but adverse effects from un cemented zones.
  – DAS data has upgoing VSP reflections over the ~700-m depth of the well.

• Aquistore Site
  – Casing deployed, 3 km
  – Good quality data
  – Repeat with wireline 3-C geophones

• DAS is very promising technology, which is still improving
• Fiber optic sensing, in general, has application for CCS:
  – Improved monitoring while reducing risk from monitoring wells
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Questions?

Photo: Citronelle
Southeast Regional Carbon Sequestration Partnership (SECARB):
Anthropogenic CO2 Injection Field Test

Monitoring Well:
Citronelle D-9-8 #2