State of the Art Monitoring Technologies

Susan Hovorka
Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of geosciences
The University of Texas at Austin

Stanford University Monitoring, Measurement, and Verification (MMV) workshop: Nov 20, 2024

GCCC GULF COAST CARBON CENTER

BUREAU OF ECONOMIC GEOLOGY

Main Points

- I see a gap between the promise of monitoring developed during past decades of research and its' application under Class VI
- My major issues:
  - No requirement/guidance in Class VI application to link monitoring to risk reduction
  - Over-reliance on geochemical methods and monitoring wells
  - Weak drivers on history matching, especially boundary conditions and AoR
- I express this with nuance and pragmatism:
  - Storage security is assured by:
    - Characterization
    - Operation and engineering
  - Monitoring is an extra added security layer.
  - Many operators have strong in-house risk management procedures that cover gaps

Discussion

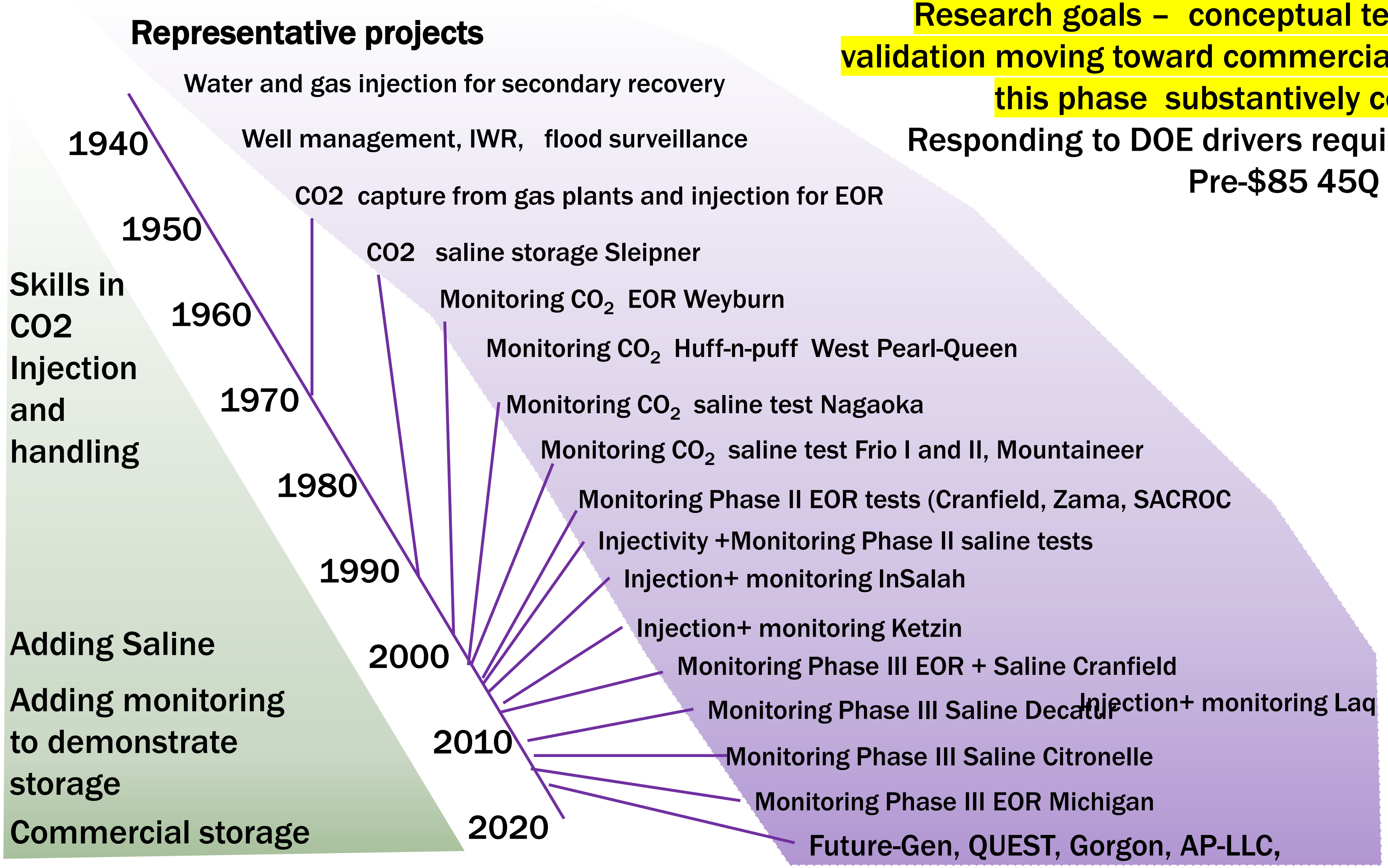
- Do you agree with me about a need to improve Class VI monitoring design?
- If so, what are the mechanisms that can be used to implement improvements?

