Stanford University

Global Climate & Energy Project

Berkeley/LBNL/Stanford Workshop
July 6, 2009

Challenges for Carbon Dioxide Capture and Storage

Professor Sally M. Benson
Energy Resources Engineering Department
Executive Director, Global Climate and Energy Project
Stanford University

Science and technology for a low GHG emission world.

Capture Options

Air

Oceans

Agricultural Lands

Forests

Air-Capture Towers

Industrial Sources

Power Plants

Fuel Production

Steel, cement, etc..

Mobile Sources

Capture Technology: Air Capture

Dilute gas capture: 390 ppm CO_2

- Oceans and other surface waters
  - Dissolution
  - Photosynthesis
    - Natural
    - Iron enhanced
    - CO_2 enhanced
  - Accelerated weathering by formation of bicarbonate (Caldiera and Rau)
- Agricultural lands
  - Photosynthesis
  - Soil carbon storage
    - Natural
    - Enhanced through land management
- Forests
  - Photosynthesis
  - Soil carbon storage
- Air-capture towers
  - NaOH and KOH absorption (Lackner, Keith)

Challenges and Opportunities: Air Capture

- Capture from a dilute source
  - Opportunities
    - Decouples capture from emission sources
  - Inefficient capture: natural ecosystems not optimized to capture CO_2
- Ocean Capture Challenges
  - Acidification (carbonic acid)
  - Enhanced uptake can interfere with natural nutrient cycle (e.g. iron cycling, oxygen availability)
  - Uncertain (doubtful) effectiveness of carbon export
- Natural and managed terrestrial ecosystems
  - Opportunities
    - Biofuel production
    - Potential co-benefit of soil quality restoration
    - Potential for biomass gasification with sequestration could lead to negative emissions
  - Challenges
    - Competition for other land and water uses
    - Changing land use may release captured carbon
    - Nutrient export from repeated harvest will deplete soils if not managed
    - Wildfires can release captured CO_2
    - Feedbacks from climate change can release captured CO_2
- Air-capture using towers
  - Large energy requirements (today: 20 x more concentrated sources, not including regeneration)

