CCS – CO_2 Storage Management and Key Technical challenges Regulators Face – "Monitoring, Modeling, Sampling & Containment"

Dr. Scott Frailey and Dr. Susan Hovorka

December 7, 2021

SPE Webinars are Sponsored by:

SPE

SPE Foundation

CO_2 Storage Resources Management System: Classifying and Categorizing Storable Quantities

Scott M. Frailey, PhD, PE
Illinois State Geological Survey
University of Illinois @ Urbana-Champaign
December 7, 2021

Storage Resources Management System (SRMS) Outline

- Purpose and Intended Users
- Development Process
- SRMS Structure:
  - Classification
  - Categorization
- Example Applications
- Expected Outcomes

4

SRMS: Intended Users and Purpose

Webinars

- Commercial CO_2 storage projects involve financial, corporate, government organizations
  - SRMS provides common terminology and clear definitions needed to classify storable quantities in the context of **active** project specifications
  - SRMS provides context for investment and tracking the performance of the investment
- Applicable to regional or basin resource assessments via a **notional** project specifications
- Define storable quantities
  - Quantities of CO_2 that can be stored as part of an estimated pore volume of a geologic formation that is accessible to CO_2 via a storage project sometime in the future
  - Requires containment
- SRMS Classifies and Categorizes storable quantities.
  - Classification: project maturation certainty
  - Categorization: storable quantities (i.e. geologic and reservoir) certainty

SPE International

5

SRMS: Development Process

Webinars

- Seed Document
  - Petroleum Resources Management System (PRMS)
  - Time tested and applied system
  - Supported by financiers, security exchanges, and governments (world)
- Committee selection
  - PRMS and storage experts
- SRMS Published by SPE Fall 2017
- SRMS-Guidelines December 2021
- Sponsoring Societies (2021)
  - SPE, SPEE, AAPG, SEG, SPWLA, WPC

SPE International

6

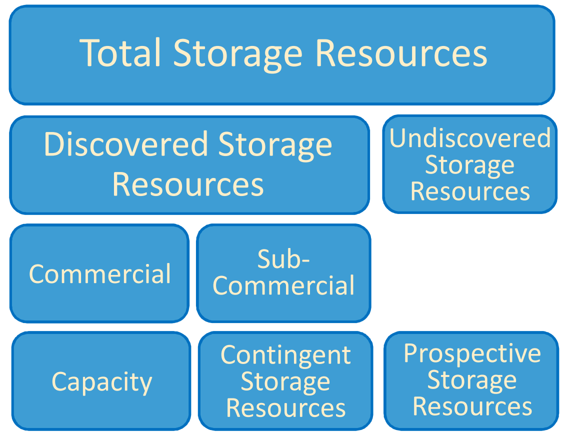
SRMS Structure: Classification of Storable Quantities

Webinars

Based on Project Maturation

- **Discovered** vs. **Undiscovered**
  - storable quantities for which one or more wells established through testing, sampling, and/or logging the existence of a quantities sufficient to meet project requirements.
- **Commercial** vs. **Sub-commercial**
  - essential social, environmental, and economic conditions are met, including political, legal, regulatory, and contractual conditions.
  - degree of commitment is such that storage project is expected to be developed and placed on injection within a reasonable timeframe.

Specific to an Active or Notional Project



**Not shown, Inaccessible SR, which has no project.*
Total SR includes Inaccessible SR: Discovered and Undiscovered ISR

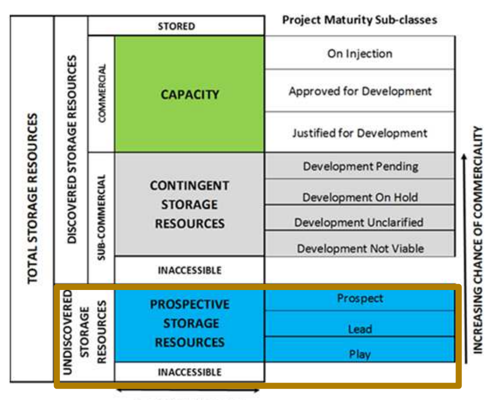
Classification: **Prospective** Storage Resources (*Undiscovered* Storage Resources)

Webinars

Well does not exist or not assessed

Increasing Chance of Commerciality

- Play: A project associated with a prospective trend of potential prospects, but that requires more data acquisition and/or evaluation to define specific leads or prospects.
- Lead: A project associated with undiscovered storable quantities that is currently poorly defined and requires more data acquisition and/or evaluation to be classified as a prospect.
- Prospect: A project associated w/ undiscovered storable quantities sufficiently defined to represent a viable drilling target
- "Ends" with a drilling prospect or existing well identified to assess



8

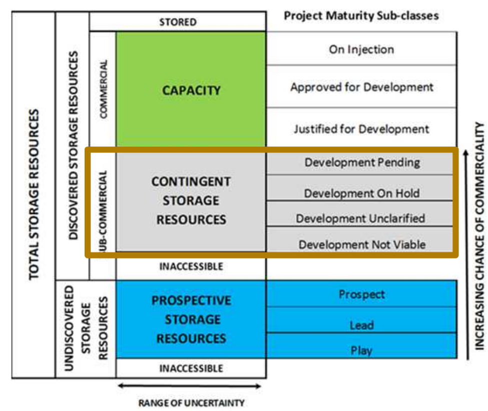
Classification: **Contingent** Storage Resources (*Discovered, Sub-Commercial* Storage Resources)

