Predicting Leakage from CO_2 Sequestration Reservoirs using Analog Site Analysis

TETRA TECH

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1 Introduction

- Protocol for FutureGen Post-Injection Risk Assessment
- Goal: Predict surface leakage due to sudden and gradual releases (well failures and diffuse caprock seepage, respectively)

2 Predicting Surface Leakage from CO_2 Sequestration Reservoirs

- Challenging task:
  - Limited data available during permitting phase
  - Limited validation of leakage models
  - Uncertainty in geologic conceptual model
- Exploration phase of petroleum reservoirs has similar issues
- Additional concern for CO_2 sequestration is assessing storage integrity over long time frames

3 Future Performance Prediction for Petroleum Reservoirs

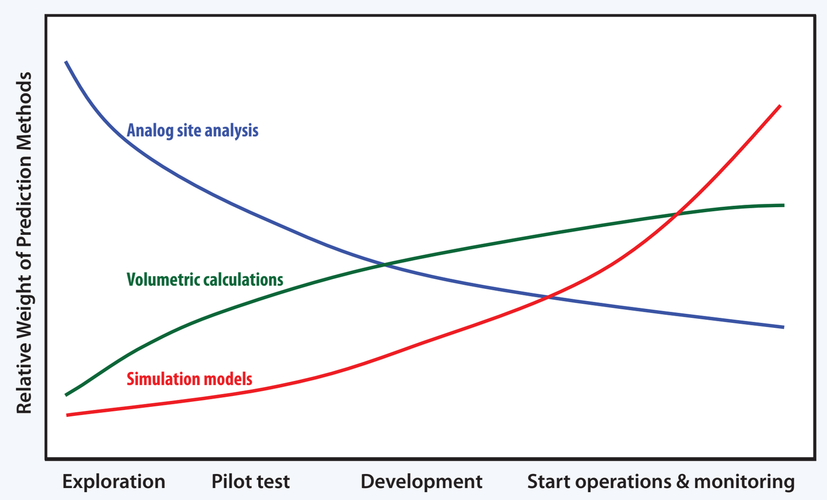
- 3 Primary Methods (SPEE, 1998)
- Analog Site Analysis
  - Extrapolate from analogous geologic site with known properties and performance
  - Apply in early phases where data are limited
- Volumetric Calculations
  - Estimate storage volumes and recovery rates
  - Requires more site specific data than analog site analysis
- Performance Analysis
  - Uses material balance, decline curve, and simulation models
  - Requires historical operating data to calibrate prediction models

SPEE, 1998. Guidelines for Application of Petroleum Reserves Definitions, Society of Petroleum Evaluation Engineers.

4 Choosing Performance Prediction Method for Petroleum Reservoirs

- "Correct" Methodology for Particular Case
  - Application of any 3 methods, alone or in combination
  - Reconciliation of results using different methods often instructive
  - Analog site analysis typically primary method during exploration and early development phase

5 Weighting of Prediction Methods for Petroleum Reservoirs



6 Predicting Leakage & Performance of CO_2 Sequestration Reservoirs

- Pattern Performance Predictions after Experience Gained in Petroleum Industry
  - Adaptation of Petroleum Industry protocols for CO_2 storage capacity estimates as proposed by NETL (DOE, 2007)
- Analog Site Analysis
  - Applicable assuming relevant analog site can be found for candidate site
  - Very likely as most early sites located in benign, well known settings
- Probably best indicator of performance in early stages of evaluation due to sparse data
- Volumetric Calculations
  - Useful for calculating storage capacity in reservoirs, even with rather sparse data
    - » Proposed by Frailey (2006) and used in NETL CO_2 Sequestration Atlas (DOE, 2007)
    - » Various sweep factors can even be assigned using analog performance data
  - Likely not as useful for calculating leakage, i.e. minute fractions of reservoir storage releases through seals
    - » Leakage through seals usually not an important issue in known petroleum reservoirs
- Performance Analysis
  - Use of simulation models to predict reservoir performance well established technology
  - Use of simulation models to predict surface leakage not a well-established technology
    - » Very limited calibration and validation has been completed for such models
    - » Uncertainty in geologic conceptual model in early project stages likely to dominate uncertainty in predictions
- Conclusion
  - Use analog site analysis as primary leakage prediction method
    - » Simulation models act as design enhancement tools during early phases
- For FutureGen, Constructed Analog Site Database
  - Contains summary of CO_2 leakage from natural CO_2 reservoirs and EOR reservoirs
  - Contains summary statistics on well failure frequencies, duration, and rates

US Department of Energy (DOE), 2007. Carbon Sequestration Atlas of the United States and Canada, U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007

Frailey, S. M., R. J. Finley, and T. S. Hickman, 2006. CO_2 sequestration: Storage capacity guideline needed, Oil and Gas Journal, Volume 104, Issue 30, Aug 14, 2006.