Looking back at research monitoring

Research goals – conceptual testing and validation moving toward commercialization – this phase substantively completed

Responding to DOE drivers requiring MMV

Pre-$85 45Q tax credit



Big change in the State of the Art: Requirements of Class VI

- After $85 45Q tax credit: Compliance with class VI is the-one-the-only goal in a permit.
- Additional information not required for Class VI compliance is a significant liability.
- Class VI terminology and structure becomes the lead driver and sets expectations
- Text paraphrased from Class VI

Class VI terminology and structure becomes critical

- Two main permit activities involve monitoring skills
  - Testing and Monitoring Plan
    - Mature injectate and injection well engineering testing
    - Geochemical testing
    - Plume and pressure front
  - PISC and closure – link to model validation and set period to closure

Engineered components injectate and of injection well - mature

- (a) Analysis of the carbon dioxide stream with sufficient frequency to yield data representative of its chemical and physical characteristics;
- (b) Installation and use, except during well workovers of continuous recording devices to monitor injection pressure, rate, and volume; the pressure on the annulus between the tubing and the long string casing; and the annulus fluid volume added;
- (c) Corrosion monitoring of the well materials for loss of mass, thickness, cracking, pitting, and other signs of corrosion, which must be performed on a quarterly basis to ensure that the well components meet the minimum standards for material strength and performance set forth in by: (1) Analyzing coupons of the well construction materials placed in contact with the carbon dioxide stream; or (2) Routing the carbon dioxide stream through a loop constructed with the material used in the well and inspecting the materials in the loop; or (3) Using an alternative method approved by the Director;
- (e) A demonstration of external mechanical integrity at least once per year until the injection well is plugged; and, if required by the Director, a casing inspection log at a frequency established in the testing and monitoring plan

But…Monitoring wells

- Extensive use in research phase of CCS – set a precedent?
- Implied in "direct monitoring" but not explicitly covered in permit application
  - states permit them on ad hoc basis.
- Value? Durability?

