CO_2 Capture Project

CCP PHASE 1: Storage Monitoring and Verification Results Workshop

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EU ROLL OUT

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SMV Program Organization

Four Technical Areas (2000-2003)

- Integrity – Competence of Natural / Engineered Systems
- Optimization – Economic Offsets, Efficiency, Transportation
- Monitoring – Performance and Leak Detection
- Risk Assessment – Probability x Consequences, FEPs, Methodologies, Modeling, Mitigation / Remediation

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Shell	Heidug, Maas
HYDRO	Eide, Böe
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SUNCOR ENERGY	Das

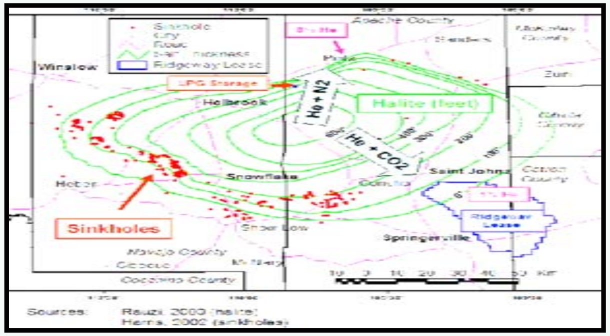
CO_2 Capture Project

Integrity – Natural & Industry Analogs

Natural CO_2 Reservoirs (ARI)

a. 3 Large US Accumulations
b. Thick Evaporite or Clastic seals
c. Lack of Faults or Self-Healing Faults

St John's Dome Structural Map



Leaky Systems (Utah State)

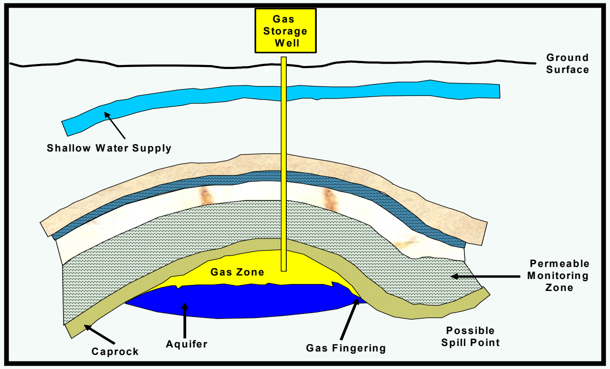
a. 3D Structure / Stratigraphy Models
b. Fluid Migration Paths & History
c. Natural CO_2 Immobilization Rate

Natural CO_2-Charged Geyser System in E. Central Utah

Natural Gas Storage Industry (GTI)

a. Widespread, Decades-Old Industry
b. Excellent Safety Record
c. Site Selection, Operations, Intervention
d. Key Implications for CO_2 Storage

Gas storage facility elements

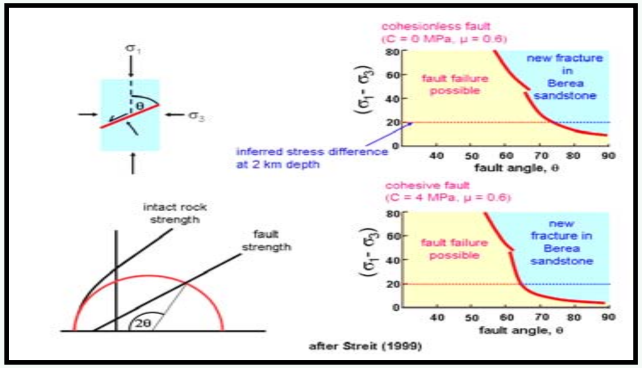


Integrity – Reservoir & Cap Rock

Geomechanical Response to CO_2 (ASP)

a. Stability of Reservoir / Cap Rocks; Faults
b. Tools to Predict Maximum Fluid Pressure
c. Development of Stress-Seismic Techniques

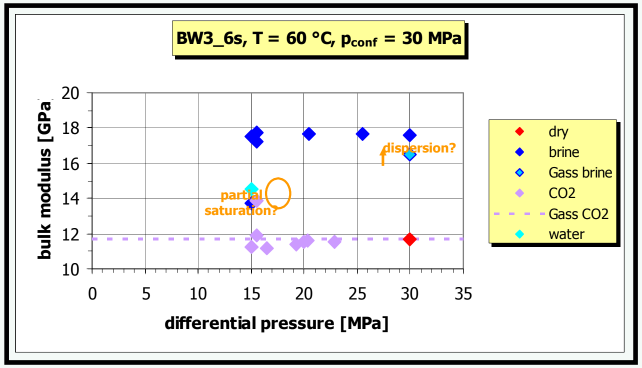
Evaluation of Fault Stability: 2D Failure Plot



Rock Response to CO_2 (GFZ-Potsdam)

a. Geophysical Attributes; Mineral Stability
b. Anomalous Effects: Flow Stability?
c. Ions Released: Mineral Dissolution

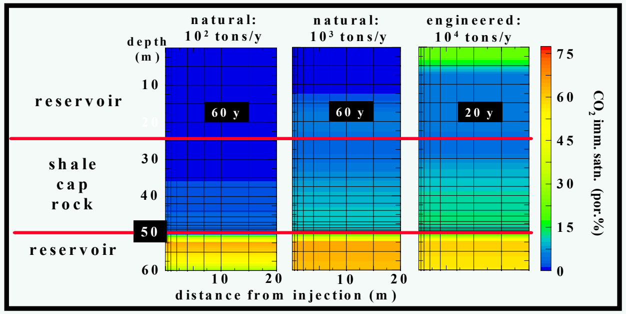
Bulk Modulus: Gassmann



Reactive Transport Modeling (LLNL)

a. Geochemical / Geomechanical Response (Permeability Decrease/ Increase, Resp.)
b. Dependency on Reservoir and Influx Parameters
c. Abatement of Effects with Time

