Frio II Brine Pilot: Preliminary results of combined well-based geophysical and geochemical monitoring methods

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Combined Well-based Geophysical/Geochemical Monitoring

Frio II utilized

— Seismic source in injection borehole
— Hydrophones in observation borehole
— In each perforated interval
  • U-tube sampler
  • Pressure/Temperature sensor
Frio II Seismic Monitoring (As Installed Sep. 2006)
Source: 1657 m (5437 ft)    Sensors 1630-1680 m (5349-5512 ft) with 6 m gap
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Injection Well Equipment

- Packer
- Seismic Source
- CO2 Injection tubing
Collocated U-Tube and Seismic Source

The ‘U’

Check Valve

Top of Seismic Source
Installation of U-tube and Seismic Source on 2 3/8” tubing

Rolls of tubing for U-tube

Seismic Source
Seismic Sensor (Hydrophone) Inside Protective Clamp

Hydrophone
Pre Injection Monitoring Channel 14 One recording every 2.5 minutes

Clock Time (1 Hour total)

Note: Expected Change due to CO2 ~ 1.5 ms
Channel 1 (Bottom) PreInjection

Clock Time (1 Hour total)

Note: Expected Change due to CO2 ~ 1.5 ms
Channel 1 (Bottom) PrelInjection Color Amplitude Display

Clock Time (1 Hour total)

Note: Expected Change due to CO2 ~ 1.5 ms
Channel 1 (Bottom)

Clock Time (10 Hours total)
9 Channels  25 Hours
9 Channels 45 Hours

Below Packer

Above Packer
All Channels - 60 Hours
Channel 14 (Top of Sand) 45 Hours
Sensor 1650 m (5413’) Top Sand

| FFID | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 | 45 | 49 | 53 | 57 | 61 | 65 |
|------|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Time (hrs) | | | | | | | | | | | | | | | | |
| 10.5 | 11 | 11.5 | 12 | 12.5 | 13 | 13.5 | 14 | 14.5 | 15 | 15.5 | 16 | 16.5 | 17 | 17.5 | 18 | 18.5 | 19 | 19.5 |

Pump Shutdown

Breakthrough

Chan 16 1650 m
Geochemical Sampling Requirements for Frio I & II Pilot Study

- Minimal perturbation to flow field
- Sample recovery of sufficient volume to introduce fresh fluid to wellbore
- Multiphase constituents preserved and representative of downhole conditions
  - Brine/supercritical CO$_2$
  - No degassing
- Quantify brine/CO$_2$ ratio
- High frequency (hourly?) for assessment of CO$_2$/tracer arrival at observation well
Sampling Technologies Considered and Rejected

- **Downhole wireline sampling** (used for baseline/postinjection monitoring)
  - Expensive
  - Small sample size (other method needed to introduce fresh fluid to wellbore)
  - Difficult/risky to perform as 24/7 operation
- **Gas lift**
  - Hard to control lift rate
  - Perturbation to flow field
  - Difficult to recover downhole conditions
- **Submersible pump**
  - Not applicable to multiphase fluids
  - Interference with seismic
  - Perturbation to flow field
New Sampling Methodology based on old technology—U-Tube Sampling

- Large volume samples - 52 liters
- No degassing
- High purity – no contamination from air
- Collection of multiphase fluids
- High frequency ~70 minute cycle time
New Sampling Methodology based on old technology—U-Tube Sampling

Sample Leg
Drive Leg
Ball Check Valve
Production Tubing
Sliding End Packer
Inlet Filter: 40µm sintered stainless steel

Vent Manifold
High Pressure
Atmospheric

High-Pressure N₂
Supply Manifold

N₂ Purge Manifold
Sample Port
Sample Leg
Sample Manifold
13 L Vessels

Observation Well

U-Tube (see Figure 1 for detail)
Sample Interval

Compressor

Pressure Regulator
Pressure Transducer
Strain Gauge
Valve
Frio II Geochemical Sampling