Webinars

Increasing Chance of Commerciality

Well exists and assessed

- Development Not Viable: Discovered storable quantities for which there are no current plans to develop or to acquire additional data at the time as a result of limited storage potential.
- Development Unclarified: Discovered storable quantities where **project** activities are under evaluation and where justification as a commercial development is unknown on the basis of available information.
- Development On Hold: Discovered storable quantities where **project** activities are on hold and/or where justification as a commercial development may be subject to significant delay
- Development Pending: Discovered storable quantities where project activities are ongoing to justify commercial development in the foreseeable future.
- "Ends" with commercial proposal to management



SPE International

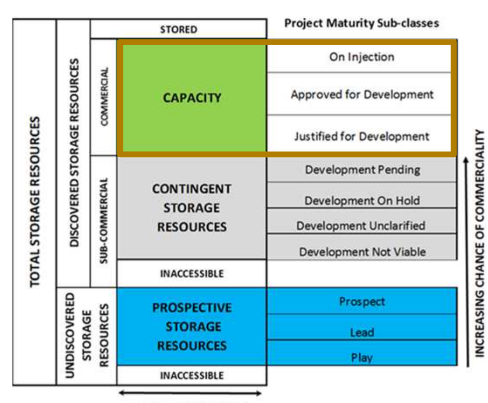
9

Classification: **Capacity** (*Discovered, Commercial* Storage Resources)

Webinars

Increasing Chance of Commerciality

- Justified for Development: Implementation of the development project is justified on the basis of reasonable forecast commercial conditions at the time of reporting, and there are ***reasonable expectations*** that all necessary approvals/contracts will be obtained.
- Approved for Development: ***All*** necessary approvals have been ***obtained***, capital funds have been committed, and implementation of the development project is underway.
- On Injection: The development project is currently injecting and storing CO_2.



SPE International

10

SRMS Structure: Categorization of Storable Quantities

Webinars

- Categorizations
  - **Low** estimate
    - High probability
    - P_{90}
  - **Best** estimate
    - Most-likely (median)
    - P_{50}
  - **High** (low probability) estimate
    - Low probability
    - P_{10}

- Categorization:
  - Indicative of certainty in storable quantities
  - Based on defined project, but **NOT** the project's maturity

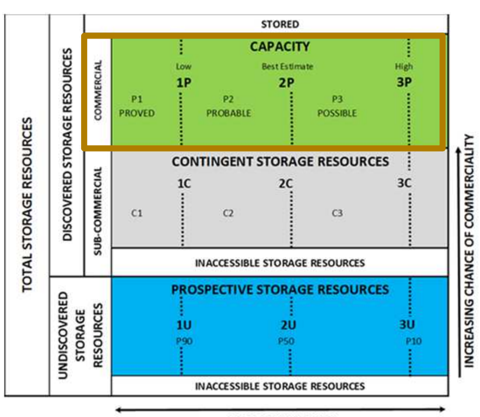
Category	Probability	Capacity	Contingent	Prospective
Low Estimate	P_{90}	1P	1C	1U
Best Estimate	P_{50}	2P	2C	2U
High Estimate	P_{10}	3P	3C	3U

SPE International

11

Categorization: Certainty in Storable Quantities

Webinars



- Proved (P1): **Proved Capacity** (P_{90}) is the quantity of storage that, by analysis of geoscience and engineering data, can be estimated with reasonable certainty to be commercially used for storage, from a given date forward, from known geologic formations and under defined economic conditions, operating methods, and government regulations.
- Probable (P2): **Probable Capacity** (P_{50}) is the additional Capacity that analysis of geoscience and engineering data indicate are less likely to be used for storage than Proved Capacity, but more certain to be used for storage than Possible Capacity
- Possible (P3): **Possible Capacity** (P_{10}) is the additional Capacity that analysis of geoscience and engineering data suggest are less likely to be stored than Probable Capacity.

SPE International

Ex: P1 + P2 + P3 = 3P

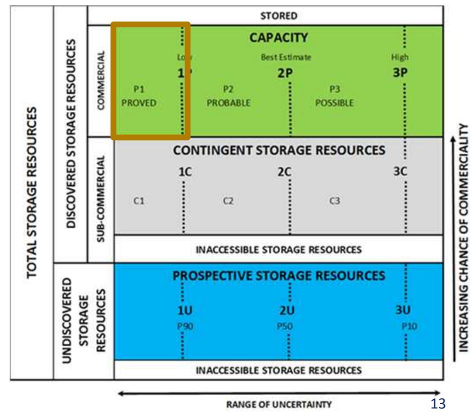
12

Proved Capacity's Status
Classification and Categorization Combined

Webinars

- Proved, Developed, Injecting: Developed Injecting Capacity is expected to be stored from completion intervals that are open and injecting at the time of the estimate.
- Proved, Developed, Non-injecting: Developed Non-injecting Capacity includes shut-in and behind-pipe Capacity.
- Proved, Undeveloped: Undeveloped Capacity is the quantity expected to be stored through future investments.