Geochemical and geomechanical response to CO_2 injection



Integrity – Well Stability

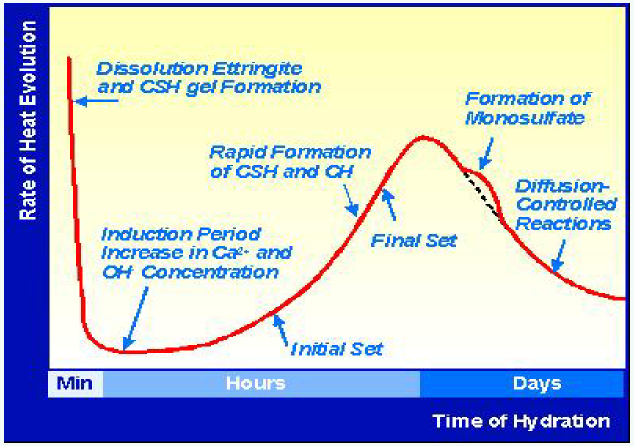
Well Integrity (SINTEF)

a. Testing of Portland Cement

b. Degradation Mechanisms and Rate

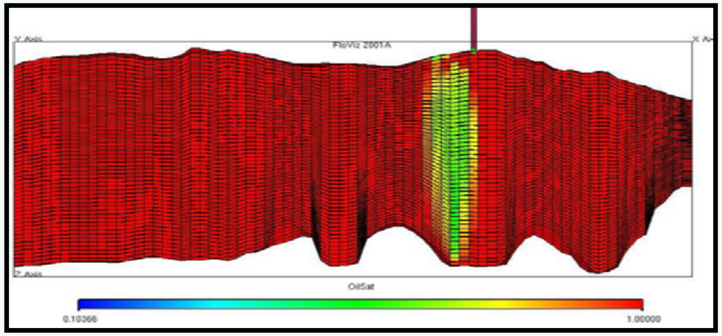
c. New Cements and Sealants

d. Well Failure Simulation

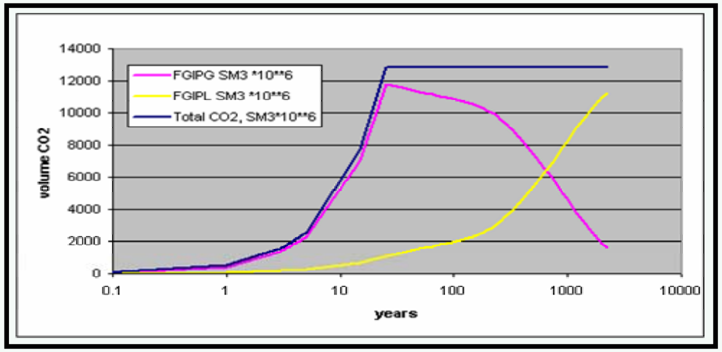


Heat Evolution Profile of Hydrating Cement

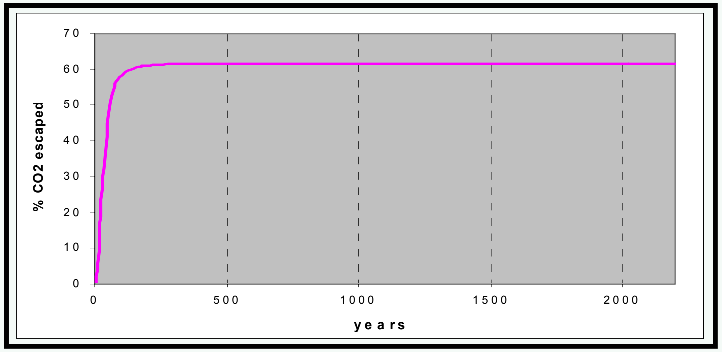
Reservoir Simulation: 5 Years



Free vs. Dissolved CO_2 With Time



A "Worst Case" Scenario

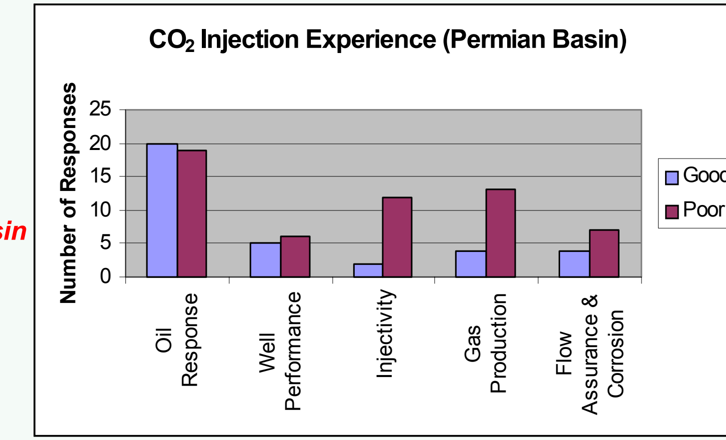


Optimization – Hydrocarbon Reservoirs

CO_2 EOR Record (NMT)

a. “Look back” - Permian Basin Survey
b. Oil Response & Breakthrough
c. Lack of Reservoir Characterization
d. Need for Monitoring
e. Anecdotal Safety Record