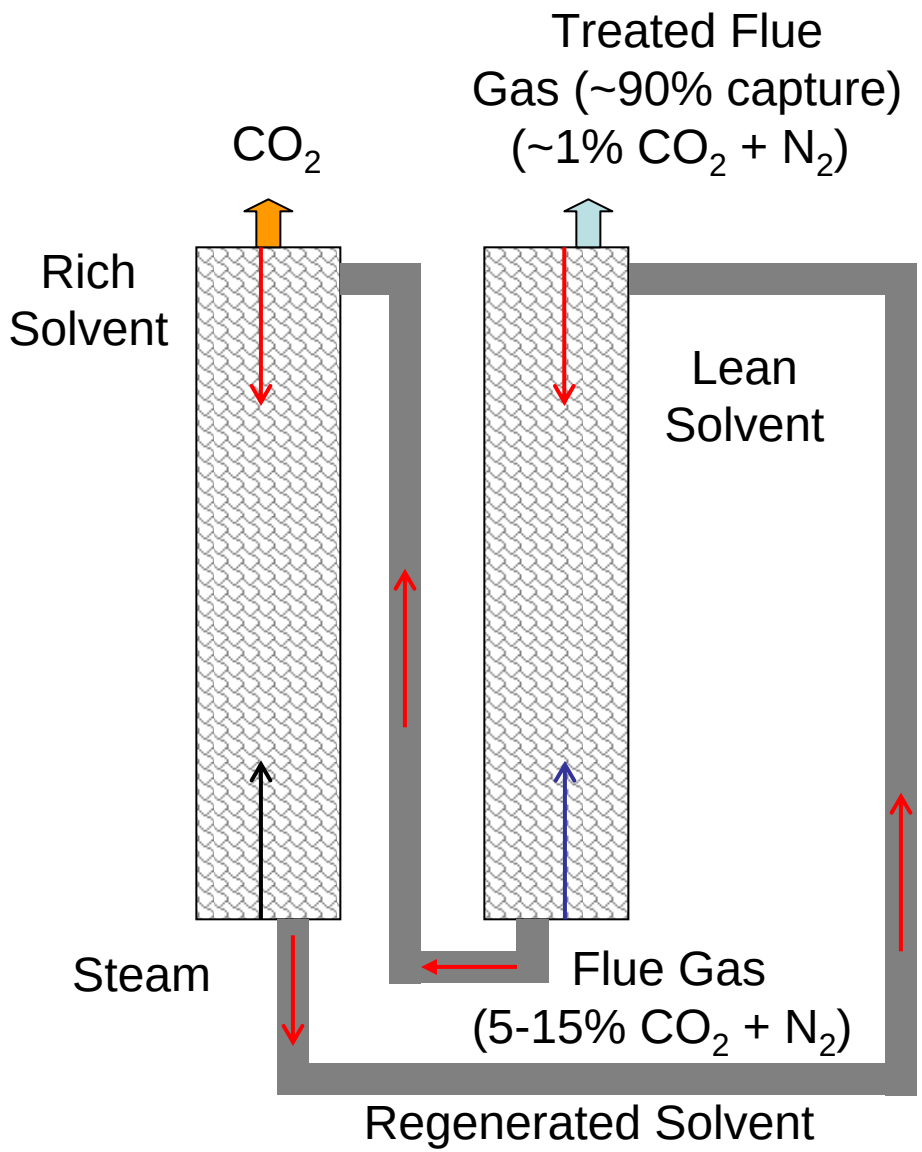
Capture Technology: Industrial Sources

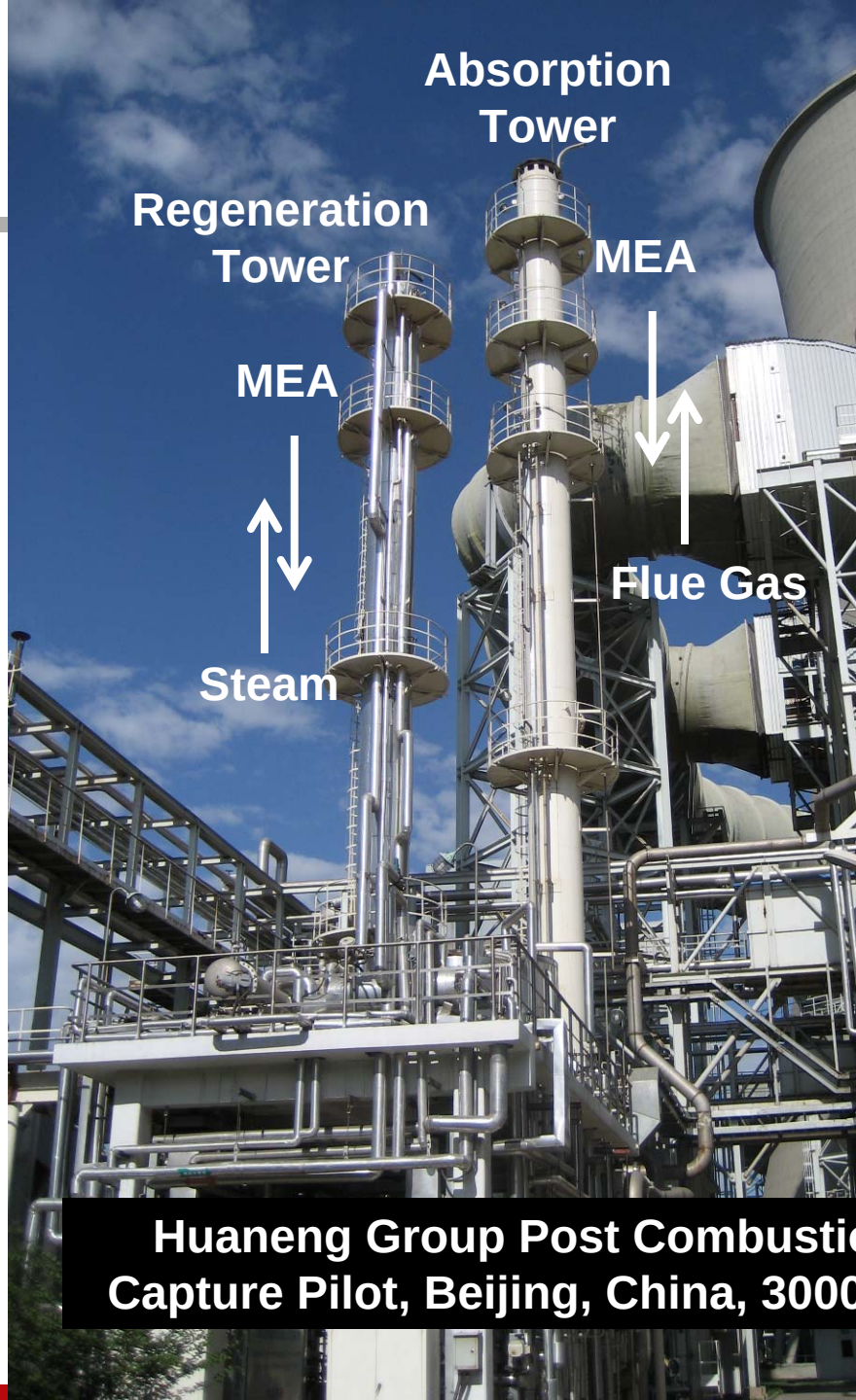
Concentrated gas capture: 5-90% CO_2

- Natural gas cleanup (2-10% CO_2)
  - MEA (temperature swing)
- Post-combustion (5-15% CO_2)
  - Gas cleanup
  - MEA (temperature swing)
  - Chilled ammonia (temp. swing)
- Pre-combustion (20-90% CO_2)
  - Gasification (H_2, CO, CO_2)
  - Separation
    - Rectisol or selexol (pressure swing)
    - Membranes
- Oxy-combustion
  - Oxygen separation
  - Combustion with oxygen
  - Gas clean-up and dehydration
- Algae
  - CO_2 enhanced algae growth in open or closed bioreactors