US Department of Energy (DOE), 2007. Carbon Sequestration Atlas of the United States and Canada, U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007.

7 Analog Database – 28 Sites

- Information on 4 CO_2 injection sites, 16 sedimentary basin sites, and 16 volcanic/hydrothermal/metamorphic (VHM) sites
- Includes major factors that control
  - Capacity of a formation to store CO_2
  - Leakage through sealing formations
  - Leakage or release along faults
  - Release from deep wells
- Includes data on cause of CO_2 release events, and effects on humans and biota
  - VHM sites provide good analog for effects on humans and biota due to large releases
- Provides CO_2 flux rates

General Site Information
Location/Site
General Site Type (Volcanic/Geothermal or Sedimentary)
Area (sq km)

Description of CO_2 Zone
Depth (m)
Areal Extent (sq km)
Structural Closure (m)
Lithology
CO_2 Origin
CO_2 Age (years)
Net Thickness (m)
Gross Thickness (m)
Gas Composition (% CO_2)
Porosity (Fraction)
Permeability (mD)
Pressure Gradient (psi/ft)
Fracture Gradient (psi/ft)
Reservoir Water Chemistry TDS (mg/L)

Description of Leakage Event
CO_2 Leakage Rate (gm/sq m/day)
Event triggering leakage
Pathway for leakage
Type of release
Surface Topographic slope (m per m)
Average Surface Wind Speed (m/sec)
Average Atmospheric Stability Class
Surface Climate Type (arid; semi-arid, etc)
Surface CO_2 Concentration (ppm)
Known Human Impacts from CO_2 Releases
Known Ecosystem Impacts from CO_2 Releases

Description of CO_2 Flux Rates & Reservoir Volume
CO_2 Zone Regional Flow Rate (m/yr)
CO_2 Production Rate (cu m/yr)
CO_2 Reservoir Volume (cu m)

Description of Primary and Secondary Seals
Lithology
Zone Areal Extent (sq km)
Zone Gross Thickness (m)
Porosity (fraction)
Permeability (mD)
Capillary Entry Pressure (Mpa)

Description of Secondary Porous Zone
Lithology
Zone Areal Extent (sq km)
Depth (m)
Gross Thickness (m)
Porosity (fraction)
Permeability (mD)
Capillary Entry Pressure (Mpa)

Description of Groundwater (GW)
Regional Flow (m/yr)
Pressure (kPA)
TDS (mg/L)
Major Cation (Type-mg/L)
Major Anion (Type-mg/L)
Primary storage formation - Regional flow (m/yr)

Description of Vadose Zone
Thickness (m)
Porosity (fraction)
Permeability (mD)
CO_2 Concentration (ppm)

Surface Water Information
Depth (m)
Lake HCO_3 (mg/L)
River HCO_3 (mg/L)

Information on Faults
Number of Tectonic Faults
Number of Normal Faults
Number of Strike-Slip Faults
Fault Permeability (mD)