Proved Capacity's Status
Classification and Categorization Combined



SPE International

13

Webinars

EXAMPLE SRMS APPLICATIONS

SPE International

14

Assumptions Common to the Examples

Webinars

- Thick, pervasive, basal sandstone (single geologic formation)
- Containment:
  - Wellbore: Few wellbore penetrations (No known minerals)
  - Geologic: Extensive, thick clay-rich shale caprock
- Depth
  - Maximum: cementation lower porosity and permeability
  - Minimum: liquid-like CO_2 density; fresh water
- Project maturation example: from regional study to active injection

SPE International

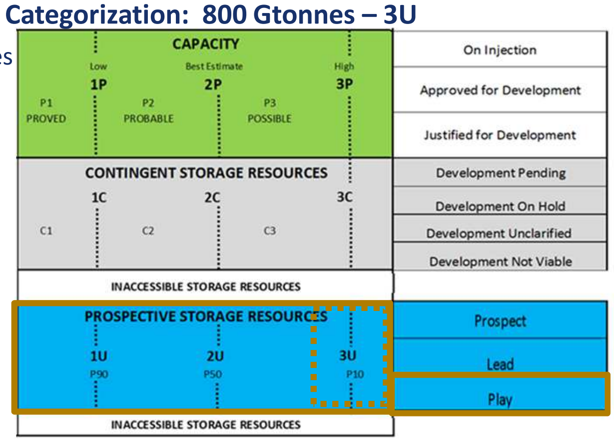
15

Regional Assessment: Notional Project

Webinars

- Purpose: storage potential
- Notional project:
  - Total regional emissions from stationary sources
  - Fully developed infrastructure
- Volumetric approach
  - Pore volume with storage efficiency
  - Single value (deterministic)
- Boundaries:
  - Perimeter: State lines
- Outcome:
  - General geographical area for a site
  - Estimate: 800 Gtonnes (high estimate)

Classification: Prospective Storage Resources–Play
Categorization: 800 Gtonnes – 3U



SPE International

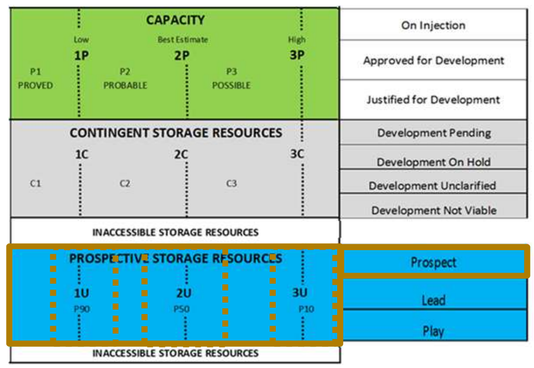
16

Regional Assessment: Notional Project Use of New Data and New Analysis

Webinars

- Objective: storage potential, site screening
- Volumetric, GIS approach
  - Efficiency: displacement, and geologic attributes
  - High, medium, low values (E= 1, 2, 4%)
- Boundaries:
  - Perimeter: State Lines
- Outcome:
  - General Geographical area for a site
  - Storing on regional dip
  - Estimate: 25, 50, 100 Gtonnes

Classification: Prospective Storage Resources – Prospect
Categorization: 25 Gt – 1U; 50 Gt – 2U; 100 Gt – 3U



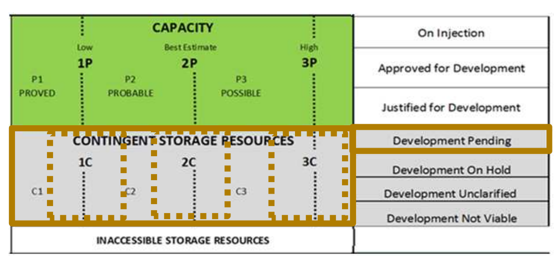
SPE International

17

Site Selected, Well Drilled, Well Assessed, Awaiting Management Commitment

Webinars

- Purpose: assess storage site for single well injection and site's CO_2 emissions
- Storage Project Status (at time of assessment)
  - Site CO_2 emissions: 3,000 tpd
  - Capture facility (planned): 1,000 tpd,
  - Management commitment NOT finalized 25 yr life
- Simulation: 8,000 tpd, well's max injection rate
- Boundaries: Storage rights and real estate ownership

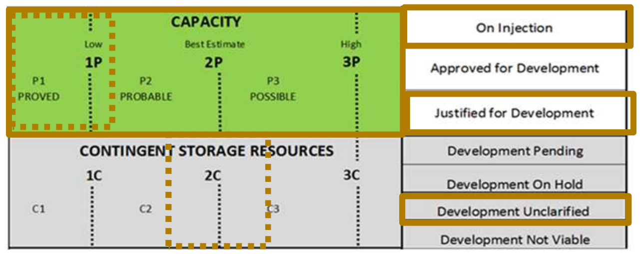


Project	Class	Subclass	Comment	Stor Quanty	Category	Comment
Facility	Contingent SR	Development Pending	No Management commitment	9 Mt (1,000 tpd)	1C	Small facility
Site	Contingent SR	Development Pending	No Management commitment	30 Mt (3,000 tpd)	2C	Total site emissions
Well	Contingent SR	Development Pending	No management commitment	70 Mt (8,000 tpd)	3C	High estimate based on well

18

Active Injection: Defined, Management Approved Project

- Purpose: Assess active project(s)
- Final Project
  - Infrastructure purchased: 1,000 tpd
  - Management commitment: 12 years
  - Permits and contracts issued/completed
- Planned Project Expansion
  - Management commitment: 1,000 tpd (incremental)
  - Reasonable expectation of permit



Project	Class	Subclass	Comment	Stor Quanty	Category	Comment
Final	Capacity	On Injection	Management commitment	4 Mt	Proved Developed Injecting, 1P	Active injection, equip. available
Planned	Capacity	Justified for Development	Management commitment; Permit expected	8 Mt	Proved Undeveloped, 1P	Permit required
Site	Contingent SR	Development Unclarified	No management commitment	58 Mt	2C	Best estimate