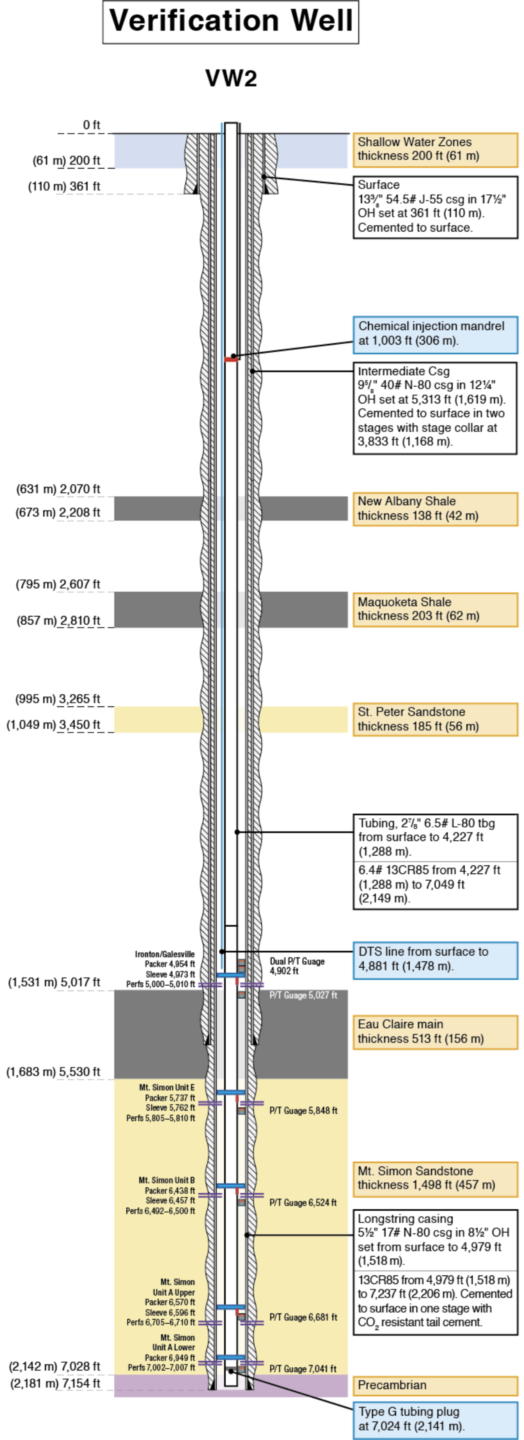
ADM Issue: Project history

- 2011 Pilot project drilled CCS Well #1 for the purpose of injection 1 MMT over 3 years. Installed deep verification well VW #1
- 2017 Industrial scale project to installed CCS well #2 to injection up to 1 million tons CO2 per year. Installed deep verification well VW #2

Source letter to EPA from Steven Murawski, August 22, 20024

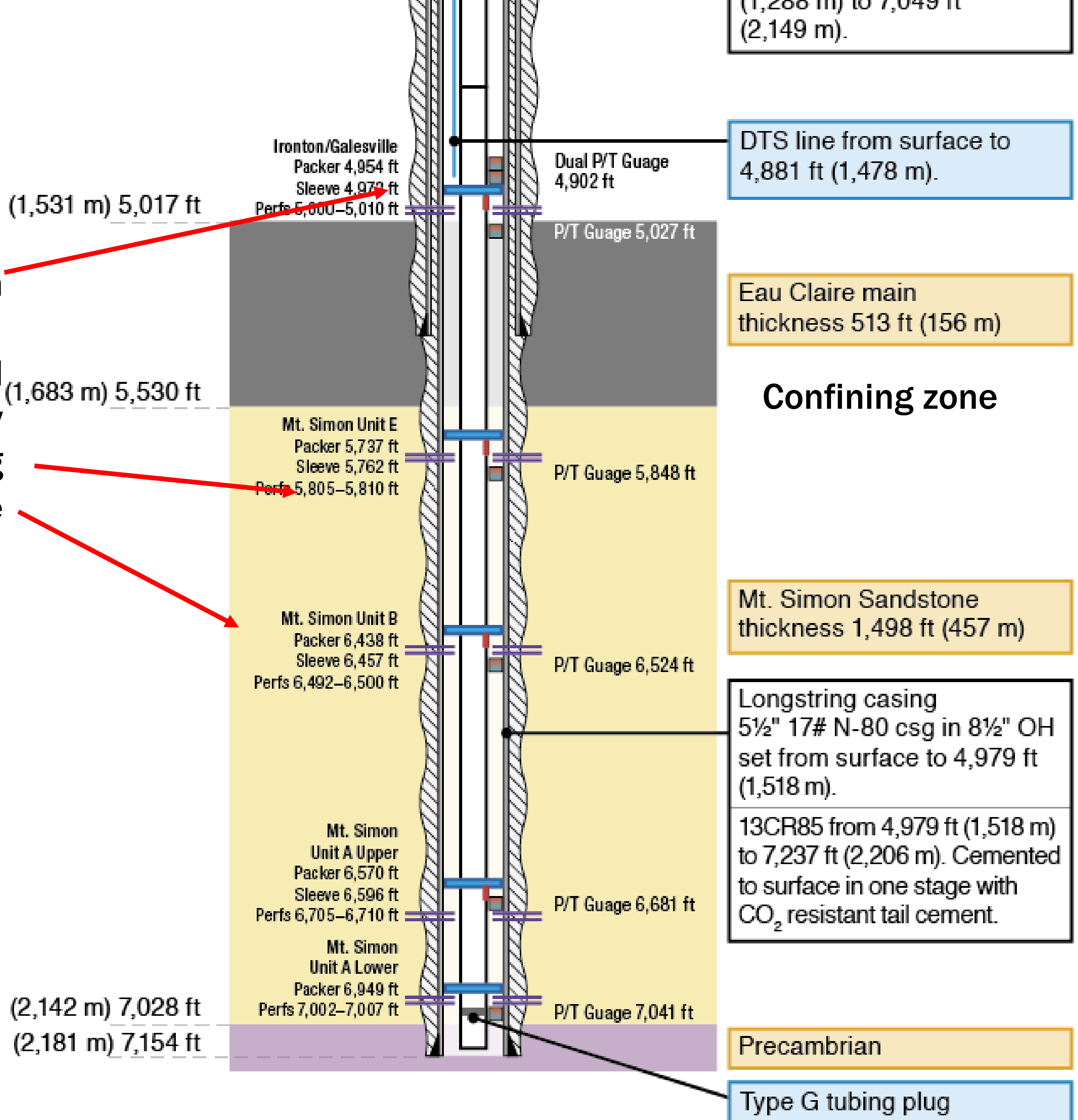
Complex design of monitoring well derived from R&D phase of IBD project under DOE funding