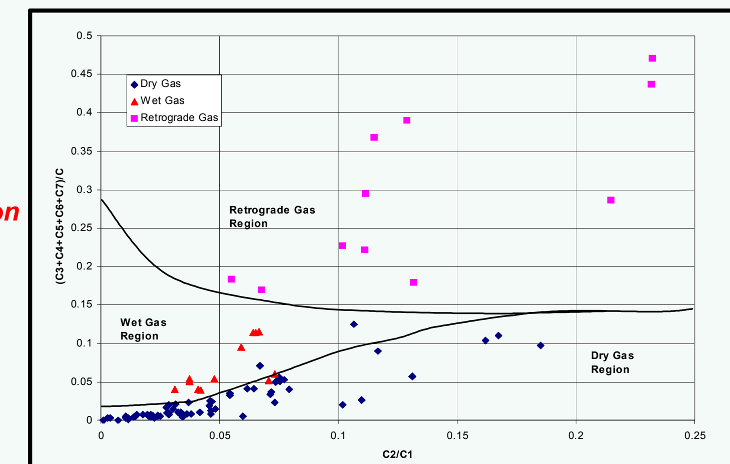
Survey Results: Permian Basin EOR Experience



Gas & Condensate Field Storage (TTU)

a. Experimental capacity / compatibility
b. Phase Behavior; Compressibility (Z)
c. “Sequestration Parameter” Screening Tool

Hydrocarbon Gas Phase Behavior

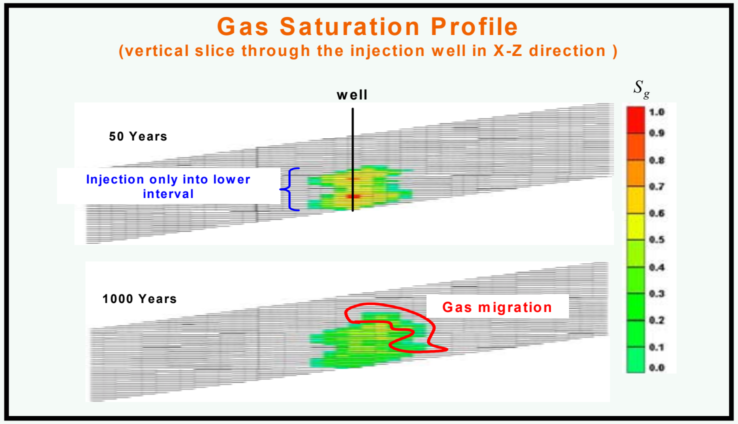


Optimization – Saline Aquifers

CO_2 Movement & Immobilization (UT)

a. Trapping Mechanisms & Timing
b. Injection Location in Reservoir
c. Petrophysical Sensitivity
d. Solubility and Residual Gas Trapping
e. Most CO_2 Immobilized by 1000 yr.
f. Mineralization Small, 10000 yr.

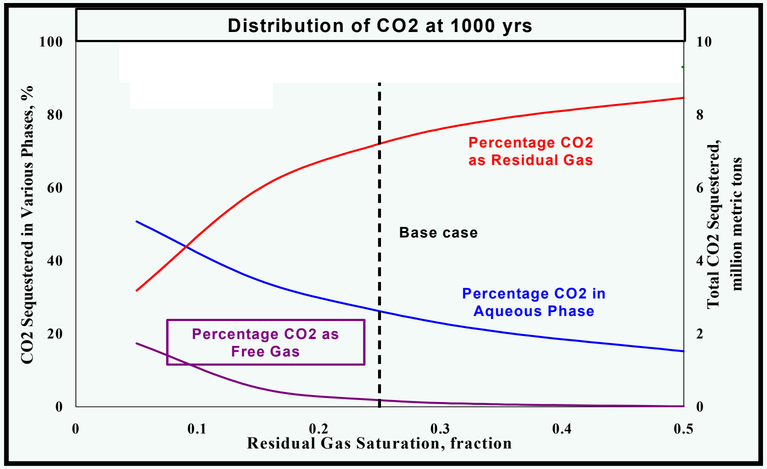
Injection Location Effect on CO_2 Dispersion



CO_2 Impurities – Subsurface (UT)

a. Impure CO_2 Streams (SNOx effects) on Injectivity, Reservoir & EOR
b. Unlikely to Affect Injectivity
c. MMP and Mobility Ratio Tradeoff in EOR

Immobili-zation States of CO_2



Optimization – Transportation

Materials Selection for Pipelines (IFE)

a. New Experimental Data for Carbon Steel (CS) Corrosion at High P
b. Existing Models Exaggerate CS Corrosion Rates
c. Pipeline Design and Inhibitor Use

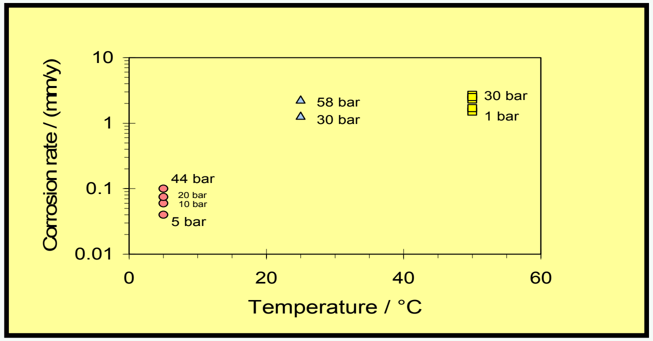
Process Design (Reinertsen Engr.)

a. Reevaluate Existing Hydration Pipeline Specifications for Norwegian Offshore Case
b. Relaxed from 60 to 600, Perhaps 1300 ppm
c. Cost Savings with Process Integration