Summary of SRMS Applications Examples

- Classification: certainty in project
- Categorization: certainty in storable quantities
- SRMS intended use is in the context of storage projects
  - Active project specifications directly influences storable quantities
  - Notional project specifications acceptable for large scale resource assessments
- Storable quantities requires containment
- Prospective Storage Resources
  - no well available for assessment
- Contingent Storage Resources
  - well assessed and expected to meet project goals
- Capacity
  - solely for commercial/ economic projects
  - Reasonable expectation (minimum) that all permits/contracts obtained
  - Essential social and environmental project conditions met
- Classification and Categorization of storable quantities are subjective

20

SRMS Usage: Expected Outcomes

Webinars

- Provides guidelines for developing commercial storage projects
- Gives standardized terminology and definitions in commercial contracts similar to other subsurface commodity industries
- Assessors and stakeholders have a methodology to follow to make comparisons between projects
- System that relates project certainty and geologic certainty to storable quantities estimate

SPE International

21

Acknowledgements

Webinars

- Society of Petroleum Engineers' members are leading and organizing the SRMS guidelines development with support of SPE staff. SPE is the largest individual-member organization serving managers, engineers, scientists and other professionals worldwide in the upstream segment of the oil and gas industry.
- The Oil and Gas Climate Initiative supports the SRMS development. Their mission is to accelerate actions that mitigate greenhouse gas emissions from the industry's operations, while still meeting the world's energy needs.
- CarbonSAFE Macon County project (US DOE DE-FE0029381) is funded by the US Department of Energy (USDOE) through the National Energy Technology Laboratory (NETL)).

SPE International

22

References

- "The CO_2 storage resources management system (SRMS): toward a common approach to classifying, categorizing, and quantifying storage resources", Scott M. Frailey, George J. Koperna, Owain Tucker, 14th International Conference on Greenhouse Gas Control Technologies (GHGT-14), October 21-15, 2018, Australia
- "The genesis of the CO_2 storage resource management system (SRMS)", Scott M. Frailey, Owain Tucker, George J. Koperna, 2016, 13th International Conference on Greenhouse Gas Technologies (GHGT-13) Proceedings. Energy Procedia 114: 4262-4269.
- https://www.spe.org/en/industry/co2-storage-resources-management-system/

23

Monitoring, Testing, Modeling, and Accounting - New Skills in Containment Assurance for Storage Projects

Susan D. Hovorka, Gulf Coast Carbon Center, Bureau of Economic Geology, Jackson School of Geoscience, The University of Texas at Austin

Major points

Webinars

- New opportunities: value from storing CO_2
- Built on mature geotechnical skills
- New need: assuring and documenting that the project is obtaining the storage value
- Direct accounting of CO_2 stored in pore space limited
  - Instead use project conformance with expectations
  - and risk assessment plus monitoring of risks.
- We propose a framework and provide some examples for optimizing these approaches to efficiently establish robust reports confirming that containment is being achieved and will continue into the future.

SPE International

GCCC CCS – CCUS Experience Base

Webinars

- Frio I and II saline tests 2004-2009
- SWP monitoring of long running SACROC CO_2 EOR
- SECARB monitoring Cranfield saline and CO_2 EOR
- Monitoring design for Air Products CO_2 to Hastings Field for EOR
- Monitoring design for NRG-Petra-Nova CO_2 to West Ranch Field for EOR
- Reviewing for numerous projects
- ISO standards Working Group 6, IEAGHG network etc.
- Multiple new commercial projects

SPE International

Why monitor a CO_2 storage project?

Webinars

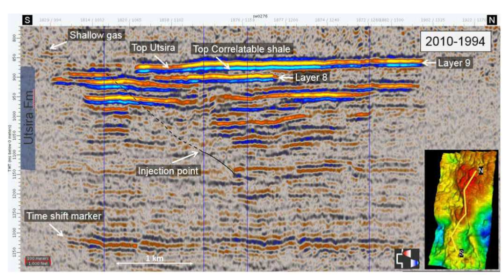
- Required by UIC regulation
- Required to get credit from 45Q or CA LCFS
- Otherwise required by funding
- Gain public acceptance
- Manage risk of unacceptable outcomes

SPE International

Limits of direct accounting

Webinars

- Measure amount of CO_2 injected ± 2% via high quality flow meter
  - Mixed fluids less precise – e.g. in EOR hydrocarbon+ CO2
- In reservoir, infer and estimate the saturation and distribution of CO_2 using combined methods
  - Limited quantification



Sliepner time lapse seismic image (Ringrose 2020)

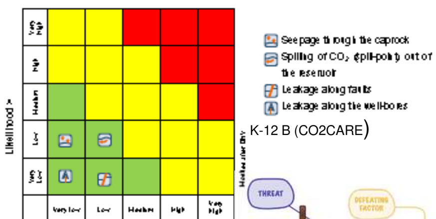
SPE International

Linking leakage risk assessment with monitoring

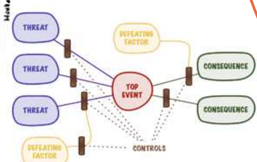
Webinars

UIC program:
Specified risk is endangerment of USDW
Support of GHG accounting rules under CAA

Risk Assessment methods



K-12 B (CO2CARE)



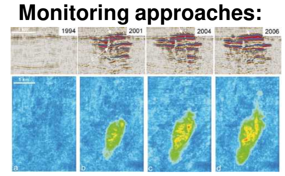
Bow tie method, Shell Quest

Experts
Engineers
Regulators

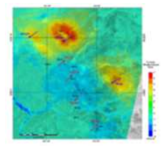
Process of designing and selecting monitoring can be complex, conducted without documented process, non-linear and therefore difficult to duplicate or justify –
how much is enough?

