Risk Assessment for Geologic Carbon Sequestration in Pennsylvania

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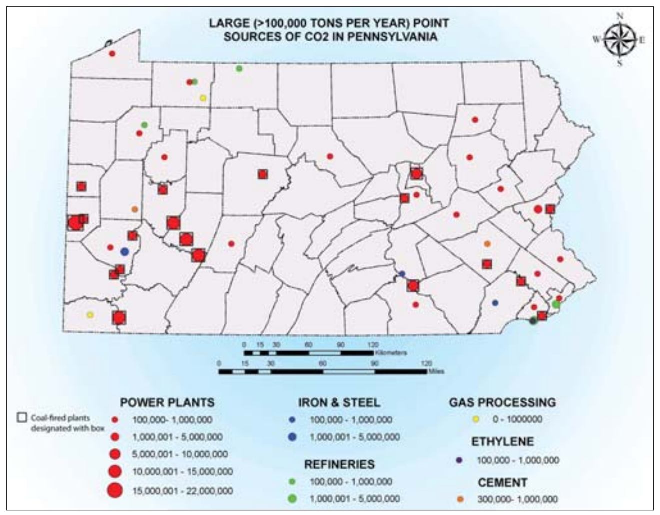
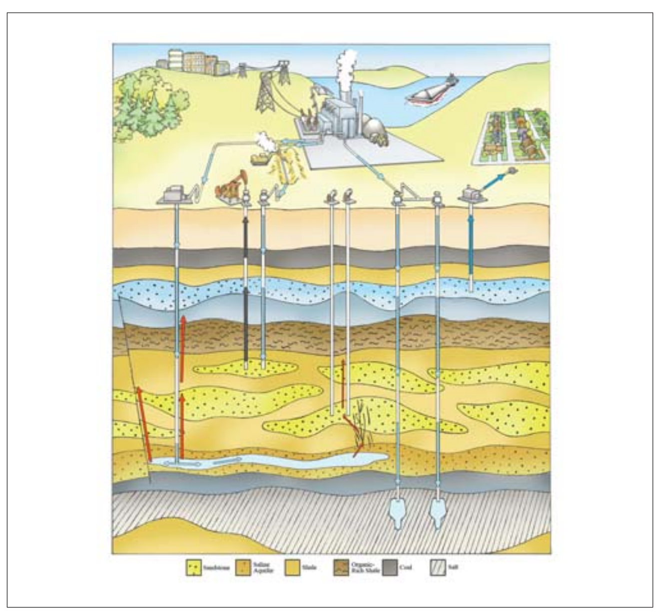
Key Technical Analysis Included:

- Integrity of primary and secondary seals of potential storage formations based on Oldenburg 2008 screening approach and analog database for subsurface releases from natural CO_2 deposits in sedimentary formations.
- Potential CO_2 leakage from large numbers of deep oil and gas wells over the past 150 years.
- Potential contamination of shallow aquifers if releases of CO_2 occur along faults, fracture zones, or improperly sealed wells.
- Storage capacity in salt bed caverns and potential impacts.
- Potential releases from CO_2 pipelines and estimating human health impacts using modeling.



Major CO_2 sources in Pennsylvania highlighting coal power plants with >1 MT/yr CO_2 emissions



Geologic storage reservoirs and potential release mechanisms

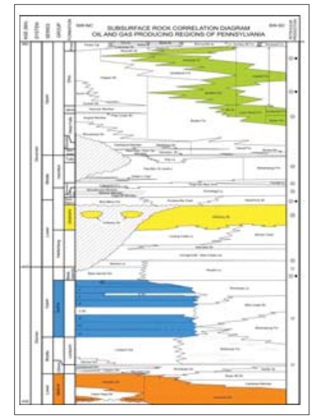
Tools Used for Screening Assessment of Subsurface Releases

- Spreadsheet analysis developed by LBNL (Oldenburg, 2008) that estimates the integrity of the candidate formation to store CO_2, in the absence of wells that might penetrate the formation.
- Analog database that can be used to predict CO_2 releases based on similarities with the candidate storage reservoirs, developed by Tetra Tech for FutureGen Risk Assessment (DOE, 2007).
- Vulnerability evaluation framework (VEF) that addresses issues of specific concern (US EPA, 2008).