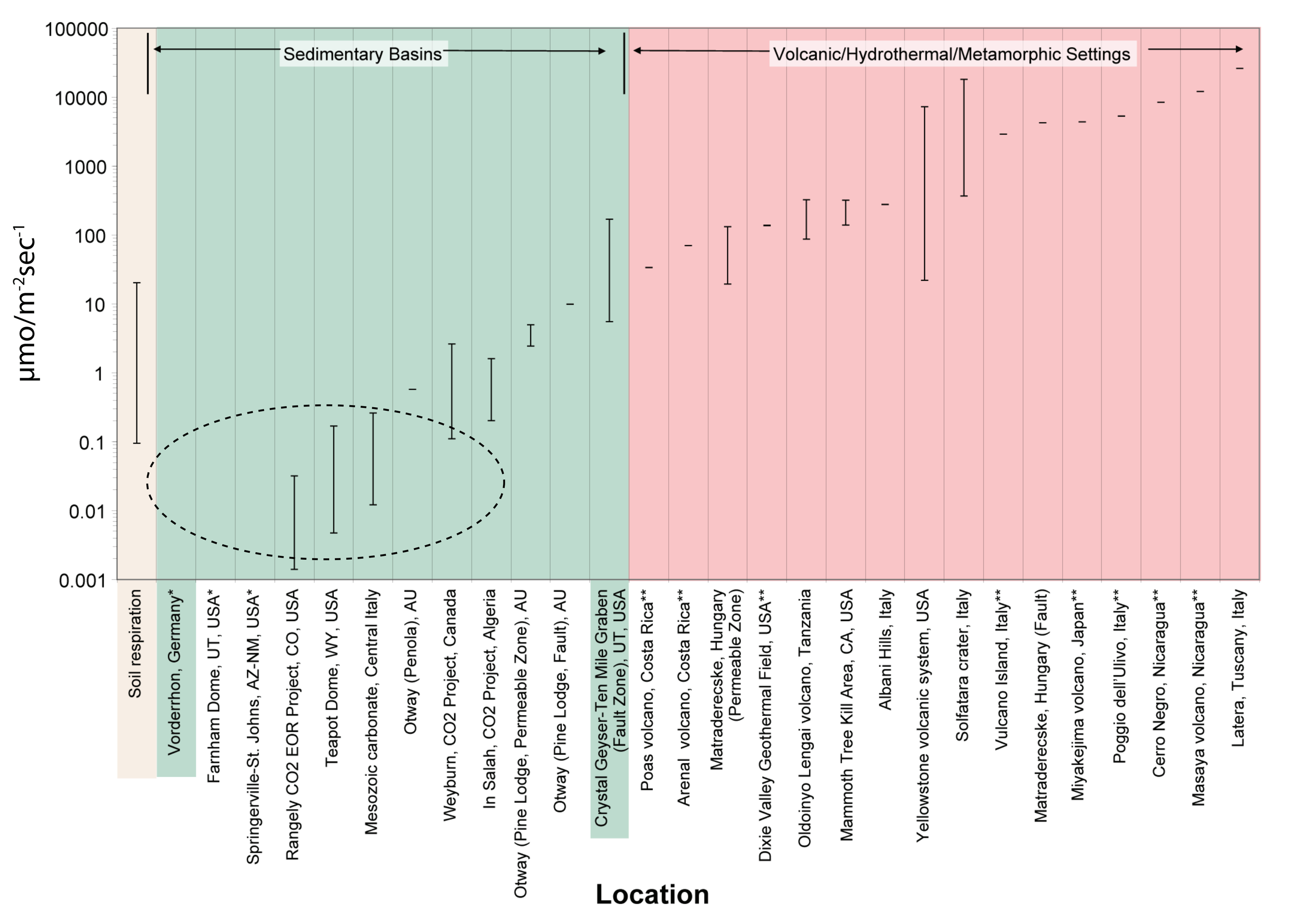
Nearby Wells
Number of Deep Wells
Number of Shallow Wells
Number of Abandoned Wells

Injection Wells
Number of Injection/Disposal Wells
Injection rate (MMt/yr)
Total reinjected (MMt)