Select monitoring systems

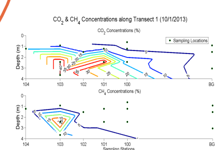
Monitoring approaches:



Plume tracking -- Chadwick BGS



InSAR at In Salah
Onuma and Ohkawa, 2009



Soil gas concentrations with depth, Romanak 2009

SPE International

Scientific Method Approach to Designing Monitoring to Document Containment

Webinars

- Part 1: Describing *material impact** quantitatively
- Part 2: Sensitivity of monitoring strategy detect material impact
- Example case
- Implications of matching monitoring to risks: site specific parameters
  - CO_2 EOR not same risk profile as saline

SPE International

* Defined next slides

Part 1: Quantify possible unacceptable outcomes "Material Impacts"

Webinars

- "Material impact" specifies what is considered "failure" or "unacceptable" to key stakeholders: define engagement.
- Replace generalities such as "safe" "effective"
- Specify magnitude, frequency or duration of material impact
- Define quantitatively how good the measurement needs to be.

SPE International

Material impact examples

(*random examples – targets need to be set for each project*)

Webinars

- Loss of CO_2 to USDW at a rate greater than 10,000 tones per year for a period of more than 10 years @ 80% confidence
- >5% probability of earthquake > magnitude 4 within 100 years
- Pressure trend that will exceed calculation mechanical stability prior to project completion @ 50% confidence
- Plume migration such that location of saturation of >5% pore volume CO_2 at stabilization is not within a footprint at 90% confidence

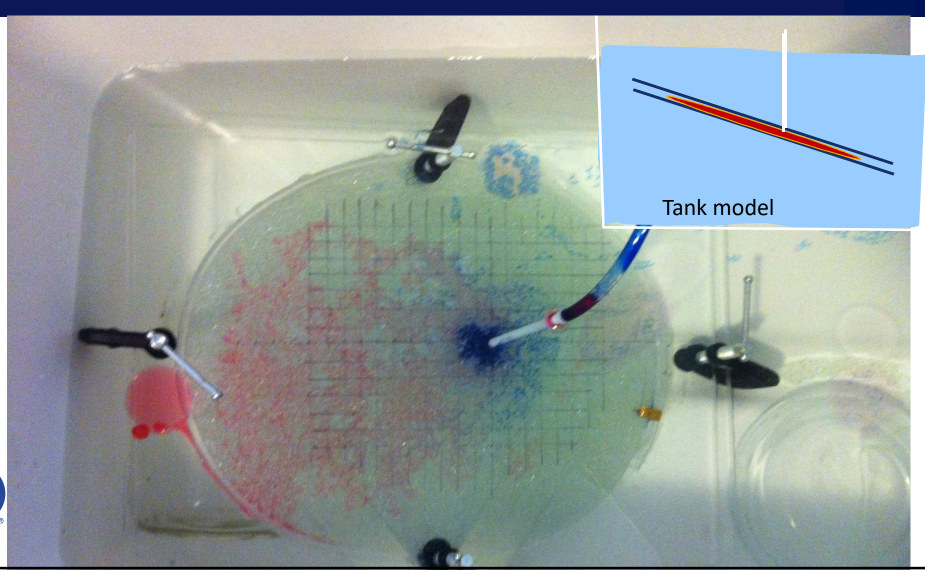
SPE International

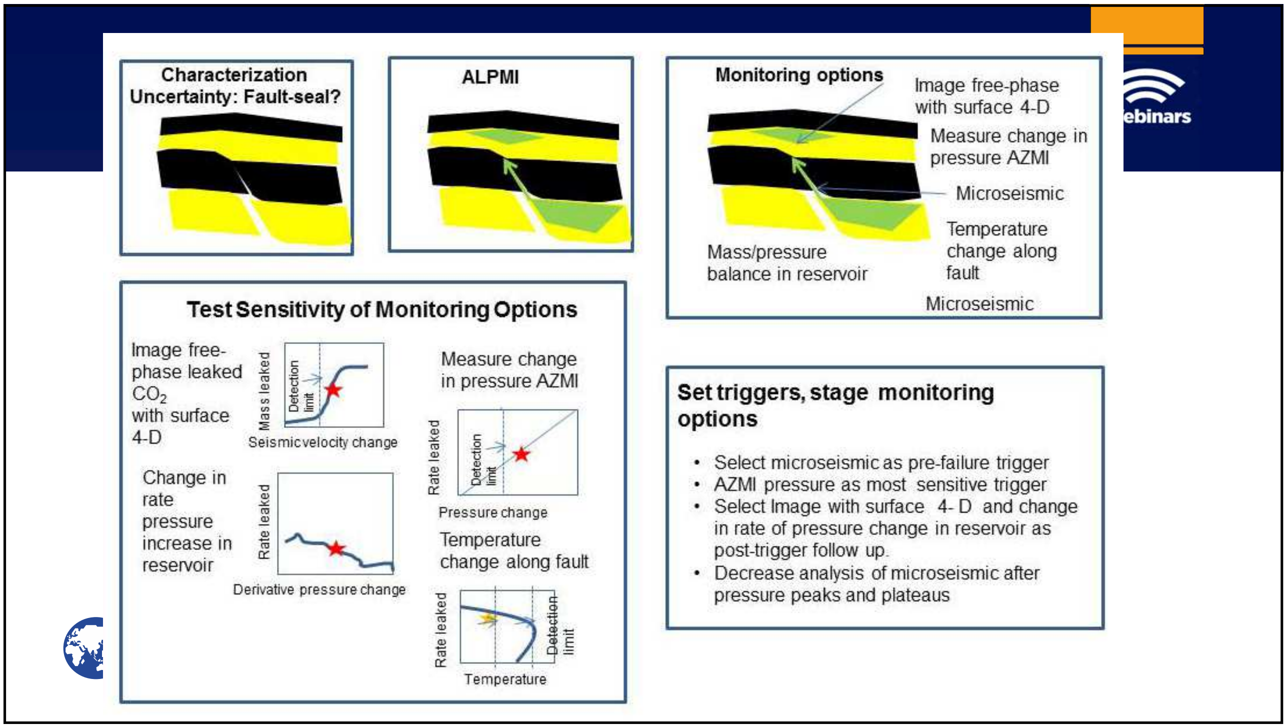
Part 2: Assess sensitivity of monitoring strategy to quantitatively designed material impact