Source Steve Whittaker



Injection zone

Three perforations in casing –
IZ and AZMI
Separated by packers and sliding sleeve



Issues with monitoring well

- September 2020 a gauge in zone 5 depth 5,027 of VW#2 began to develop intermittent electrical malfunctions.
- January 2022, all VW#2's gauges were malfunctioning.
- October 2023, pulled VW#2's completion assembly.
  - Discovered corrosion (primarily pitting) on tubing below zone 5 packer which prevented recovery of the entire completion
- Set two bridge plugs in the casing, and stopped using VW#2
  - relying instead on the remaining monitoring network capabilities of CCS Well #1, CCS Well #2 and VW#1 for data collection

Source letter to EPA from Steven Murawski, August 22, 2024

Cross-formational flow/Out-of-zone migration

- March 2024, as part of ongoing testing and monitoring, discovered zone 2 formation fluid just above confining zone in VW#2 at 5000 ft.
- With third party assistance determined unexpected fluid is related to previous addressed corrosion condition
- At no time since the discovery of these developments has there been any impact to the surface or groundwater or any threat to public health

Source letter to EPA from Steven Murakowski, August 22, 2024

Reporting

- Since 2021 semi-annual and testing reports
- February 2024 met with EPA
- Proposal to restore VW#2 to operating condition solely for monitor ing Zone 5.
- June 2024 EPA's on-site inspection
- July 2024 revised proposal for next steps

Source letter to EPA from Steven Murawski, August 22, 20024

Available technical details

- The migration was up the VW#2 tubing at depth of 5000 ft
- Pulsed neutron testing showed an average CO_2 saturation of 21% 5004-5007 ft
- Same interval in 2024 shows 0% saturation
- March 2024 reservoir fluid sampling in VW#2
  - Initial samples showed characteristics of heavy brine used during recompletion operation
  - Subsequent sampling produced lighter brine with characteristics of zone 2 fluid and entrained CO_2

Source letter to EPA from Steven Murawski, August 22, 2024

Migration was stopped

- Dual bridge plugs isolated the Ironton-Galesville from lower zones. Tested by pressure, temperature and spinner surveys.
- Produced over 3,000 bbls of reservoir fluids with very little change in the fluid characteristics.