Radon Information

References

8 CO_2 Emission Rates at 28 Analog Sites



9 Analog Site Database – Observations

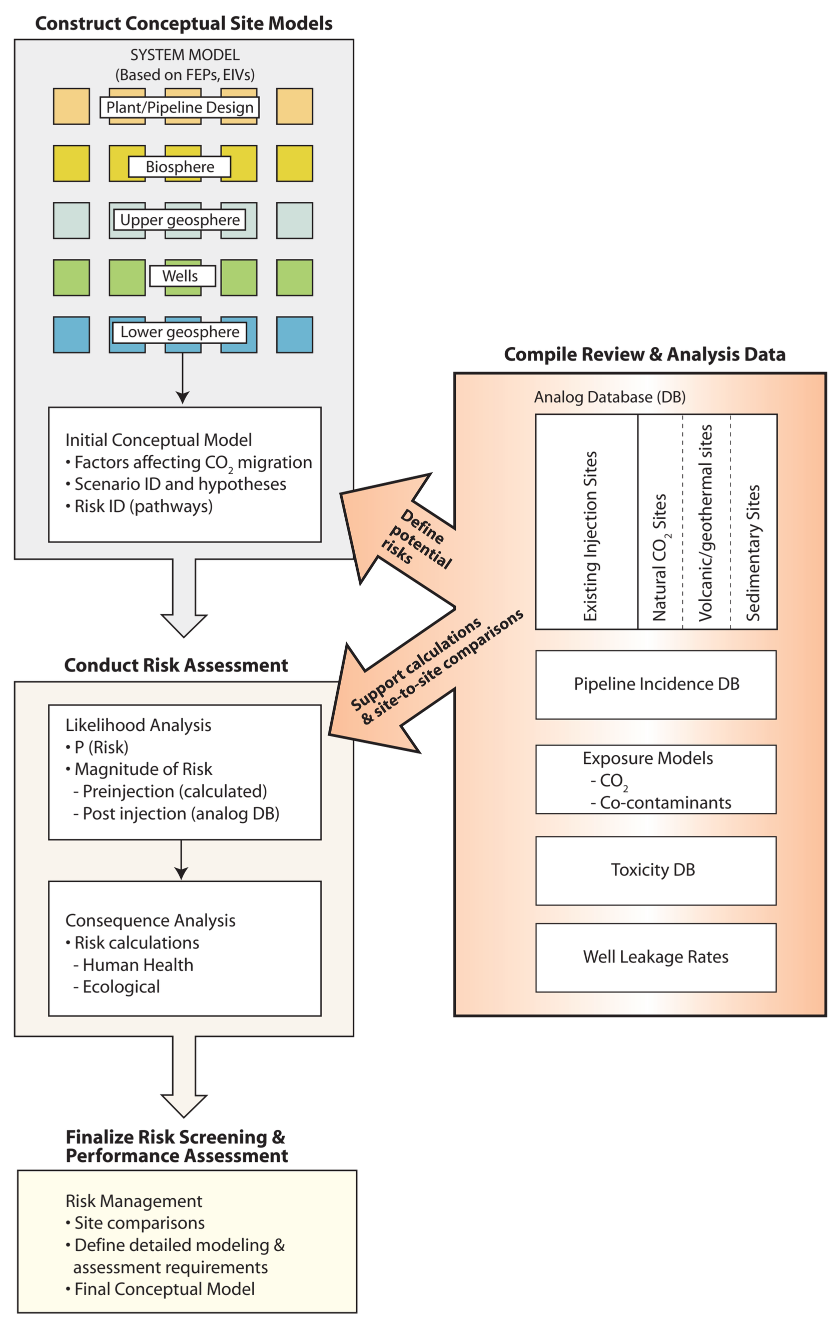
- At most locations in sedimentary basins CO_2 release rates are often below typical soil respiration rates
  - Release rates above typical soil respiration are usually associated with fault zones
- "Fractures seem to control CO_2 migration..." (IEA, 2005)
  - Unsealed fault and fracture zones may act as fast and direct conduits for CO_2 flow from depth to the surface. Determining the potential for and nature of CO_2 migration along these structures (Lewicki et al., 2006) is, therefore, important.
- Some CO_2 fields in sedimentary basins leak, usually via carbonated springs or dry seeps
  - "This results in either no ecosystem damage or only very localized ecosystem damage" (IEA, 2006)
  - "There are many CO_2 fields in sedimentary basins that have held CO_2 for millions of years without any evidence of leakage or environmental impact" (IEA, 2006)
  - "In some cases, springs are observed at faults/wells, but more commonly, CO_2 appears at the ground already dispersed to surrounding strata at very low seepage rates (IEA, 2006)"
- Changes in groundwater chemistry due to CO_2 leakage can occur due to acidification and interaction with host rocks along flow paths, but waters remained potable in most cases (Lewicki et al., 2006)
- Wells may rapidly release large quantities of CO_2, but frequency of events is historically small (1 in 100,000 per year)
  - Extrapolating historical observations gathered over relatively small time scales to the long time scales significant source of uncertainty

IEA Greenhouse Gas R&D Programme, 2005. "Natural Analogues for the Geological Storage of CO_2 (NASCENT) Report Number 2005/6, March.