Example using Screening and Ranking Framework (SRF) (Oldenburg, 2008)

SRF evaluates three basic characteristics of a geological storage site:

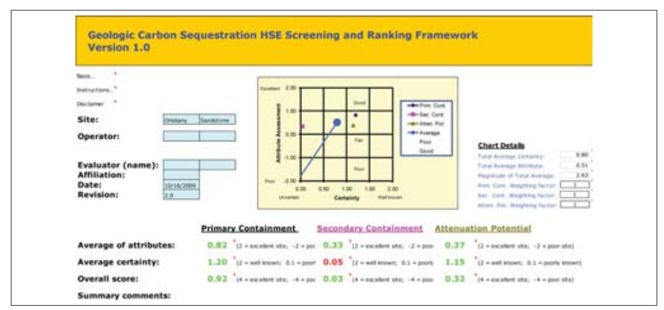
1. Potential of target formation to maintain long-term containment of CO_2.
2. Potential for secondary containment if the primary seal leaks.
3. Potential of the site to attenuate or disperse leaking CO_2 if the primary formation leaks and secondary containment fails.



Potential Geologic Storage Formations in Pennsylvania

Example Site Analysis for Oriskany Sandstone Formation

- Target Storage Formation: Oriskany Sandstone at depth of about 6800 ft below the surface.
- Primary Seal: Needmore Shale and secondary seal: Marcellus Shale Formation.
- Analysis indicates good primary containment, while secondary containment and attenuation factors are fair, with relatively high uncertainties.
- Limitations are that does not account for faults and deep wells.



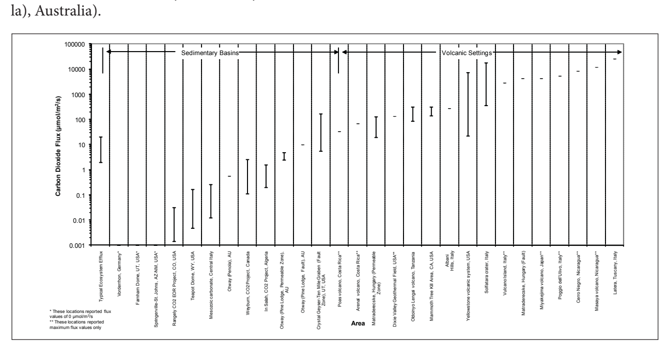
CO_2 fluxes from both natural and EOR sites in sedimentary basins

Fluxes were measured that are essentially zero at three sites (Vorderrhon, Germany; Farnham Dome, Utah; and Springerville-St. Johns, Arizona-New Mexico)

Fluxes were measured at 0.01 to 1 µmol/m²-s at four sites (Rangely CO_2 EOR Project, Colorado; Teapot Dome, Wyoming; Mesozoic carbonate site in Central Italy; and Otway (Penola), Australia).

Fluxes were measured at to 1 to 10 µmol/m²-s at four sites (Weyburn, CO2 Project, Canada; In Salah, CO_2 Project, Algeria; Otway (Pine Lodge, Permeable Zone and Pine Lodge, Fault, Australia).

Fluxes were measured at 5 to 170 µmol/m²-s at Crystal Geyser-Ten Mile Graben (Fault Zone), Utah.



CO_2 emission rates for 28 analog sites (DOE, 2007).

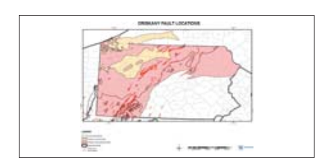
Comparison of CO_2 Release Rates from Natural Sandstone Sites and Potential Site

Category	Potential Site Oriskany	Farnham Dome, Utah	Teapot Dome, Colorado
CO_2 zone depth, m	2,000	900	1,600
CO_2 zone lithology	Oriskany Sandstone	Jurassic Navajo Sandstone	Pennsylvanian Sandstone
CO_2 zone thickness, m	10-20	12-100	Unknown
CO_2 zone porosity	0.05	0.12	Unknown
CO_2 zone permeability, md	2.2	>100(?)	Unknown
Gradual leakage flux, µmole/m²-s	Likely to be Background (0.1 to 10)	Reported as 0	0.00482 to 0.1688