Source letter to EPA from Steven Murawski, August 22, 2024

Class VI Testing and Monitoring

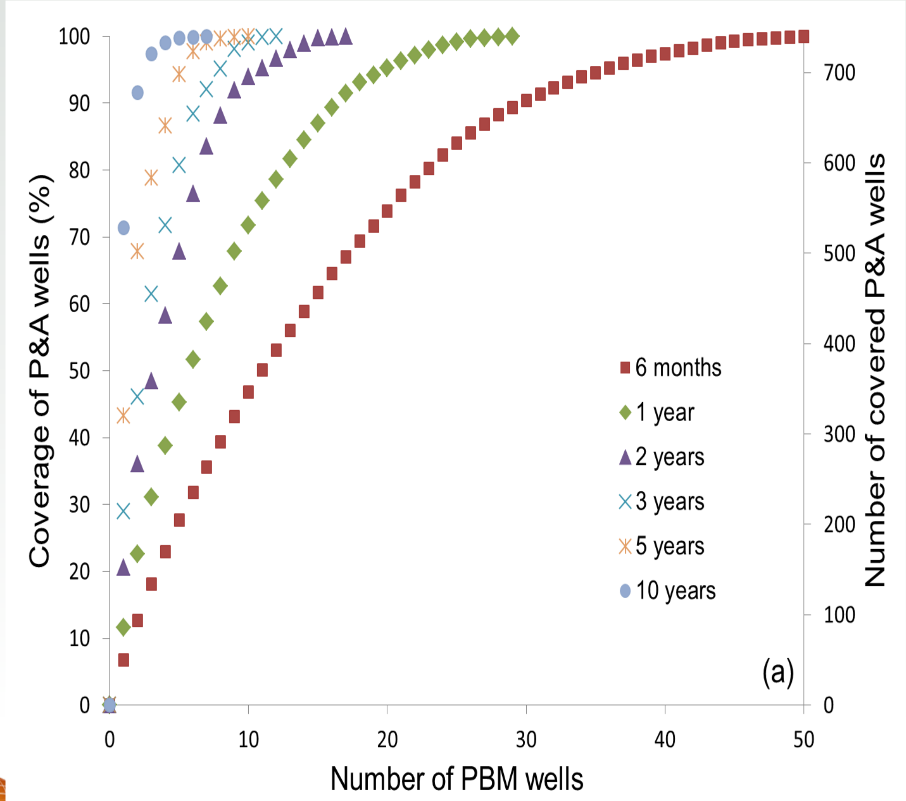
- Baseline geochemical data on subsurface formations, including all USDWs in the area of review]
- [Periodic monitoring of the ground water quality and geochemical changes above the confining zone(s) that may be a result of carbon dioxide movement through the confining zone(s) or additional identified zones