MEA: $NH_2CH_2CH_2OH$ (C_2H_7NO)

Post-Combustion Capture





Comparison of Industrial Capture Options

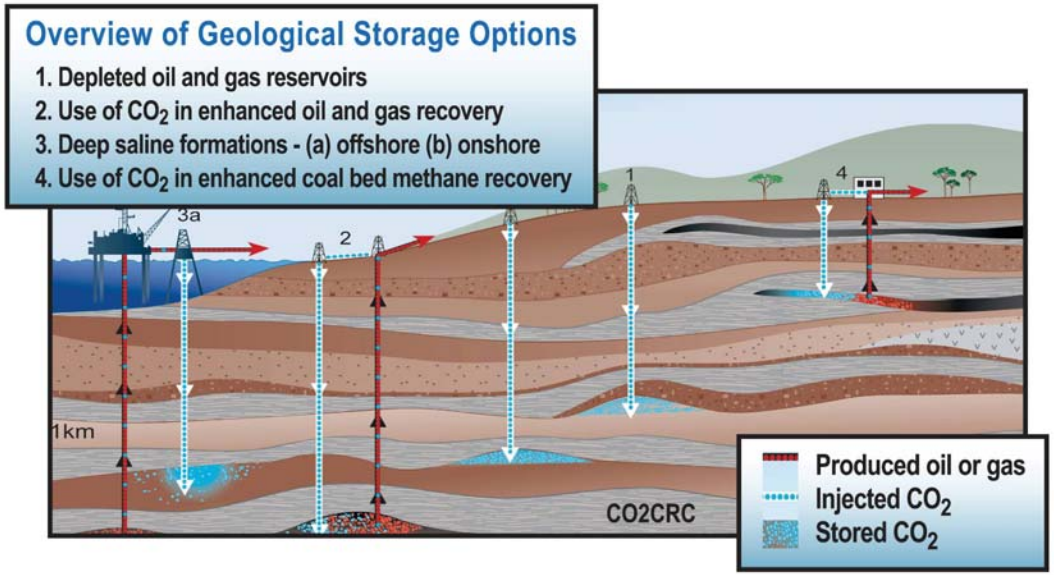
Technology	Opportunities	Challenges
Post-Combustion	• Mature technology components • Retrofit potential for existing fleet	• Integration challenges • High energy penalty from regeneration (~30%) • High cost for capture
Pre-Combustion (IGCC)	• Potentially lower capture costs than post-combustion • Lower energy penalties (10-15%) • H_2 production	• Complex chemical process • Little experience in power sector • Repowering • Large capital investment
Oxygen-Combustion	• Avoid complex post-combustion separation • Potentially higher generation efficiencies	• New materials needed for higher temperatures • Inefficient oxygen separation • Repowering investment

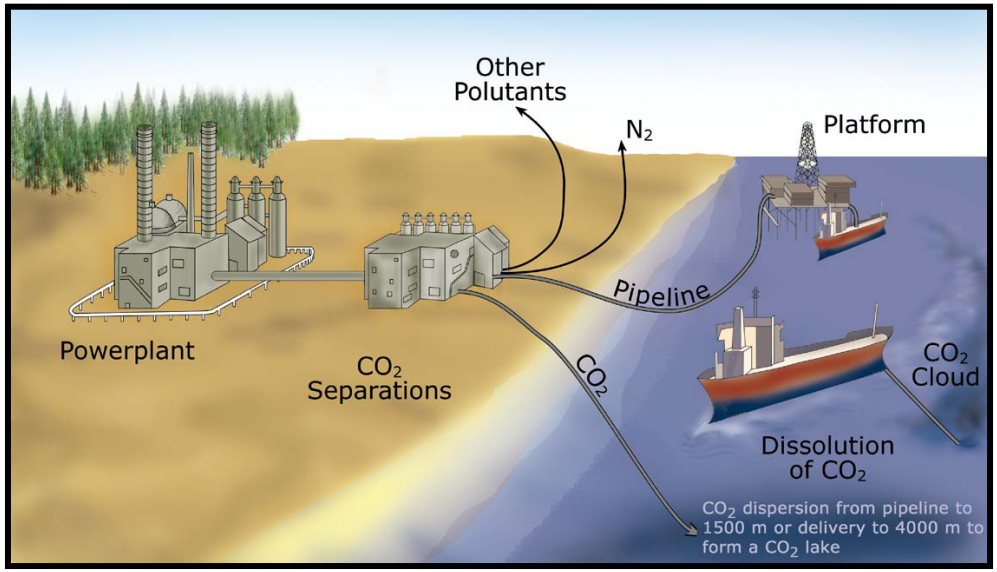
Today's Industrial Capture Technology

- Energy penalty: 10 to 30%
- Cost
  - \$50 to \$100/tonne CO_2 for the nth plant
  - Significantly more for the 1st plants (\$150 to \$250/tonne CO_2)
  - Cost of electricity generation: 50 to 100% increase
- Uncertain reliability