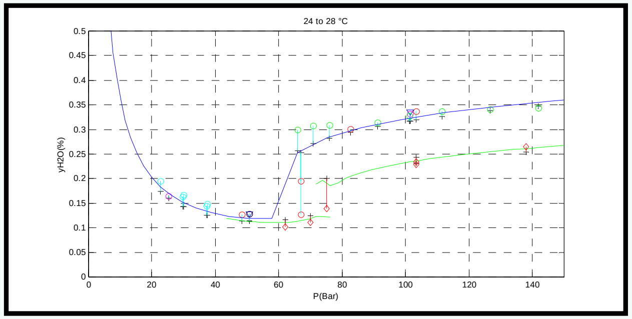
Impurities and Surface Equipment (Battelle)

a. Acid Gases Likely to Impact Surface Equipment
b. Further Work on Gas Phase Behavior Needed

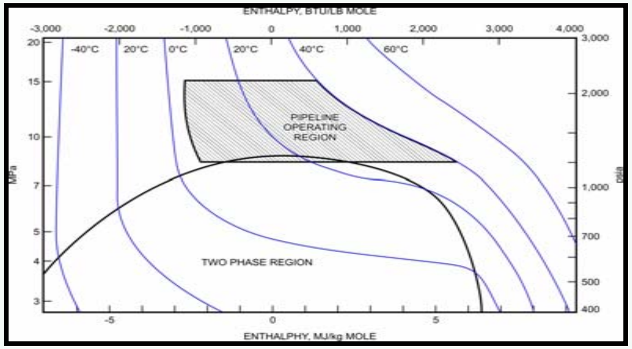
Corrosion Rates w & w/o Inhibitor



Water Solubility on CO_2 (w & w/o CH_4)



Pipeline Operation in 2 phases with Addition of 5% each N_2 and CH_4



Monitoring – General

Survey of Monitoring Applications (TNO)

a. Well Monitoring: P&T, ER, TDT, Microseismic, VSP, Cross well Seismic, fluid sampling

b. Surface Geophysical: 4D seismic, Sub-bottom profiling and Sonar (marine), gravity, EM, InSAR, tiltmeters

c. Geochemical: GW sampling / analysis, tracer surveys, atmospheric detection, geobotanical hyperspectral

d. Applicability matched with FEPs (e.g., casing / cement well failure)

e. Seismic modeling

Suitability of Surface Geophysical Monitoring Techniques by FEPs

	time lapse seismic	sub-bottom profiling	Sonar	Gravity	EM	Geodetic	InSAR	Tilt meters
Fault activation (high pressure)	not likely	x	x	x	x	not likely	not likely	when down-hole
Dissolution or dehydration of seal	not likely	x	x	x	x	x	x	x
Casing / cementation failure	x	x	x	x	x	x	x	x
Deterioration cement plug	x	x	x	x	x	x	x	x
Corrosion of casing	x	x	x	x	x	x	x	x
Formation damage due to drilling	not likely	x	x	x	x	x	x	x
Operational well failure	x	x	x	x	x	x	x	x
Fractures seal	possible	x	x	x	x	x	x	x

Suitability of Geochemical Sampling Monitoring by FEPs

	Groundwater sampling	(Isotopic) tracers	Atmospheric monitoring network	Geo-botanical monitoring
Cap rock integrity (leakage)	In case of leakage to the surface	Injected CO_2 discrimination	In case of leakage to the surface	In case of leakage to the surface
Ground movements	x	x	x	x
Lateral spreading	x	x	x	x
Verification or mass balance	x	x	x	x

Monitoring – Geophysical & Geochemical

Geophysical

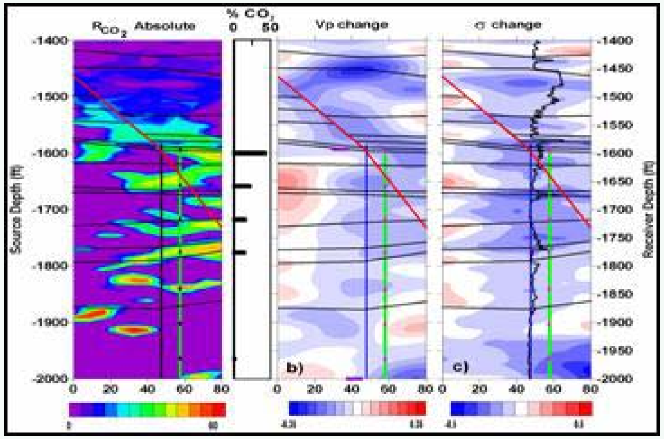
Novel Geophysical Techniques (LBNL)

a. Resolution and Applicability of Seismic and Non-Seismic Geophysical Monitoring

b. Seismic Amplitude Analysis and AVO Detect Changes in Water w/ CO_2

c. Gravity, EM, SP Have Variable Resolution but may Offer Significant Cost Saving