Struggles with chemistry

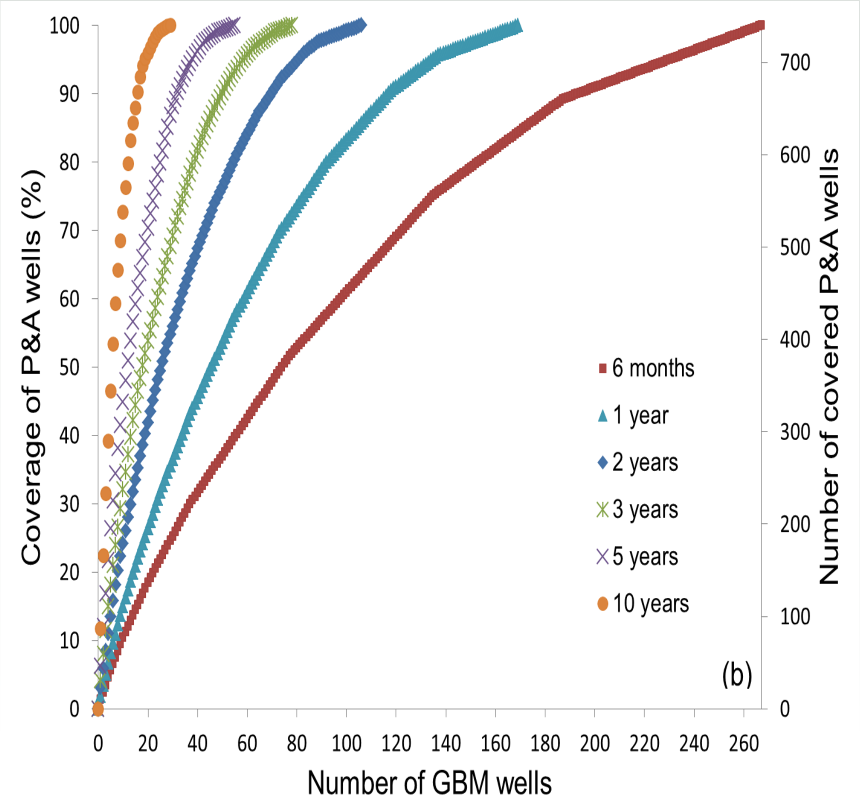
- Multi-phase flow problem
  - Impossible to accurately sample unfractionated in-situ brine and CO_2
  - Fractionation at perforations
  - Separation with in well bore
  - Re-equilibration during transport to surface and lab analysis
- Pressure and temperature variable dissolved phases also difficult to sample and analyze
- Is this the best approach?

Sensitivity analysis for above-zone leakage detection time in models

Detecting pressure signal



Detecting geochemical signal

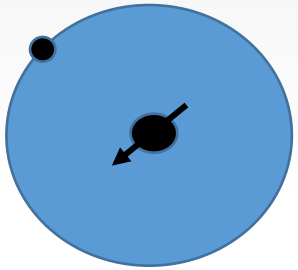


GCCC GULF COAST CARBON CENTER ECONOMIC GEOLOGY

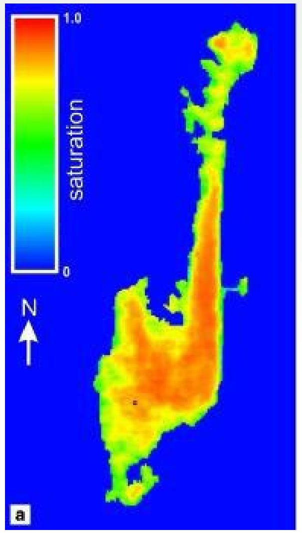
Behni Bollhassani, UT MS thesis

Plume tracking

- Testing and monitoring to track the extent of the carbon dioxide plume and the presence or absence of elevated pressure (e.g., the pressure front) by using:
  - Direct methods in the injection zone(s); and,
  - (2) Indirect methods (e.g., seismic, electrical, gravity, or electromagnetic surveys and/or down-hole carbon dioxide detection tools)
- Could required pressure fall-off test at injection well serve as direct monitoring per Bob VV?



Single monitoring well on predicted year 5 plume validates a model if high symmetry assumed