CO_2 Storage Options

- Deep geological formations
  - Oil and gas
  - Coal
  - Saline aquifers
  - Basalts
  - Deep ocean sediments
- Terrestrial ecosystems
  - Standing stock
  - Soil carbon
  - Exudates and dissolved CO_2
- Oceans
  - Direct injection
  - Ocean fertilization
  - Bicarbonate formation
- Solids
  - Minerals
  - Cement
  - Other





Generic Storage Challenges

- Huge scale of emissions
  - 7 x mass of petroleum production
- Establishing permanence
  - 100’s to 1000’s of years
- Environmental risks
- Cost
- Energy use

Comparison of Today's Storage Options

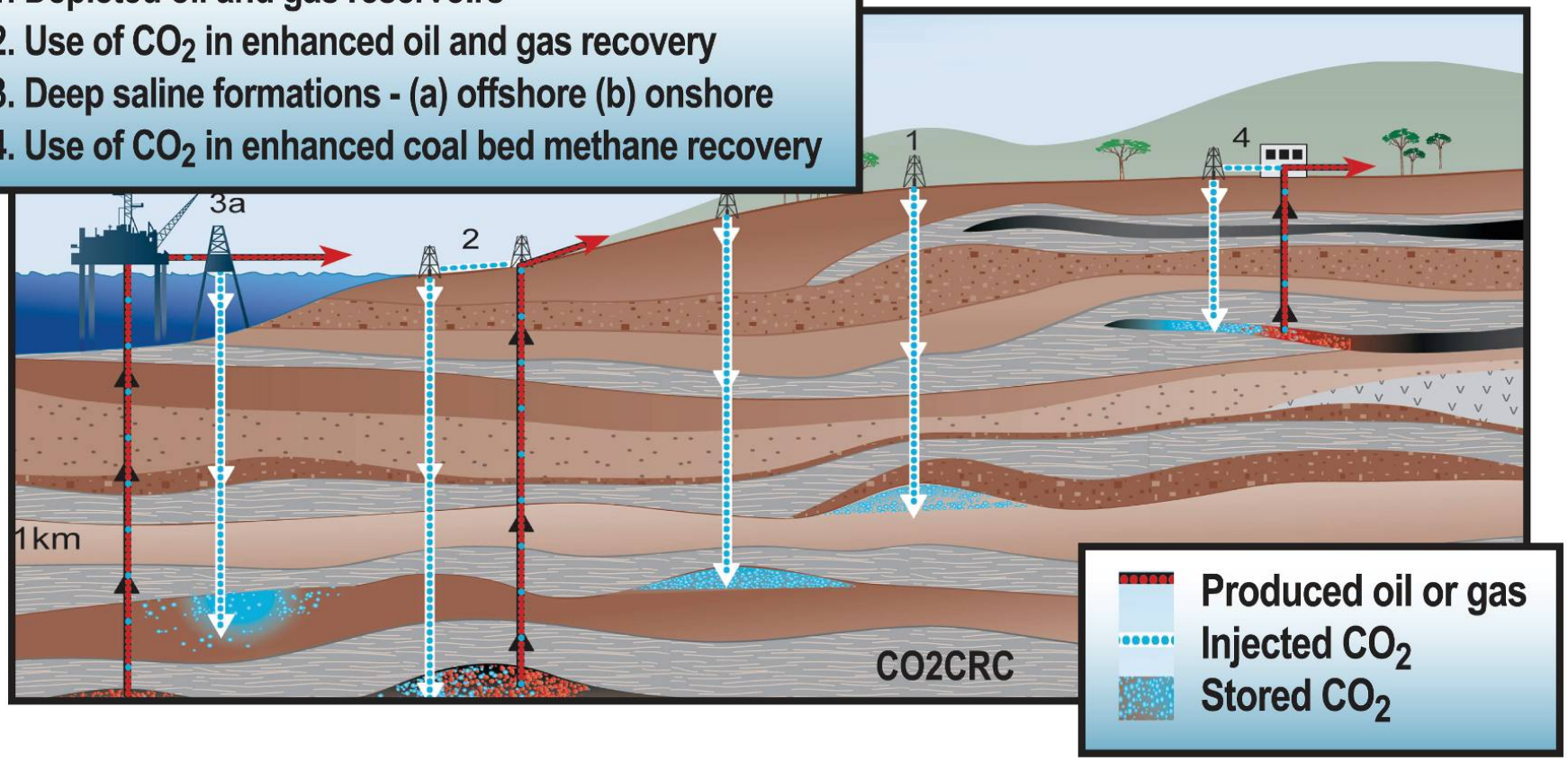
	Deep Geological Systems	Terrestrial Ecosystems	Ocean	Solids Mineral
Permanence	M - H, depends on site selection	L, for most options	L- M, depends on site selection	H
Environmental and Safety Impacts	L-M, groundwater and pipelines	L-H, water use, fertilizer, habitat	M-H, acidification, ecosystems	M, mining for reactants, disposal
Energy Use	M, compression cost	L-M, fertilizer, transport of biomass	M, compression, shipping	H, high T or grinding for high rates
Cost	L-M, energy, capital plant	L-H, competing land use	H, offshore and shipping, energy	H, energy, reactants and capital plant