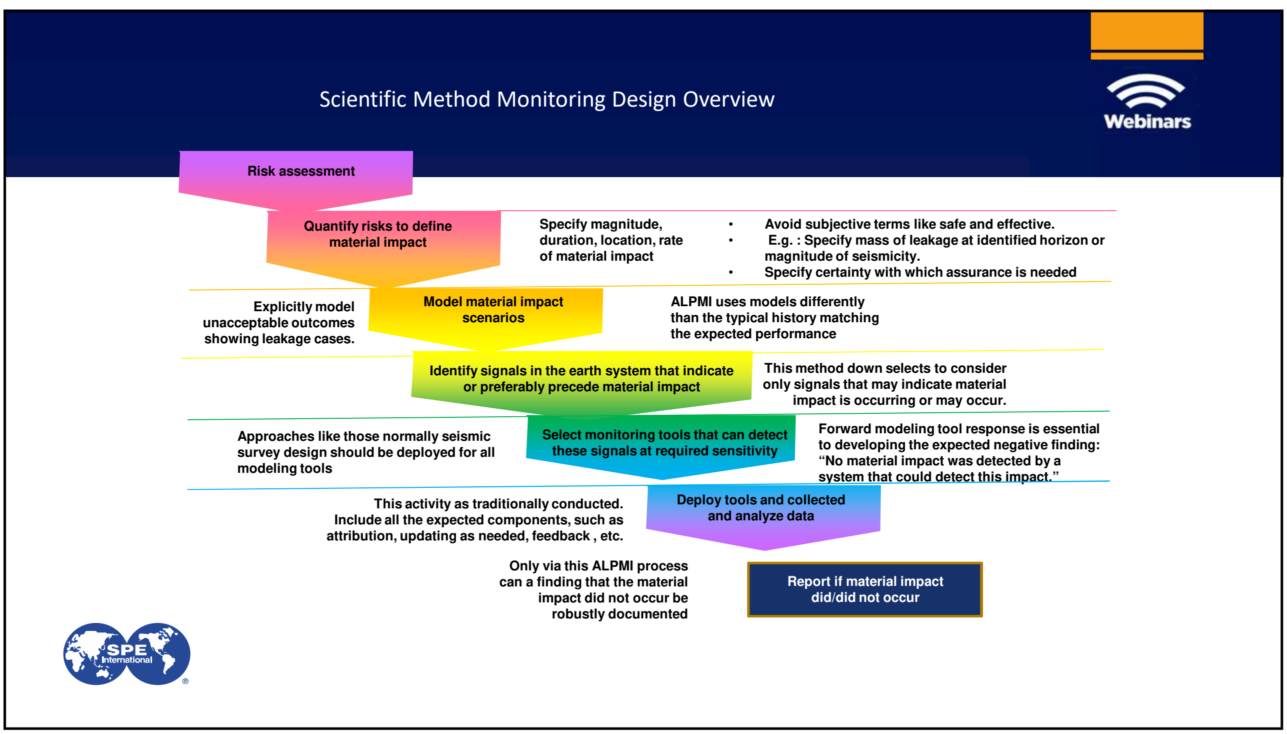
- Forward model impact
  1. Create material impact scenarios

     e.g. make conditions for CO_2 leakage or change in pore pressure that would increase seismic risk
  2. Evaluate sensitivity of instruments, spacing, frequency of data collection, other statistical measures against scenarios.

Modeling material impact: Long term plume stabilization Wrong imbibition curve: plume migrates too far




Characterization Uncertainty: Fault-seal?
ALPMI
Monitoring options
Image free-phase with surface 4-D
Measure change in pressure AZMI
Microseismic
Temperature change along fault
Mass/pressure balance in reservoir
Microseismic
Test Sensitivity of Monitoring Options
Image free-phase leaked CO_2 with surface 4-D
Mass leaked
Detection limit
Seismic velocity change
Measure change in pressure AZMI
Rate leaked
Detection limit
Pressure change
Change in rate pressure increase in reservoir
Rate leaked
Derivative pressure change
Temperature change along fault
Rate leaked
Detection limit
Temperature
Set triggers, stage monitoring options
• Select microseismic as pre-failure trigger
• AZMI pressure as most sensitive trigger
• Select Image with surface 4-D and change in rate of pressure change in reservoir as post-trigger follow up.
• Decrease analysis of microseismic after pressure peaks and plateaus
ebinars


Scientific Method Monitoring Design Overview
Webinars
Risk assessment
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
SPE International

Class VI requires periodic update model via monitoring: key to assuring Plume Stabilization

Webinars

Predicted plume footprint year 5 of >5% CO_2 saturation in zone

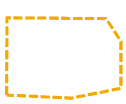
Measured plume footprint year 5 of >5% CO_2 saturation in zone

Match to model OK or not OK?