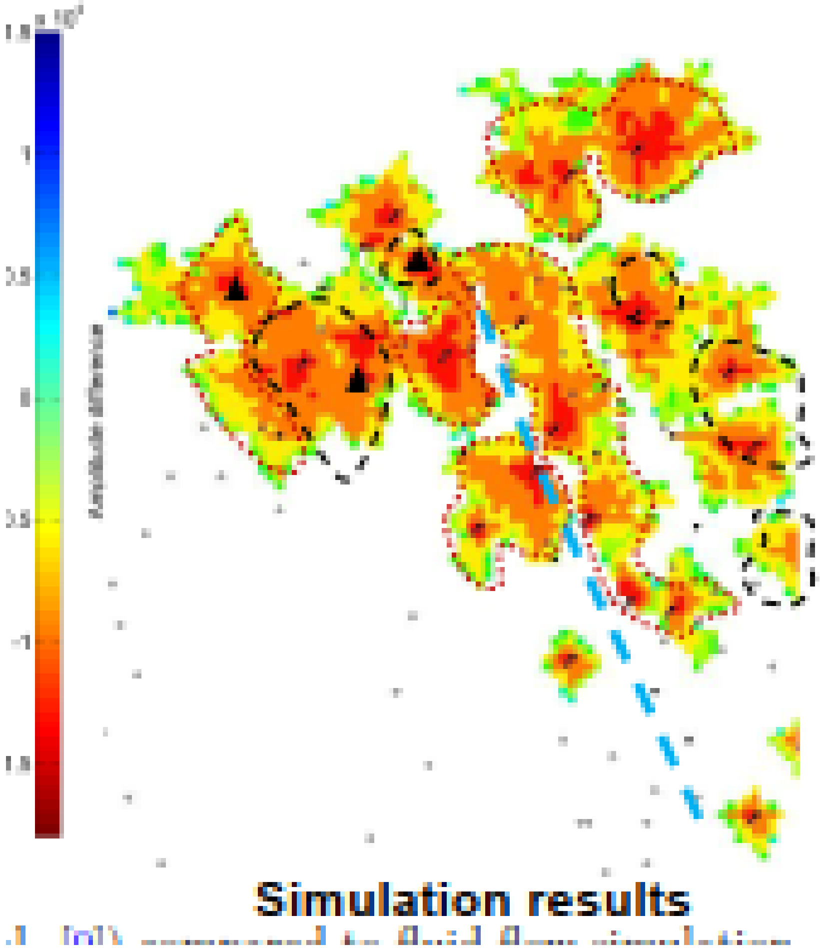


Unexpected asymmetry is expected in geologic settings

Williams and Chadwick 10.1190/GEO2011-0449.1

GCCC GULF COAST CARBON CENTER
BUREAU OF ECONOMIC GEOLOGY

CO_2 plume simulation history match with breakthrough



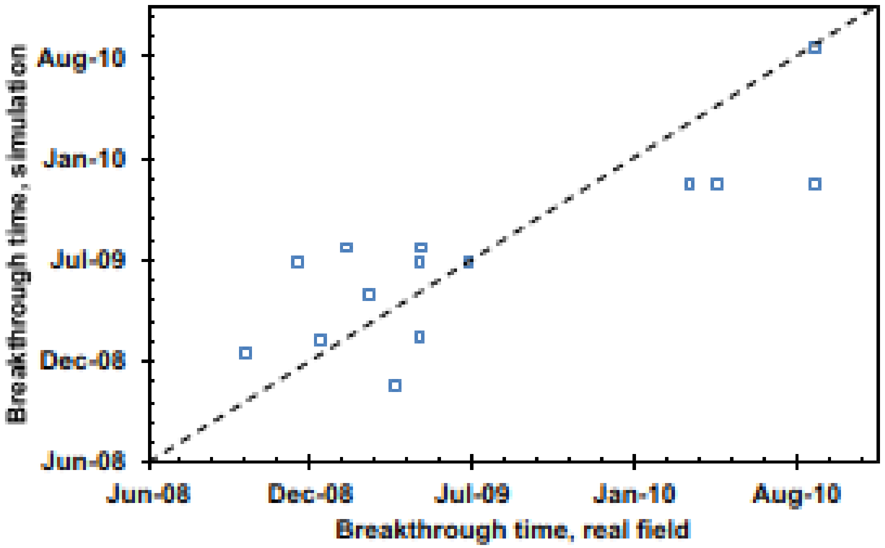


Figure 8: Comparison of actual and simulated CO_2 breakthrough times in production wells shows that current model performance is acceptable and has no bias toward underestimating or overestimating breakthrough times.

Title: Integration of reservoir simulation, history matching, and 4D seismic for CO2-EOR at Cranfield, Mississippi, USA

: Masoud Alfi; Seyyed Abolfazl Hosseini

Optional air and soil monitoring (not being used much?)