H = high M = medium, L = Low

Major Options for Geological Storage

Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO_2 in enhanced oil and gas recovery
3. Deep saline formations - (a) offshore (b) onshore
4. Use of CO_2 in enhanced coal bed methane recovery



World Wide Capacity Estimates

Reservoir Type	Lower Estimate of Global Storage Capacity ($GtCO_2$)	Upper Estimate of Global Storage Capacity ($GtCO_2$)
Oil and gas fields	675[a]	900[a]
Coal seams (ECBM)	3–15	200
Saline aquifers	1000	~ 10,000

a. Estimates would be 25% larger if undiscovered reserves were included.

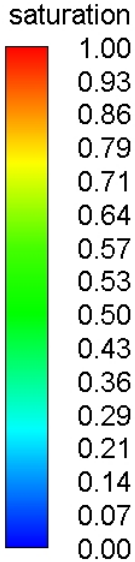
IPCC, 2005

3,283 to 12,200 Gt CO_2

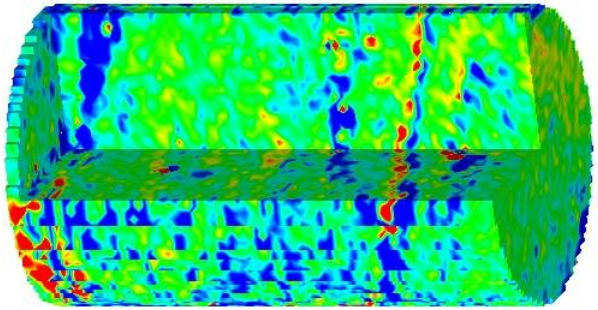
Current Estimates for Saline Aquifer Storage Capacity in North America (U.S. DOE)

In aggregate…sufficient for 100 years or more

Multiphase Flow of CO_2 and Brine

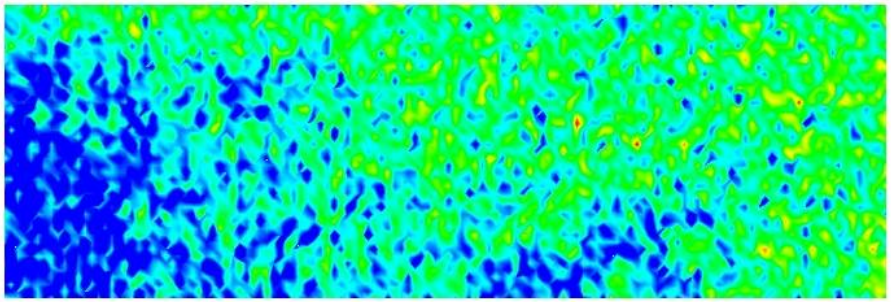


Influence of Heterogeneity



Waare C Sandstone

Influence of Buoyancy

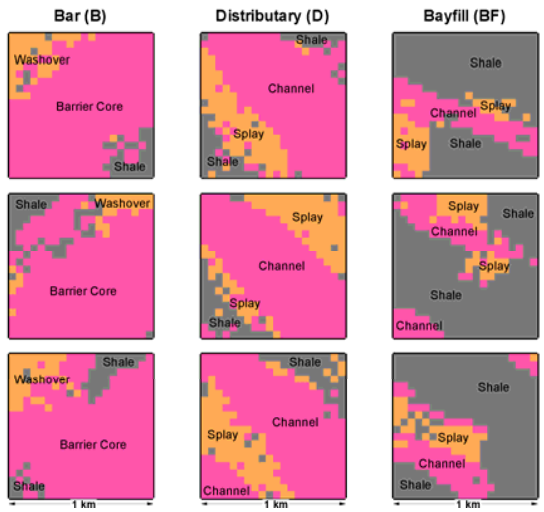


Berea Sandstone

- What fraction of the pore space will be occupied?
- What will be the footprint of the plume?
- How much dissolution and capillary trapping can be expected?

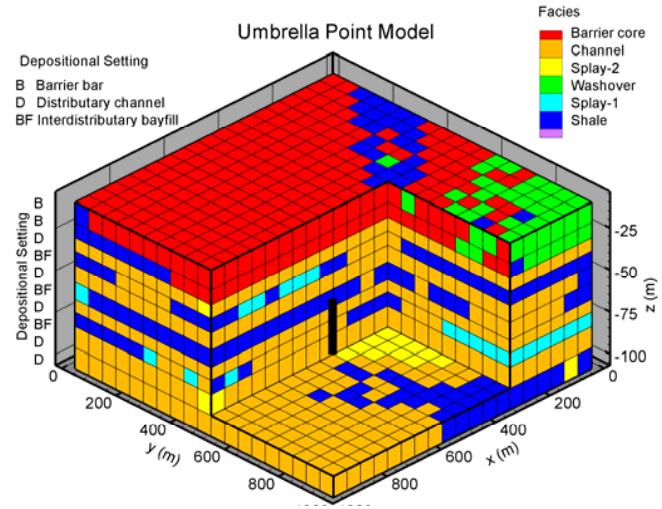
Is the current approach for simulating multiphase flow good enough to answer these questions?