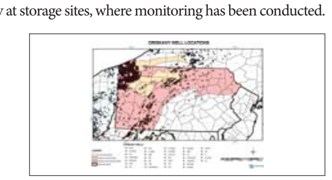
Post-Sequestration Risk Assessment Results Based on Analog Database (DOE, 2007)

Release Scenario	Exposure Duration	Potential Volume	Initial Release to	Receptors	Conclusions
Upward leakage through the cap rock due to catastrophic failure and quick release	Short-term	Variable, could be large	Air	Humans Ecological	See Note 1*
Upward leakage through the cap rock due to gradual failure and slow release	Long-term	Small	Air, ground-water	Humans Ecological	See Note 2
Upward leakage through the CO_2 injection well(s)	Short-term and long-term	Variable, could be large	Air, ground-water	Humans Ecological	See Note 3
Upward leakage through deep oil and gas wells	Short-term and long-term	Variable, could be large	Air, ground-water	Humans Ecological	See Note 4
Upward leakage through undocumented, abandoned, or poorly constructed wells	Short-term and long-term	Variable, could be large	Air, ground-water	Humans Ecological	See Note 5
Release through existing faults due to the effects of increased pressure	Long-term	Variable, could be large	Air, ground-water	Humans Ecological	See Note 6
Release through induced faults due to the effects of increased pressure	Long-term	Variable, could be large	Air, groundwater	Humans Ecological	See Note 7
Lateral or vertical leakage into non-target aquifers due to lack of geochemical trapping	Long-term	Variable	Groundwater	Humans Ecological	See Note 8
Lateral or vertical leakage into non-target aquifers due to inadequate retention time in the target zone	Long-term	Variable	Ground-water	Humans Ecological	See Note 9
Radon release	Long-term	Low	Ground-water	Humans Ecological	See Note 10

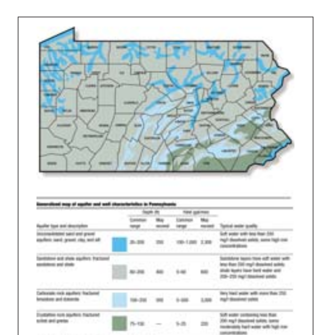
1. This type of release has been documented to occur only at VHM settings, and not in sedimentary formations of the type investigated here. Risks from this type of release are negligible.
2. Leakage rates for sedimentary basins are expected to be near natural soil respiration levels (0.1 to 10 µmole/m²-s) and not to cause risks.
3. Upward leakage through the injection wells has occurred. If many injection wells are needed per site, probability of at least one failure increases. Potential risks could result, but modeling shows impact area small.
4. Many deep oil and gas wells that could penetrate the seal and storage formation exist in much of western and northern Pennsylvania (PA DCNR database). Thus, CO_2 leakage from these wells could occur.
5. Due to the long history of oil and gas exploration in Pennsylvania, many abandoned wells may exist. Proper abandonment procedures needed in vicinity of site to reduce potential leakage pathway.
6. Faults do exist throughout much of Pennsylvania, particularly in western area. Releases through faults possible due to effects of increasing pressure, but depends on location and formations affected.
7. See Note 6. Should such faults be induced, however, they may not reach the surface. CO_2 release would be attenuated along the pathway.
8. Based on analog database, leakages are expected to be similar to natural soil respiration levels (1-10 µmoles/sec). However this amount of CO_2 could potentially leak into non-target aquifers. Site-specific data needed for evaluation.
9. See Note 8. Site-specific data needed for detailed evaluation.
10. Radon releases have not been known to intensify at storage sites, where monitoring has been conducted.