SPE International

Example assuring Plume Stabilization

Webinars

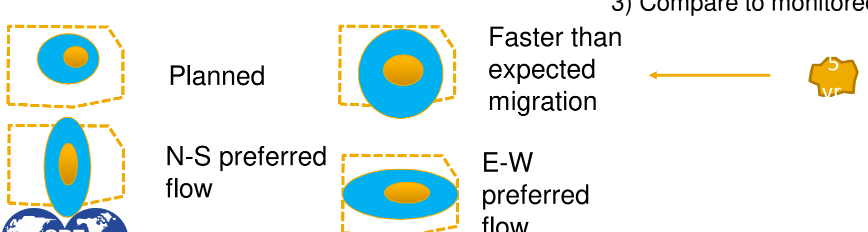


1) AOR defined boundary between acceptable and unacceptable extent of >5% saturation plume at stabilization 20 post end injection

2) Modeled plume evolution -- acceptable and unacceptable

5 year plume   Stabilized plume

3) Compare to monitored to modeled plume at 5 years



Match to model shows not OK plume is growing too big too fast

SPE International

[Key scientific method step – use model to explore what failure looks like]

Update to role of near-surface monitoring

- Direct surveillance of soil, fresh water, air
  - Protected resources
  - Low cost installations
- Layout to provide coverage
  - water wells, grids, towers, airborne, satellite
- Required in permits and accreditation

Problems and limits on near surface monitoring

- High noise esp. in CO_2-related activities
  - Daily, seasonal, lateral variability
  - Leakage detection threshold set too high to avoid false positive, may miss leakage
  - Trend, e.g. climate change, ecosystem evolution
- Poor lateral coverage
  - Examples from controlled releases
  - Yang et al, 2015, poor detection coverage in groundwater
- Cost not so low
  - Need to automate – still not ready
  - High expense to attribute

~~Current~~ Last years Thinking on "Natural Variability"

Webinars

- Measure "baseline" CO_2 for 1 years before project starts to document seasonal variability.
- Monitor CO_2 during project and compare to baseline.
- Significant increase from baseline during a project could signal a leak

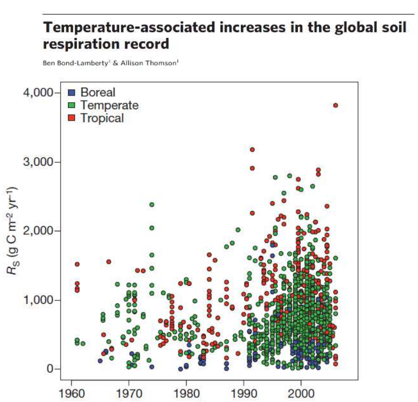
SPE International

Katherine Romanak

41

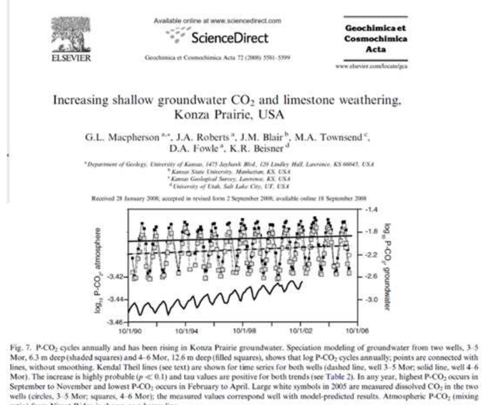
"Baselines" are Shifting!

Webinars



nature Vol 464 | 25 March 2010 | **doi:10.1038/nature08930**

RS = the flux of microbially and plant-respired CO_2 from the soil surface to the atmosphere,



ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 72 (2008) 5581–5599

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Increasing shallow groundwater CO_2 and limestone weathering, Konza Prairie, USA

G.L. Macpherson[a,*], J.A. Roberts[a], J.M. Blair[b], M.A. Townsend[c], D.A. Fowle[a], K.R. Beisner[d]

[a] Department of Geology, University of Kansas, 1475 Jayhawk Blvd., 120 Lindley Hall, Lawrence, KS 66045, USA
[b] Kansas State University, Manhattan, KS, USA
[c] Kansas Geological Survey, Lawrence, KS, USA
[d] University of Utah, Salt Lake City, UT, USA

Received 28 January 2008; accepted in revised form 2 September 2008; available online 18 September 2008

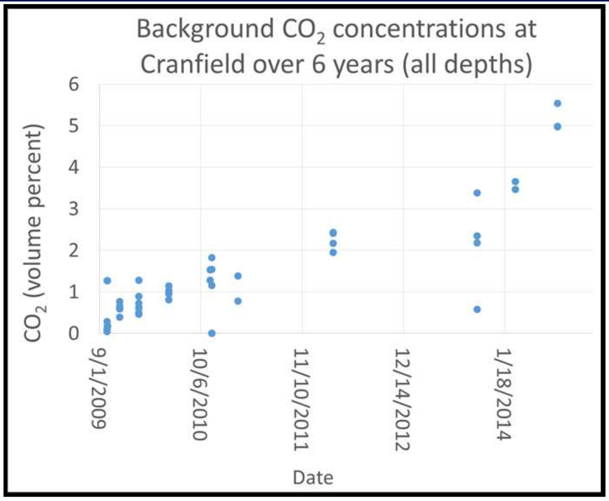
Fig. 7. P-CO_2 cycles annually and has been rising in Konza Prairie groundwater. Speciation modeling of groundwater from two wells, 3–5 Mor, 6.3 m deep (shaded squares) and 4–6 Mor, 12.6 m deep (filled squares), shows that log P-CO_2 cycles annually; points are connected with lines, without smoothing. Kendal Theil lines (see text) are shown for time series for both wells (dashed line, well 3–5 Mor; solid line, well 4–6 Mor). The increase is highly probable ($p < 0.1$) and tau values are positive for both trends (see Table 2). In any year, highest P-CO_2 occurs in September to November and lowest P-CO_2 occurs in February to April. Large white symbols in 2005 are measured dissolved CO_2 in the two wells (circles, 3–5 Mor; squares, 4–6 Mor); the measured values correspond well with model-predicted results. Atmospheric P-CO_2 (mixing ratio) from Niwot Ridge is shown as a heavy line.