Current Approach for Assessing Capacity in Saline Aquifers



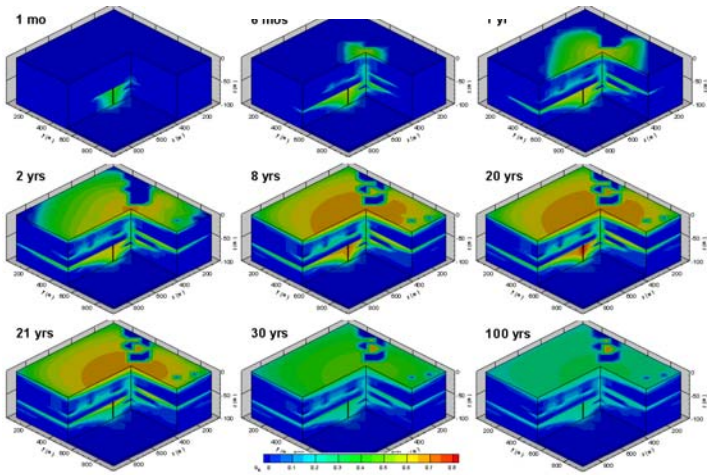
Models

Geology



Simulations

Statistics



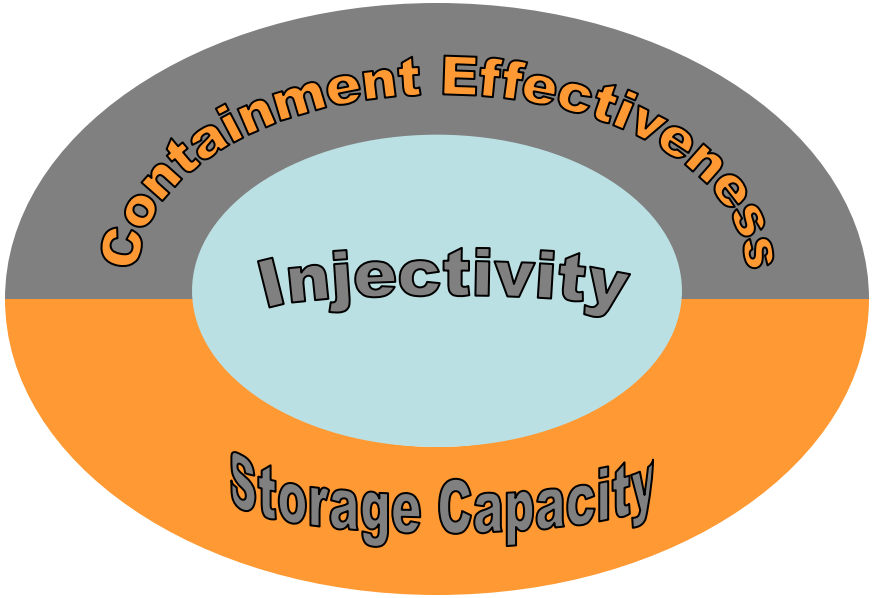
"Rules of Thumb"

CO_2 Storage Capacity = 1 to 4% Total Pore Volume[1]