- On-line high pressure pH, EC
- Liquid samples for
  - Aqueous chemistry (USGS)
  - PFT/Difluoro- Dibromo-methane tracers (ORNL/UT)
  - Fluorescein tracer (LBNL)
- Gas samples for
  - CD$_4$ Tracers (CO2CRC)
  - Quadrupole Mass Spectrometer Analysis
    - CO$_2$/CH$_4$
    - Kr/Xe/SF$_6$ Tracers (LBNL)
Gas Analysis—Quadrupole Mass Spectrometer

- Pressure Regulator
- Pressure Transducer
- Strain Gauge
- Valve

Diagram of gas analysis setup with labels for sampler pressure, vent, peristaltic pump, gas/liquid separator, and quadrupole mass spectrometer.
Mass Spectrometer Data

Quadrupole Gas Analysis

- Air
- Frio Gas

- Methane
- Nitrogen
- Oxygen
- Argon
- Carbon Dioxide

Normalized Detector Ion Current vs. AMU
Results from Frio II

[Graph showing gas concentrations over time]

- CO2
- CH4
- O2
High Pressure/Bench pH Measurements

Frio II - Observation Well - U-tube

- bench pH
- in-line pH

preliminary
Frio II Alkalinity

Elapsed Time (hours)

Alkalinity (mg/L)
Determination of Sample Fluid Density

Strain Gages

Sliding Sleeves
Frio I Sample Density

Fluid Density (kg/m$^3$)

Brine Density = 1068 kg/m$^3$
Frio II Sample Fluid Density

Density (kg/m³)

Sample Pressure (PSI)

9/28/2006 0:00 9/28/2006 12:00 9/29/2006 0:00 9/29/2006 12:00 9/30/2006 0:00
Tracer Testing

Tommy Phelps, Phil Szymcik – ORNL
High pressure piston pumps for Perfluorocarbon Tracers

Jim Underschultz – CSIRO Petroleum
collects isotubes for CD$_4$ analysis
Frio II Results—Evidence of Rapid CO₂ Dissolution

- Kr
- SF₆
- Xe

[Graph showing PPM levels from 09/25/06 to 10/01/06]
Frio II Results-Evidence of Rapid CO$_2$ Dissolution

Krypton injected 16 hours after start of CO2 injection!
What does the future hold for well-based methods?

- Multiple completions in each borehole
- Multifunction completions
  - Electrical
  - Seismic
  - Hydrologic/Geochemical sampling
  - ???
- Fiber-optic based sensors
  - Distributed Temperature Sensors
  - Down-hole geochemical measurements
  - Advective flux measurement
- Vigilence required to incorporate technologies from other fields as they develop
Example of technology not yet applied to monitoring CO₂—DTPS

- Application—monitoring of conditions at Yucca Mountain Nevada, USA for High-Level Radioactive Waste storage
- Completion consists of:
  - 4 U-tube samplers
  - Distributed Thermal Perturbation Sensor (DTPS)
- Similarity to M&V CO₂ sequestration
  - Regulatory driven activity aimed at waste isolation
  - Long-duration monitoring (~100 yrs)
  - Economic drivers—high well cost ⇒ sparse data
Therefore need to maximize data from a single wellbore
Distributed Thermal Perturbation Sensor

Fiber-Optic DTS

Constant Wattage Heater

Temperature
Installation of DTPS with 4 U-tubes
Getting U-tube Ready for Deployment
Low Tech Installation
DTPS Heating Data

Depth (mbgs)

Temp (°C)
Data Converted into Advective Flux

![Graph showing changes in temperature and flux with depth.](image-url)
Frio II Lessons Learned

- Integration between monitoring technologies is key to success
- Time-lapse seismic cross-hole worked!!!
- Sample fluid location has a large impact on what is measured
  - Borehole fluid≠formation fluid
  - Two U-tubes (shallow and deep) should be located to collect samples biased towards gas and liquid
- Do not limit yourselves to “accepted” modalities and methodologies for M&V
- **Engineer** for simplicity and robustness- Future U-tube deployments will be simpler.
Lessons learned continued

• For pilot scale (scientific) testing all critical processes/parameters need to have a clearly designated technical lead
• Expect the unexpected
  — Early breakthrough
  — No breakthrough
  — All points in between