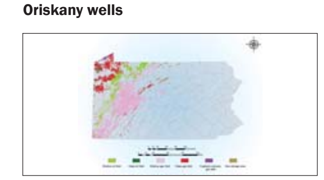
Oriskany faults (PA DCNR GIS database)



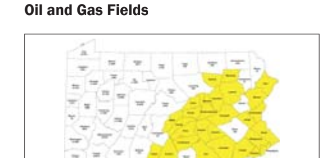
Oriskany wells



Four major aquifer types in Pennsylvania (PA Geological Survey, 1999 from EPA, 2008)



Oil and Gas Fields

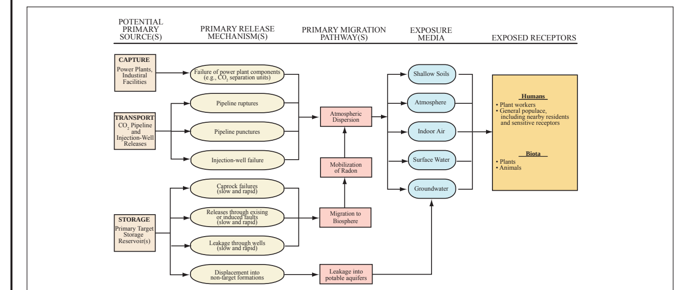


Oil and gas wells >2,500 ft by county; counties without such wells shown in yellow (Data from Well Information System, 2009)

US EPA's Vulnerability Framework

Main attributes included in VEF (EPA, 2008) used to evaluate four formations are as follows:

- Faults and fracture zones,
- Other tectonic or geothermal activity,
- Wells,
- Potable groundwater,
- Radon, and
- Surface water.



Vulnerability Factors by CO_2 Storage Formation

Category	Medina Group	Salina Group	Oriskany Sandstone	Upper Devonian
Faults and Fracture Zones				
Earthquakes (last one 1.3 magnitude at 1 km located 15 miles SSW of Harrisburg)	not since 1990	not since 1990	unknown	not since 1990
Induced Faulting/Seismicity	possible in NW	low seismicity	possible in NW	low seismicity
Ground Dilation	Low-Thick rock formation	Possible if subsidence of salt beds occur	Low-Thick rock formation	Low-Thick rock formation
Other Tectonic Activity				
Deep faults present	few deep faults	none identified	faults in SW & Central to North Central part	none identified
Geothermal activity	None	None	None	None
Wells				
Oil and Gas Wells	High[1]	High[1]	Many wells in NW and central SW-N swath, High[1]	High[1]
Abandoned or Unknown Wells	Unknown[2]	wells in SW, Unknown[2]	Unknown[2]	Unknown[2]
Deep Water Supply Wells	Due to aquifer depths < 500 ft, deep water supply wells are likely to be more than 2000 ft above CO_2 storage locations			
Potable Groundwater				
Migration to USDW	The potential storage formations are 2000 ft or more below USDWs and vertical migration of CO_2 into those formations unlikely, although uncertainty level is high. There is high density of oil & gas wells that needs to be considered.			
Displacement of Brine into USDW	Because potential storage formations are 2000 ft or more below USDWs and multiple seals present, brine displacement is unlikely to affect USDWs.			
Radon	No evidence of enhanced radon migration at few CCS sites where measured.			
Surface Water				
Migration into SW	The probability of direct migration into surface water is uncertain, but unlikely due to depth of storage formations (>2500 ft).			
Leakage into SW	The probability of leaks into surface water is uncertain. However, Pennsylvania has over 80,000 miles of surface water, indicating analyses for pipeline routes needed.			
Changes to Human Health and Environment Due to Above Categories	Possible human health and environmental impacts			

1. Oil and gas wells at depths of greater than 2500' are plentiful, and may offer conduits for leakage.
2. Little is known about abandoned wells, but due to long history may be present; could serve as conduit for leakage.

Potential for Subsurface Releases after Injection

1. The spreadsheet approach (Oldenburg, 2008) showed that Oriskany Sandstone has suitable primary seal; secondary seal and attenuation mechanisms were more uncertain.
2. Due to many oil and gas wells > 2500 ft deep (minimum depth for carbon storage sites), there is increased risk that wells can act as conduits for CO_2 leakage. Such wells need to be located and properly plugged.
3. If gradual releases of CO_2 from sedimentary storage sites occur through cap rock, releases likely to be small,l in the range of natural background respiration rates.
4. Widespread use of groundwater as water supply indicates need for detailed evaluation of potential releases along faults, fracture zones, or improperly sealed wells.
5. Appropriate site selection is key to reducing potential risks.
6. Monitoring in all phases of carbon capture and storage is important.