[1] *Values used in the North American Carbon Sequestration Atlas, 2008*

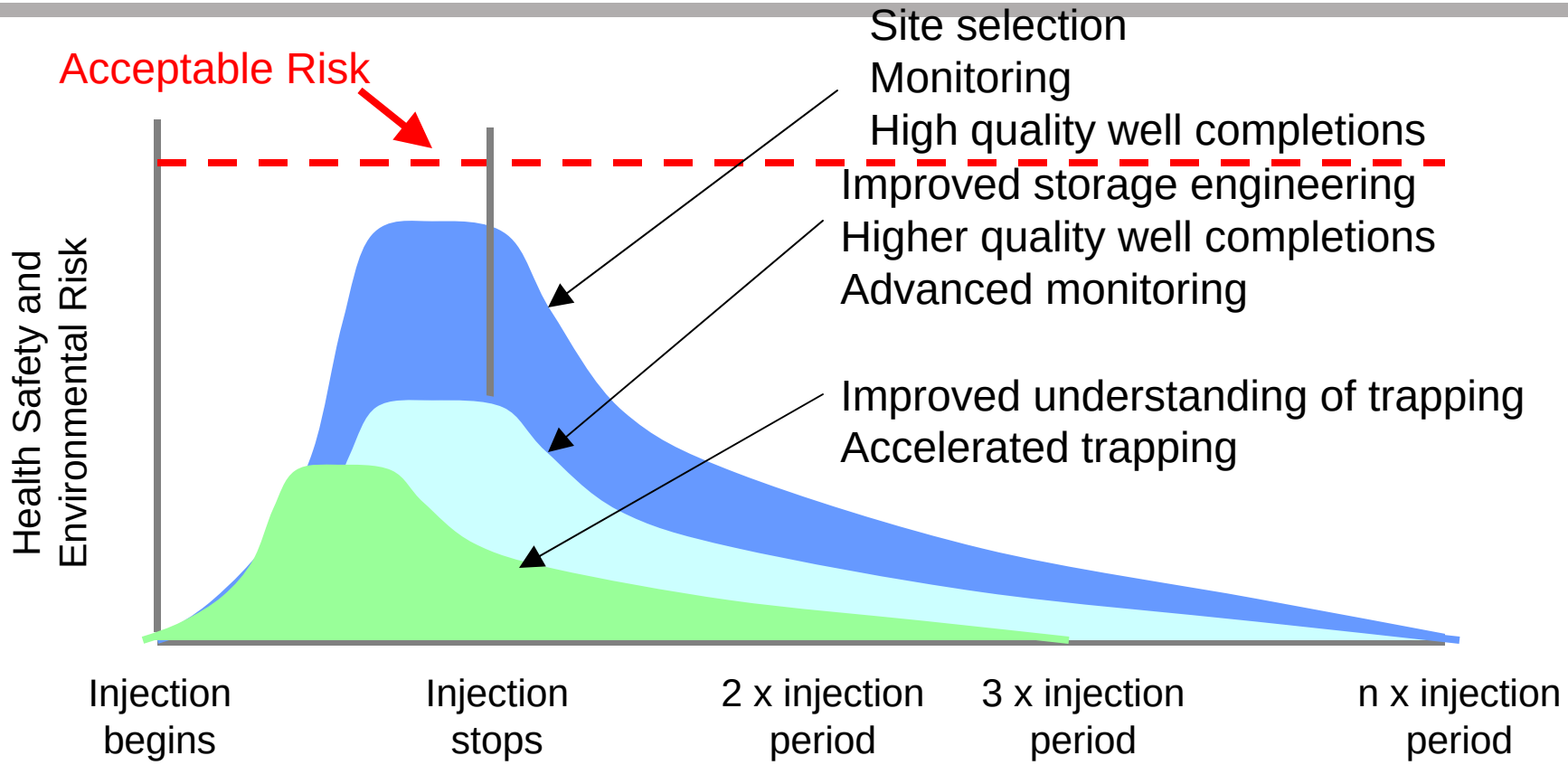
Site Characterization and Site Selection

- Oil and gas reservoirs
  - Current and future abandoned wells
  - Geomechanical impacts to seal
  - Capacity
- Saline formations
  - Seal adequacy over ~ 100 km^2
    - Closed trap vs. open trap
  - Capacity
  - Plume size
- Coal beds
  - Injectivity
  - Containment
    - Adsorption
    - Seals
    - Hydraulic fractures



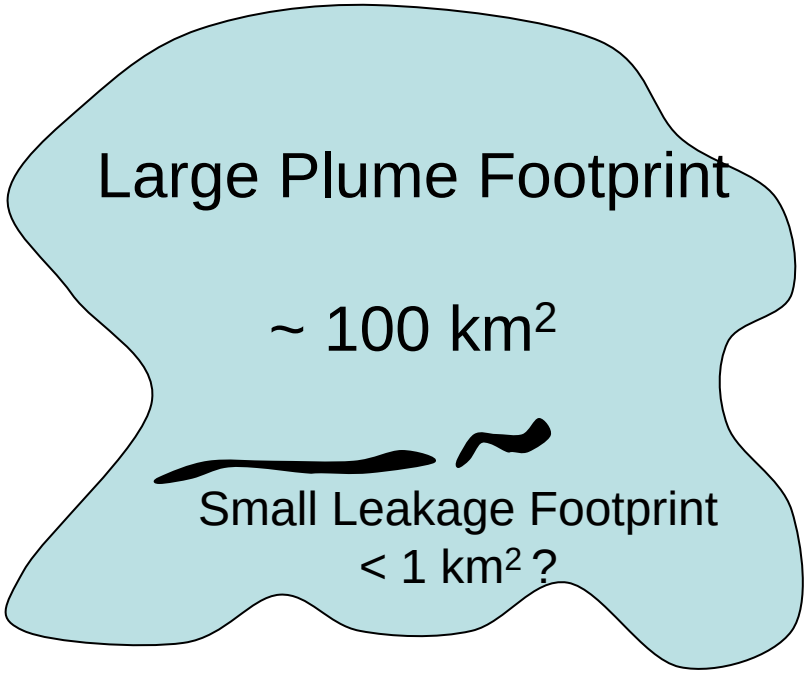
From prospectivity to site selection…
How much information is needed?
What will it cost?