Image Enhancement Using EM



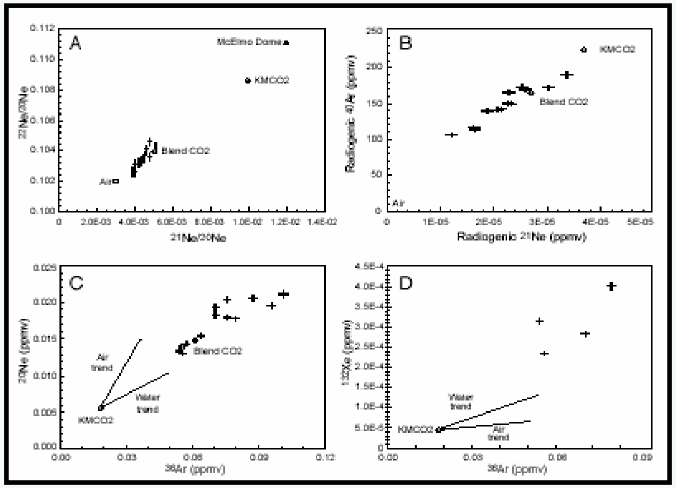
Geochemical

Noble Gas Tracers & Costs (LLNL)

a. Selection: Cost, Availability, Transport, Distinctiveness (Xe)

b. Gas Selection and Quantification for Mabee Field

Distinguishing Gases Using Noble Gas Isotopes

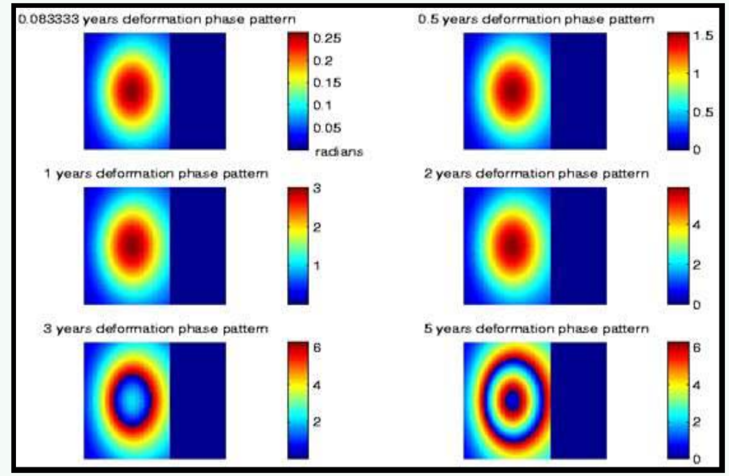


Monitoring - Remote

InSAR Resolution (Stanford)

a. Satellite-Based Theoretical Detection of Ground Movement with Model Injection Project
b. Pressure Profiles and Deformation Maps
c. Sensitivity to Topographical Effects

Deformation Maps from Pressure Profiles



Hyperspectral Geobotanical (LLNL)

a. Indirect detection of floral responses
b. Mammoth Lake – Satellite Detection of Tree Kills
c. Rangely Field – Aerial detection of Long-Term Habitat Redistribution

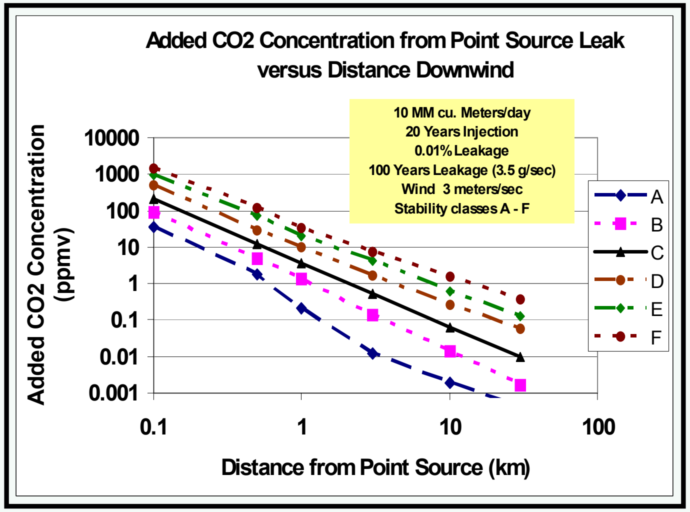
Aerial hyperspectral Image of Rangely CO_2 EOR Field, Colorado

Monitoring - Atmospheric

State-of-the-Art Atmospheric (Caltech)

a. Available Technologies: Applicability for Time / Length and Costs
b. Detectability of 0.01%/year leak
c. Spreadsheet Application to Model Detector Applicability Given Point or Diffuse Leaks, Flux, Atmospheric Conditions (>10 ppm Over Background)

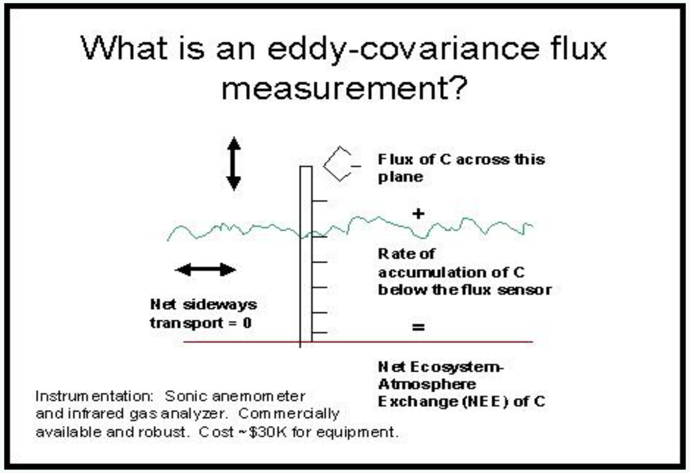
Detectability as a Function of Atmospheric Conditions



Eddy Covariance (Penn State)

a. Tower-Based Laser Spectrometry
b. Established for CO_2 flux; Suitable for CO_2 storage
c. Resolution for leak types: 10^{-1} to 10^{-5} $kgm^{-2}s^{-1}$ (Well Failure to Fault, resp.)