- The Director may require surface air monitoring and/or soil gas monitoring to detect movement of carbon dioxide that could endanger a USDW.
- Design of Class VI surface air and/ or soil gas monitoring must be based on potential risks to USDWs within the area of review;
- The monitoring frequency and spatial distribution of surface air monitoring and/or soil gas monitoring must be decided using baseline data, and the monitoring plan must describe how the proposed monitoring will yield useful information on the area of review delineation and/or compliance with standards

Requirements to review and update plan

- The owner or operator shall periodically review the testing and monitoring plan to incorporate monitoring data collected, operational data collected and the most recent area of review reevaluation
- At least every five years. Based on this review, the owner or operator shall submit an amended testing and monitoring plan or demonstrate to the Director that no amendment to the testing and monitoring plan is needed.

Updates provide an in-place mechanism to improve

Post-injection site care and site closure monitoring

- The pressure differential between pre-injection and predicted post-injection pressures in the injection zone(s)
- The predicted position of the carbon dioxide plume and associated pressure front at site closure
- Post-injection monitoring location, methods, and proposed frequency and duration (50 years default, alternative plan option)

Need for monitoring to validate predictions

GCCC GULF COAST CARBON CENTER · BUREAU OF ECONOMIC GEOLOGY

Non-specific requirement to improve

- Any additional monitoring, as required by the Director, necessary to support, upgrade, and improve computational modeling of the area of review evaluation and to determine compliance with standards (non-endangerment)
- Gives the Director broad powers to optimize monitoring

High level material impact catalog

Impact	Monitoring
Capacity more limited than expected - pressure exceeds rock/well completion strength/ geomechanical stability field	Surface + at least intermittent downhole pressure at injection well
CO_2 plume grows beyond AOR encounters transmissive fault, fracture system non-isolating well, or impinges on another subsurface use	Monitor extent of CO_2, confirm model
Elevated pressure area grows beyond AOR and encounters transmissive fault, fracture system non-isolating well, or impinges on another subsurface use	Monitor extent of elevated pressure, confirm model
A transmissive feature (well or fracture set) within the AOR was missed or mischaracterized as isolating	Monitor potentially transmissive features within planned area of CO_2 plume and pressure elevation; Above-zone monitoring;
Induced seismicity	Monitor to confirm correct geomechanical model

GCCC Scientific Method Monitoring Design (ALPMI)

Risk assessment method as usual

Quantify risks to define material impact

Specify magnitude, duration, location, rate of material impact

- Avoid subjective terms like safe and effective.
- E.g. : Specify mass of leakage at identified horizon or magnitude of seismicity.
- Specify certainty with which assurance is needed

Explicitly model unacceptable outcomes showing leakage cases.

Model material impact scenarios

ALPMI uses models differently than the typical history matching the expected performance

Identify signals in the earth system that indicate or preferably precede material impact

This method down selects to consider only signals that may indicate material impact is occurring or may occur.

Approaches like those normally seismic survey design should be deployed for all modeling tools

Select monitoring tools that can detect these signals at required sensitivity

Forward modeling tool response is essential to developing the expected negative finding: “No material impact was detected by a system that could detect this impact.”

This activity as traditionally conducted. Include all the expected components, such as attribution, updating as needed, feedback , etc..

Deploy tools and collected and analyze data

Only via this ALPMI process can a finding that the material impact did not occur be robustly documented

Report if material impact did/did not occur

Conclusions

- I see a gap between the promise of monitoring developed during past decades of research and its' application under Class VI
- My major issues:
  - No requirement/guidance in Class VI application to link monitoring to risk reduction
  - Over-reliance on geochemical methods and monitoring wells
  - Weak drivers on history matching, especially boundary conditions and AoR
- I express this with nuance and pragmatism:
  - Storage security is assured by:
    - Characterization
    - Operation and engineering
  - Monitoring is an extra added security layer.
  - Many operators have strong in-house risk management procedures that cover gaps

Discussion

- Do you agree with me about a need to improve Class VI monitoring design?
- If so, what are the mechanisms that can be used to implement improvements?