Increased dissolution of CO_2 in groundwater and associated mineral dissolution

SPE International

…and at our Monitoring Sites

Webinars



Changbing Yang and Katherine Romanak

Attribution focus to near-surface monitoring

Webinars

- Incident – a release may have occurred
  - Determine if any damages
  - Quantify release
- Allegation - concern, need to determine if there was/was not an incident
- Once a signal detected, requires follow up to determine if change is from injection or not

Dixon and Romanak 2015

Weyburn allegation

Anderson et all, 2017 (attribution of a non-leak)

Groundwater System Complexities

Webinars

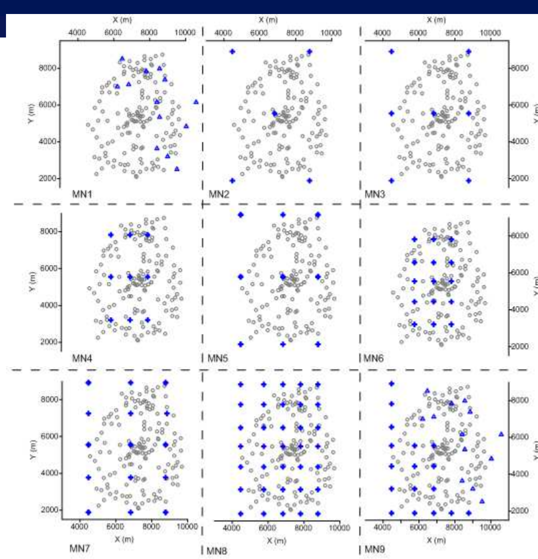
Correct groundwater monitoring requires detailed characterization
Do not rely on "baseline"

- Correct identification of major and minor elements in CO_2 reactive minerals
  - Carbonates
  - Organics
  - Sulfides
- Buffering and areal limits of migration
- Recharge mechanism
- Hydraulic gradient
- Aquifer heterogeneity

SPE International

Monitoring Network Efficiency -35 years after leakage to surface

Webinars



Unit: wells/km²

MN1: 0.322
MN2: 0.124
MN3: 0.173
MN4: 0.223
MN5: 0.223
MN6: 0.371
MN7: 0.371
MN8: 0.866
MN9: 0.742

SPE International

Conclusions

Webinars

- Scientific method–based selection of monitoring approaches
- Fully and quantitatively conceptualize “material impact”
  - Endangerment of USDW
  - Loss of CO_2 from storage decreasing GHG value
  - Induced seismicity
  - Other
- Design monitoring to detect material impact
- Finding of project success possible!

SPE International

More Information: www.gulfcoastcarbon.org

Webinars

Thank you!

Susan.Hovorka@beg.utexas.edu

SPE International

Selected references

Webinars

- Bolhassani, Behnaz, Hovorka, S. D., Hosseini, S. A., Young, M. H., Anderson, J.S., and Yang, C, 2017, Model-based assessment of the site-specific cost of monitoring, Energy Procedia, 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland
- Dixon, T.E, and Romanak, K.D., 2015, Improving monitoring protocols for CO2 geological storage with technical advances in CO2 attribution monitoring: International Journal of Greenhouse Gas Control, v. 41, p. 29-40, http://doi.org/10.1016/j.ijggc.2015.05.029.
- Hovorka, S.D., 2017, Assessment of low probability matrial impacts, 13 International conference on GHGT -13, Energy Procedia
- Hovorka, S. D, Nicot, J.-P, Zeidouni, M. Sun, A., Yang, C. Sava, D., Mickler, P., and Remington, R.L, 2014, Expert-based development of a standard in CO_2 sequestration monitoring technology, final status report, Conducted under Funding Opportunity Number EPA-G2008-STAR-H1, Integrated Design, Modelling and monitoring of geologic sequestration of anthropogenic carbon dioxide to safeguard sources of drinking water
- Romanak, K. D., Bennett, P. C., Yang, C., and Hovorka, S. D., 2012, Process-based approach to CO2 leakage detection by vadose zone gas monitoring at geologic CO2 storage sites: Geophysical Research Letters, v. 39, L15405, doi:10.1029/2012GL052426.
- Wolaver, B. D., Hovorka, S. D., and Smyth, R. C., 2013, Greensites and brownsites: Implications for CO2 sequestration characterization, risk assessment, and monitoring: International Journal of Greenhouse Gas Control, v. 19, p. 49-62, doi: http://dx.doi.org/10.1016/j.ijggc.2013.07.020.
- Yang, C., Hovorka, S. D., Treviño, R. H., and Delgado-Alonso, J., 2015, Integrated framework for assessing impacts of CO2 leakage on groundwater quality and monitoring-network efficiency: case study at a CO2 enhanced oil recovery site: Environmental Science & Technology, v. 49, p. 8887-8898, http://doi.org/10.1021/acs.est.5b01574.

SPE International