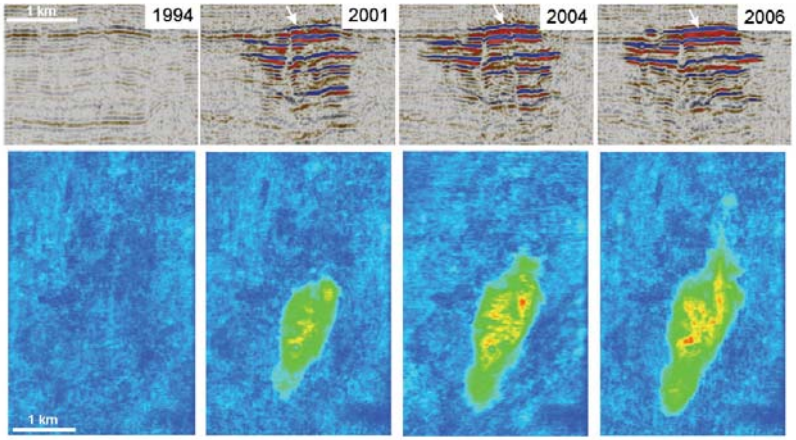
Storage Engineering



- *How many wells are needed for injection?*
- *How can storage security be enhanced with advanced engineering?*
- *Can sub-optimal sites be used for storage with advanced storage engineering?*

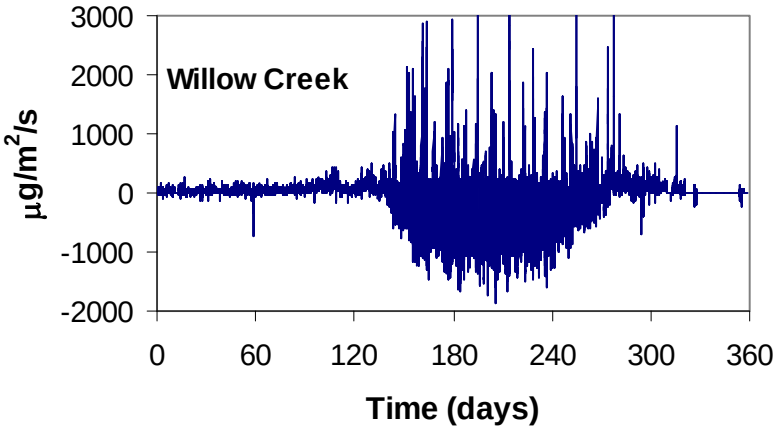
Key Questions: Monitoring





Courtesy of Andy Chadwich, GHGT-9

Large Fluctuations in Background CO_2 Fluxes

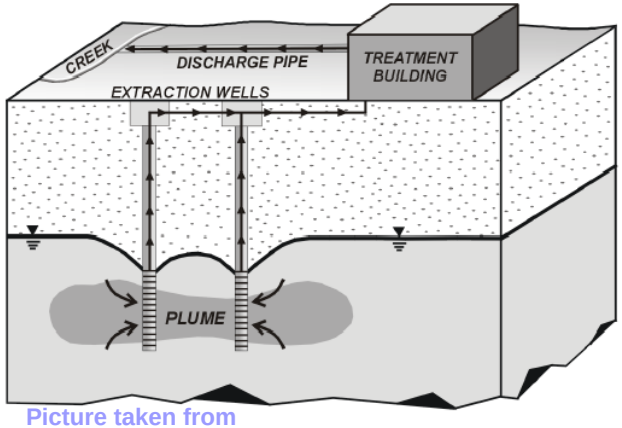


Courtesy of Ken Davis and Paul Bolstad

Can geophysical methods be used obtain an inventory of the injected CO_2? What is the best method(s) for distinguishing natural fluxes from leakage?

Remediation Options: Groundwater

- Passive methods
  - Natural attenuation by dissolution, migration, and mineralization
- Active methods
  - Gas phase pumping
  - Groundwater extraction to dissolve plume
  - Single well dissolution system: inject and produce water
- Methods to deal with other contamination due to dissolution of minerals by CO_2
  - Pump and treat wells
  - Containment by managing hydraulic heads
  - Treatment walls



Picture taken from
http://www.clu-in.org/download/remed/542r01021b.pdf

If CO_2 gets into the groundwater, what remediation actions will be needed, and how much will they cost?

Institutional Issues

- Regulations for storage: siting, monitoring, performance specifications
- Long term liability for stored CO_2
- Legal framework for access to underground pore space
- Carbon trading credits for CCS
- Clean Development Mechanism (CDM) credits for CCS
- Public acceptance

None is likely to be a show stopper, but all require effort to resolve.

Emerging Questions

1. How much does pressure buildup limit storage capacity, and how should we account for this in local, regional and global capacity estimates?
2. What approaches are available for managing pressure buildup during large scale injection?
3. Where does the displaced water go and what is the risk to groundwater?
4. To what extent, if any, do geochemical interactions between CO_2 (and H_2S, SO_2) and the host rock compromise storage security?

Summary: Big Opportunities

- Lowering the cost of all types of capture
- Increasing confidence in geological storage permanence
  - Making less than ideal site adequate
- Lowering potential environmental impacts of all types of storage
- Biomass gasification with sequestration for negative emissions
- CO_2 reuse on the scale of emissions (e.g. scale of energy use)