Model-based Monitoring Design for Determining Plume Stabilization: A Proposed Plan for the Citronelle Geometry

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Need for monitoring tools designed to validate closure models

• After closure flow physics dominated by buoyancy and capillary forces
  – Viscous forces no longer relevant because of decreased differential pressure and lead to decreased velocity

• Some jurisdictions require post-closure planning prior to permitting

• Projects may need to close early
What properties lead to most uncertainty during change of flow regime?

• During injection model improvement using monitoring data decreases uncertainty in characterization

• Need modeling now to identify after-injection end uncertainties:
  – Imbibition dominates over drainage
  – Significance of vertical anisotropy increased?
Citronelle MVA geometry

0.2 miles

AOR -300,000 injection over 3 years
Actual: 100,000 tons over 3 years
+50,000

2 degree Dip on dome flank
What to avoid:
Wrong imbibition curve: plume migrates too far

Tank model
WRI 2008 Potential for Rapid or Unexpected post-injection migration

- Combination of geophysical measurements and validated model predictions to satisfactorily demonstrate that the plume will stabilize and does not endanger human health and the environment.

- To rely on this approach, the models would need to be vetted by experts and would need to have been updated, calibrated, and validated through the operational life of a project as well as during the post-injection monitoring period.
EPA Class VI UIC program

• The owner or operator shall monitor the site following the cessation of injection to **show the position of the carbon dioxide plume** and pressure front and demonstrate that USDWs are not being endangered.

• Conduct monitoring as specified in the Director-approved post injection site care and site closure plan for at least 50 years or for the duration of the **alternative timeframe** approved by the Director.
Alternative Time Frame

• A demonstration of an alternative post-injection site care timeframe must include consideration and documentation of:
  • (i) The results of computational modeling....
  • (ii) The predicted timeframe for pressure decline within the injection such that formation fluids may not be forced into any USDWs; and/or the timeframe for pressure decline to pre-injection pressures;
  • (iii) The predicted rate of carbon dioxide plume migration within the injection zone, and the predicted timeframe for the cessation of migration;
  • (iv) A description of the site-specific processes that will result in carbon dioxide trapping including immobilization by capillary trapping, dissolution, and mineralization at the site;
  • (v) The predicted rate of carbon dioxide trapping in the immobile capillary phase, dissolved phase, and/or mineral phase....
A common conceptualization at end injection

4-D Seismic

Modeled plume
Projects observing after closure

- West Pearl Queen
- Nagaoka
- Frio Test
- Ketzin
- InSalah
- CO2-CARE closure case - Sleipner
Timeline

- 2004
  - RST
  - VSP 1 Cross well 1
  - PFT - NETL
  - VSP 2 Cross well 2
  - PFT - Seeper trace
  - CAASSM
- 2005
  - RST
  - RST
- 2006
  - RST
  - RST
  - Workover, squeeze, reperforate deeper
- 2007
  - RST
  - P&A inj well
  - P&A obs well
- 2008
  - P&A inj well
- 2009
  - P&A obs well

Legend:
- Red square: injection
- Green circle: fluid sampling (gas)
- Brown circle: fluid sampling (brine)
First test: Post injection CO$_2$ Saturation Observed with Cross-well Seismic Tomography vs. Modeled
Measurement at a Well:
Saturation logging (RST) Observation well to measure changes in CO₂ saturation – match to model

Shinichi Sakurai, Jeff Kane, Christine Doughty
Frio Time Lapse VSP: Reflection

Pre Injection
July 2004

Post Frio-I; Pre Frio-II
November 2004

Post Frio-I and Frio-II
May 2009

1600 tons
2004

300 tons
2006
January 2006, attempting to produce the CO$_2$ back – no success. CO$_2$ is underground but cannot be produced
Production Test – end of Frio 1

• Produced CO₂ from the “C” sand in the injection well at month 16 after the end of injection.
• Wellbore filled with gas-phase CO₂, with atmospheric pressure at wellhead. Brine at 100 m = approximate original pressure in zone, no flow of gas or brine.
• Swabbing the well to produce brine decreased pressure about 14 bars well produced brine and CO₂ under weak gas lift
• The ratio of water to gas was 13,600 to 1
• CO₂ was produced at an average of 0.17 tons/hour, but the rate did not decline during the one day production period.
• Post injection leakage risk small
End injection

- Green: Mobile CO₂
- Blue: Residually trapped CO₂
- Black: Water
Post injection fluid mobility

Injection well: Critical sample point

- Mobile CO\(_2\)
- Residually trapped CO\(_2\)
- Water

1X injection period
Post-injection fluid mobility

2X injection period

Mobile CO₂
Residually trapped CO₂
Water
CO2 CARE

• As uncertainties reduce, predictive capability improves, but focus must still be maintained on the less likely ‘end-member’ model scenarios to avoid the possibility of unexpected or divergent future outcomes

• At site abandonment, predictive models calibrated by monitoring data can reduce the uncertainty envelope sufficiently for unexpected or divergent outcomes to be ruled out
What to avoid:
Wrong imbibition curve: plume migrates too far
Model using change in gas saturation at injection well as monitoring point post injection

Hysteretic model

Non-hysteretic model

The plume size 10 years after end of injection

Mehdi Zeidouni
CO\textsubscript{2} – soluble conservative tracer 1 placed 6 months before project end.

Tracer 2 placed 1 month before project end.

Tracer 3 placed 1 week before project end.
CO$_2$-soluble conservative tracer return to injection well under gravity

Hysteretic

Non-hysteretic

Mehdi Zeidouni
Conclusions

- Need for monitoring tools designed to validate closure models
- Some jurisdictions require post-closure planning prior to permitting
- Projects may need to close early
- Value of injection well as closure monitoring point