Eddy Covariance Concept

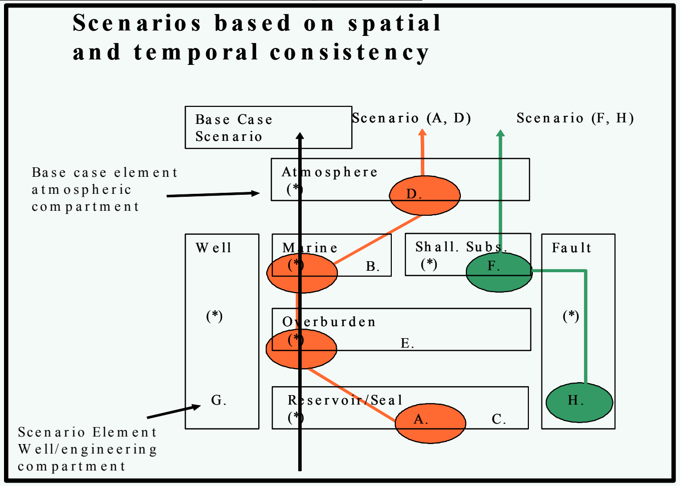


Risk Assessment – Comprehensive Methodologies

SAMCARDS (TNO)

a. Scenario & FEP Analysis, Quantitative Model Development, Consequence Analysis; Performance Assessment
b. Test on Netherlands On-Offshore Aquifer (No Leakage Over 10000 yr.)

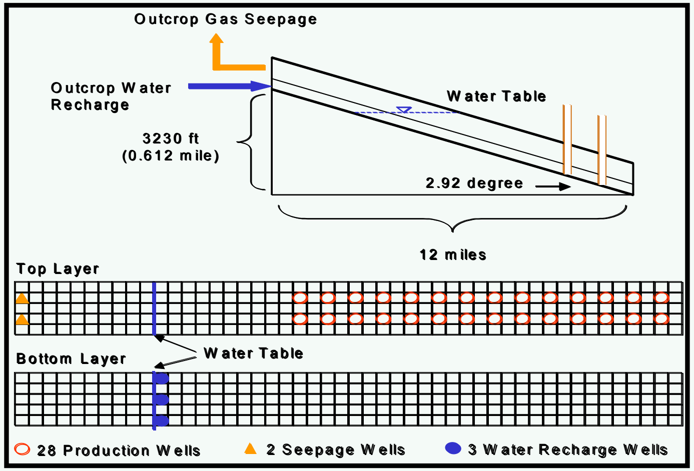
Multicompart-ment Risk Assessment Model



Probabalistic (INEL)

a. 4 Elements & 6 Functional Constituents Geomechanics Module
b. MS Access Prototype Application w/ Monte Carlo Simulation
c. Coal Bed Tests: Predictive Modeling for Well Placement & Operation Parameters
d. Coal Characterization
e. History Matching & Future Injection
f. Previous Production Effects

Represent-ative Seepage Model

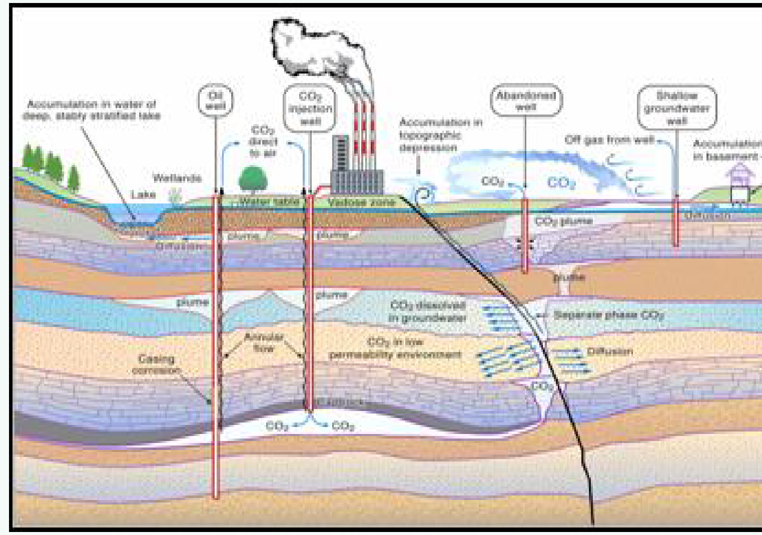


Risk Assessment – Seepage Modeling, Intervention & Remediation

Early Detection, Intervention & Remediation (LBNL)

a. Early Detection Monitoring Approaches
b. Leakage / Seepage Scenarios
c. Existing / Needed Intervention and Remediation Technologies from Other Industries
d. Site-Specific Contingency Planning

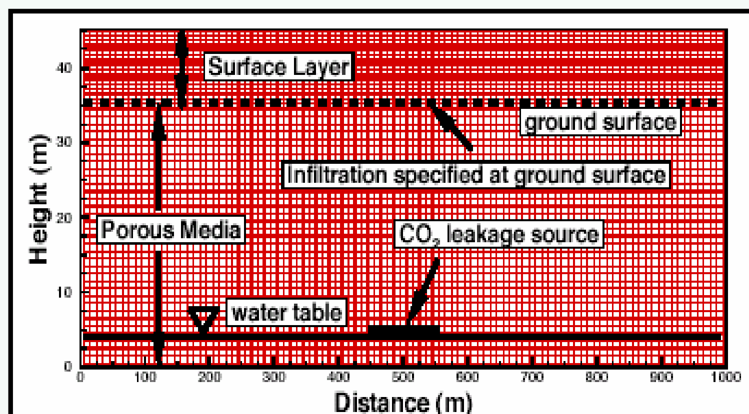
Leakage and seepage scenarios



Flow Simulation (LBNL)

a. Leakage / Seepage Coupling
b. Flux and Atmospheric Conditions
c. Case Studies

Coupled Subsurface – Surface Dispersion Problem Model



Risk Assessment – Environmental / Public Perception

- HSE Review (LBNL)
  a. Natural Analogs and Industrial Experience
  b. Regulatory Framework and HSE Effects
  c. Magnitude of Hazard & Principal Risks
  d. Regulatory Paradigms & Risk Assessment