Lewicki et al., 2006. "Natural and Industrial Analogues for Release of CO_2 from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned", LBNL-59784, February 2006.

IEA Greenhouse Gas R&D Programme, 2006. "Natural Releases of CO_2", Accessed July 21, 2006 at http://www.ieagreen.org.uk/glossies/naturalreleases.pdf

10 Role of Analog SiteDatabase in Risk Assessment at Four FutureGen Sites



11 Leakage Analysis for FutureGen Sites: Key Post-Injection Release Scenarios

- Upward leakage through caprock: catastrophic failure or gradual release
- Release through existing faults or induced faults
- Lateral or vertical leakage into non-target aquifers
- Upward leakage through inadequately constructed, abandoned, or un-documented wells

12 Evaluation of Gradual Release Scenario

- Release flux rates selected based on following characteristics:
  - Formation type, e.g. sandstone
  - Seal type, e.g. salt or shale and thickness
  - Depth to target formation and thickness
  - Proximity and type of faults
  - Injection pressure and
  - Stress regime in target formation
  - Likelihood of facies change in seal formation

13 Evaluation of Well Release Scenario

- Well release information compiled from natural gas storage industry, oil & gas industry, and literature on natural CO_2 resevoirs
  - Information available for fluxes from four well incidents
  - Estimates of frequency and duration based on industry experience in US and Europe
  - Leakage rate estimates obtained for two Australian CO2 sequestration sites (Hooper et al, 2005)
- Information on number, type of existing wells if present, and depth were obtained.
- Low flux rate for poorly constructed or abandoned wells set at 200 metric tons for all sites, based on low estimate for Australian sites
- High flux rate selected for the four sites based on the permeability, thickness, and depth of the target reservoir at each site
- High flux rates for poorly constructed or abandoned wells ranged from 500 to 5,000 metric tons
- Frequency of release based on estimated number of wells at each site

14 Example Leakage Rates and Frequency from Analog Sites and Database

Release Scenario	Analog Site(s)	Release Rate	Annual Frequency	P(at least 1 failure)*
Upward leakage through caprock (catastrophic failure)	Stable sedimentary formations, underground natural gas storage sites	-	2×10^{-10}	1×10^{-6}
Upward leakage through caprock (gradual release)	Teapot Dome, Farnham Dome	0 - 0.17 µmol/m2-s	4×10^{-5}	2×10^{-1}
Release through existing faults	Pine Lodge, (STOMP Model)	1 - 30 µmol/m2-s	2×10^{-8}	1×10^{-4}
Release through induced faults	Pine Lodge, (STOMP Model)	1 - 30 µmol/m2-s	2×10^{-8}	1×10^{-4}
Leakage into non-target aquifer (unknown structural/stratigraphic connections)	Crystal Geyser	5 - 170 µmol/m2-s	-	1×10^{-5}
Leakage into non-target aquifer (lateral migration)	Pine Lodge	1 - 30 µmol/m2-s	10^{-6} per 5,000 yr	1×10^{-6}
Upward Migration (undocumented deep wells)	Underground natural gas and industrial storage sites	0.2 - 11 * 103 MT per year	10^{-3} per year	9.9×10^{-1}

*Lifetime = 5,000 years

15 Summary

- Using data from analog sites, and limited site specific information, estimates of CO_2 leakage from sequestration reservoirs (gradual and catastrophic) were developed and provided the basis for estimating health risks
- Methodology was applied to four potential FutureGen sites as part of the risk assessment performed for the EIS
- The methodology is generally applicable for the permitting phase of CCS projects where very limited subsurface data might be available

16 Future Enhancements to Analog Site Analysis

- Expand analog database for key release routes
  - Expand survey of CO_2 well failures
  - Expand survey of groundwater/soil gas conditions above CO_2 reservoirs
  - Expand survey of stress and faulting in CO_2 reservoirs and leakage
- Supplement estimates of CO_2 storage capacity using volumetric calculations
  - Assign storage efficiency factors based upon geologic depositional environment, etc.
    - » Similar to determining sweep efficiency factors when estimating petroleum reserves