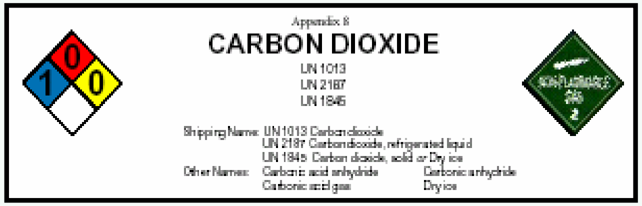
Nuclear Storage Lessons Learned

a. Not Comparable in Hazard Level but Lessons from Technical Assessment and Stakeholder Engagement
b. Technical Review of Gas Migration

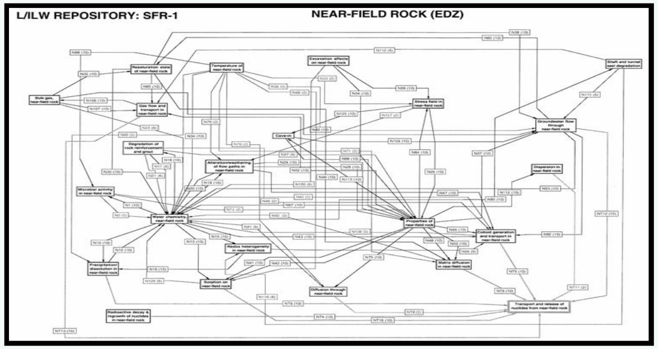
Subsurface Ecosystems (Princeton)

a. NGO concern for Biodiversity
b. CO_2 Affects Microbial Assemblages Which Could In Turn Affect Performance (Gas Generation, Pore Plugging)

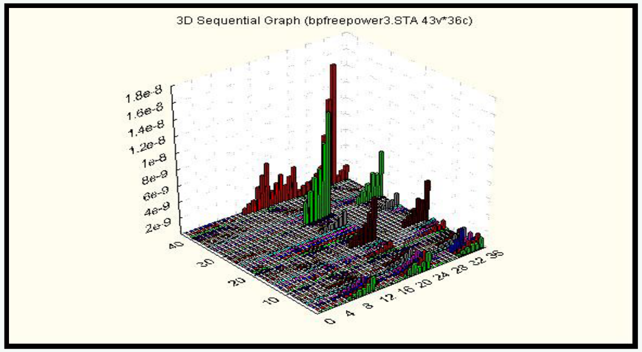
MSDS for CO2



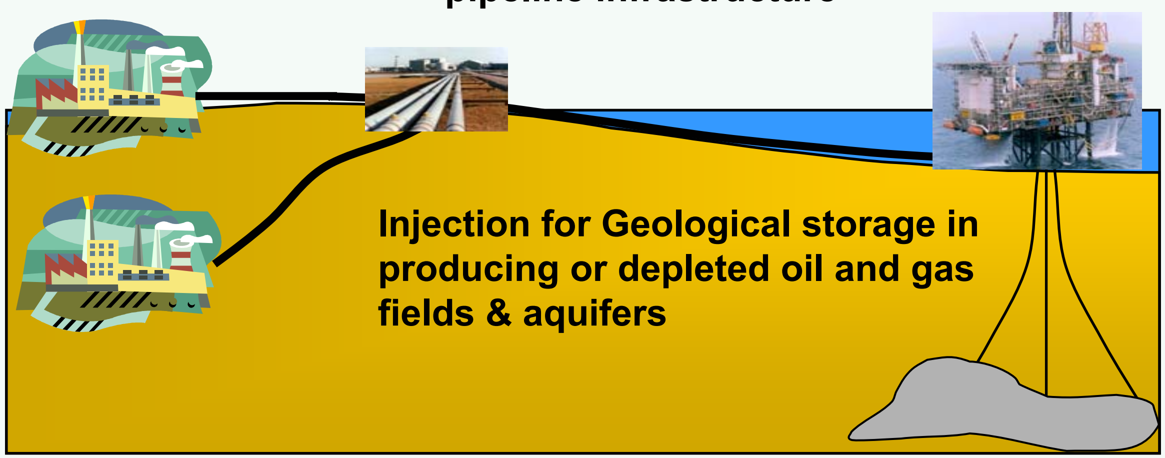
Process Influence Diagram



Microbial Power Simulation



CO_2 cost chain



Cost $3 – 160 /t → $1 - 25/t* → $2 - 5/t* = **$6 – 190/t****

* Cost principally distance dependant

** These numbers are indicative only

CCP-SMV Findings & Implications

Main Positive Results…(1)

- Insight into why natural systems are competent or leaky and how this can be assessed (features, 3D modeling)
- Excellent safety record of CO_2 handling and natural gas storage operations (30+ yr. CO_2 EOR; 90 yr. gas storage)
- Natural gas storage is much more challenging than CO_2 storage (shallow, mobile fluid, seasonal stress, flammable)
- Adaptations of gas storage technologies to CO_2 storage (e.g., competence testing, monitoring, mitigation)
- Potential for natural systems to immobilize CO_2 (mineral transformations; permeability & solubility trapping, bacterial interactions)
- Compatibility of GC reservoirs for CO_2 storage / enhanced recovery (CO_2 storage up to 5X original gas volume)

CCP-SMV Findings & Implications

Main Positive Results…(2)

- Practical guidelines to avoid leakage in ECBM (injector position relative to outcrop and water table)
- Injection and performance not significantly affected by CO_2 impurities (e.g., NOx, SOx, others)
- Potential cost-savings on pipeline transportation (front-end engineering & inhibition)
- Seismic monitoring likely to succeed in most settings (high resolution time lapse)
- Non-seismic monitoring may have adequate resolution and cost-effectiveness (surface & downhole gravity / EM; surface SP)
- Tracer technology versatile for performance & leakage (unique noble gas assemblages & indigenous tracers; early warning capability)

CCP-SMV Findings & Implications

Main Positive Results…(3)

- Instruments to monitor ground movement associated with CO_2 injection may be viable (e.g., InSAR)
- Remote hyperspectral techniques detect CO_2 effects on plants (Mammoth Lake, CA tree kills from volcanic CO_2)
- Resolution and deployment strategies for ground-based monitoring are adequate (e.g., 1% leak; above biological background)
- New tools, scenarios, models and case studies are being developed (FEP based, coupled, case studies)
- Leakage scenarios matched with possible mitigation / remediation solutions (surface, near-surface situations & settings)
- Risk assessment methodologies now up and running.

The SMV Contribution to CO_2 Storage - 1

Establishing the Relevance of Industrial Analogs

- A credible industry analogs HSE review established "relative" risk of CO_2 storage
- The HSE and operational records from these processes were "keyed" to CO_2 storage

Systematic Evaluation Process

- Site evaluation protocols: "Integrity", "Optimization", "Monitoring" and "Risk Assessment"
- Development of theory, experiments, models and simulation
- Performance, economics and tradeoffs issues investigated

ID of Likely Leakage Modes and their Characterization / Quantify / Avoidance / Remediation

- Venue quality is predictable using 3D geologic models and fluid history analysis
- Geologic systems offer several mechanisms of CO_2 immobilization, facilitated by operation methods
- Well failure is a greater than most geologic issues; Engineered and remediative solutions available

Applicability of Monitoring and Verification Technologies for CO_2 Evaluated

- Several technologies applied from various vantage points investigated
- Preferred approaches based on level of development, reliability, cost-effectiveness

Systematic Risk Assessment Methodologies Applicable to CO_2 Storage

- Independently developed, comprehensive methodologies are available
- Leakage scenarios, flow simulation models, intervention & remediation strategies

Technical Networking, Stakeholder Engagement Activities

- Technical workshops with non-CCP participation; Inter-JIP collaboration
- NGO engagement and response to concerns

The SMV Contribution to CO_2 Storage - 2

The CCP-SMV effort has developed methodologies for CO_2 storage venue assessment that reduce uncertainty and instill confidence of stakeholders. It has a unique place among related JIPs in that studies comprise a mix of practical industry experience and meticulous academic theory and research. The methodologies employed include those applicable generically and to specific geological storage venue types (e.g., coal, depleted oil and gas, saline aquifers). Networking with other JIPs and NGO engagement has enhanced the program's relevance and increased the likelihood of stakeholder acceptance of CO_2 storage. Continued CCP-SMV efforts will focus on methodology integration, performance / economic issues, networking and development of demonstration projects.

CCP-SMV Findings & Implications

Issues Needing Attention …(1)

- Some storage venues will require extensive 3D modeling and some testing (particularly aquifers)
- Geomechanical integrity of reservoir / cap rocks and faults / fractures need quantified assessment (esp., depressurization and repressurization; geochemical reactions)
- Well materials integrity is an important issue, particularly in depleted oil fields (workover, remediation, special materials)
- Ultimate storage capacity of depleted oil fields is not fully understood (tradeoffs between oil yield and capacity; “over” pressure)
- ECBM operations may experience operational difficulties (injectivity limitations, CO_2 storage capacity; methane yield)
- Methane may be liberated from reservoir overburden

CCP-SMV Findings & Implications

Issues Needing Attention…(2)

- Transportation costs (pipelines) need to be lower (up to 90% post-capture & compression costs)
- Geophysical monitoring resolution varies by reservoir fluid composition & depth (density contrast needs to be significant)
- Geochemical monitoring may be expensive / raise environmental issues (rare noble gas isotopes / CFCs, PFCs, SF_6)
- Remote / aerial detection applicability? (needs to be expanded to direct detection and secondary on microbes & minerals?)
- Risk assessment methodologies reflect reality? (difficult to test; analogs)
- Present intervention / remediation technology applicable? (more R&D needed)

Present Technology & Process Gaps / CCP2 Solutions

Integrity

- Geologic Systems – Analog development: Natural gas and / or EOR
- Engineered Systems – Well material resistance; Failure scenarios

Optimization

- Storage Venue Characterization – Coupled Geochemical / Geomechanical
- Operations – Injection rate / location; Storage performance
-Economics – EOR strategies
- Abandonment – Performance criteria for liability release

Monitoring

- Subsurface Imaging – Cost-effective alternatives
- Remote Detection – Direct approaches
- Monitoring Wells – Dual use wells; Compartments and breakthrough prediction

Risk Assessment

-Existing methodology evaluation and testing
-- Quantitative bracketing of risk relative to familiar hazards

Demonstrations

- Test CCP concepts & technologies
- Alberta Basin ECBM, In-Salah aquifer/EGR, Teapot Dome Engr. Leak, Castor

Networking

- North American, European, Australian JIPs