CO_2 Storage Lecture
Carnegie Mellon University

19-656 Mini Course:
CO_2 Capture and Sequestration

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NETL Office of Program Performance & Benefits

February 17, 2015

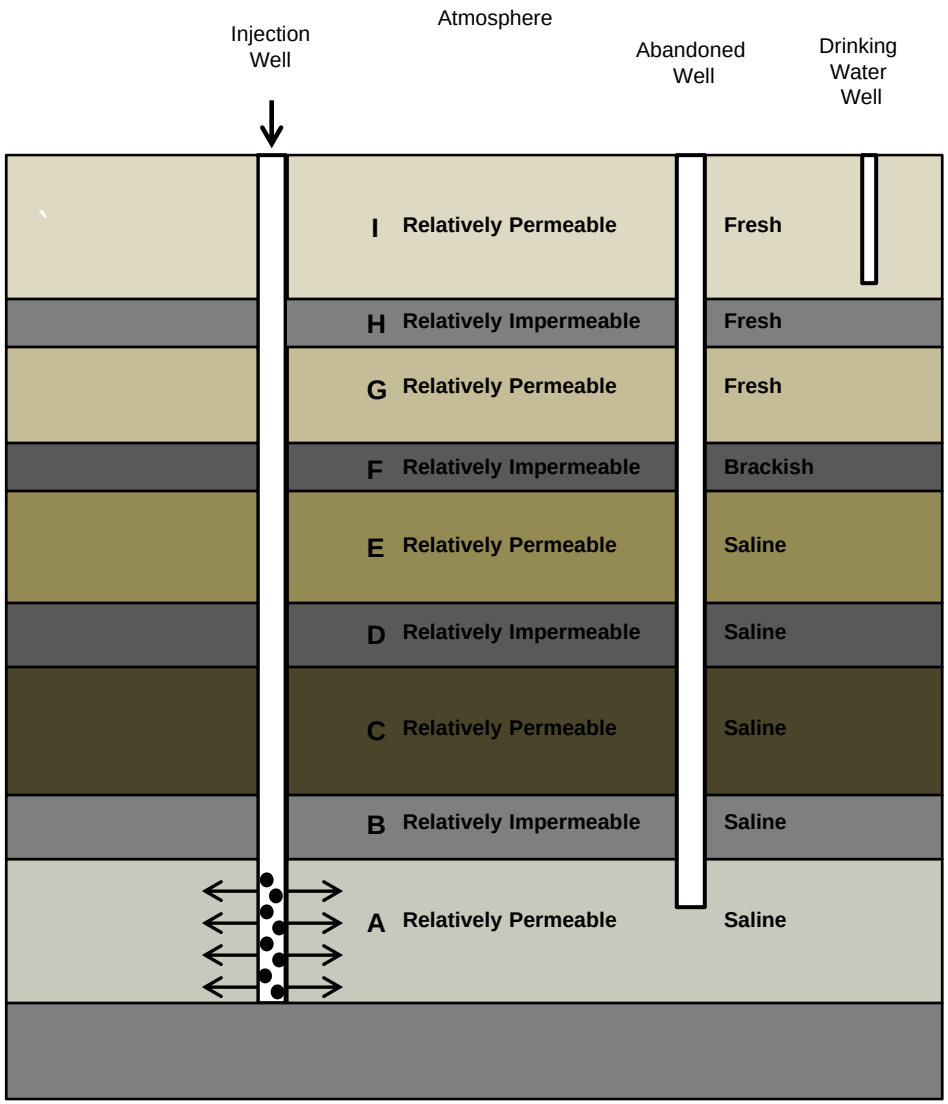
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

DOE/NETL-2015/1704

Why Do CO_2 Storage?

- **Mitigate climate change**
- **Clean coal technology**

What is CO_2 Storage?



Source: NETL.

- **Find a deep, relatively permeable, saline aquifer with a relatively impermeable cap rock**
- **Install deep injection wells**
- **Inject CO_2 into deep, saline formation**

A Little Background Material

- **Geology**
- **Properties of CO_2**
- **CO_2 storage concepts**
- **Environmental risks from CO_2 storage**
- **CO_2 storage regulations and design considerations**
  - Area of Review (AoR)
  - Financial Responsibility
- **Class VI permitting activity**
- **Modeling CO_2 storage costs**

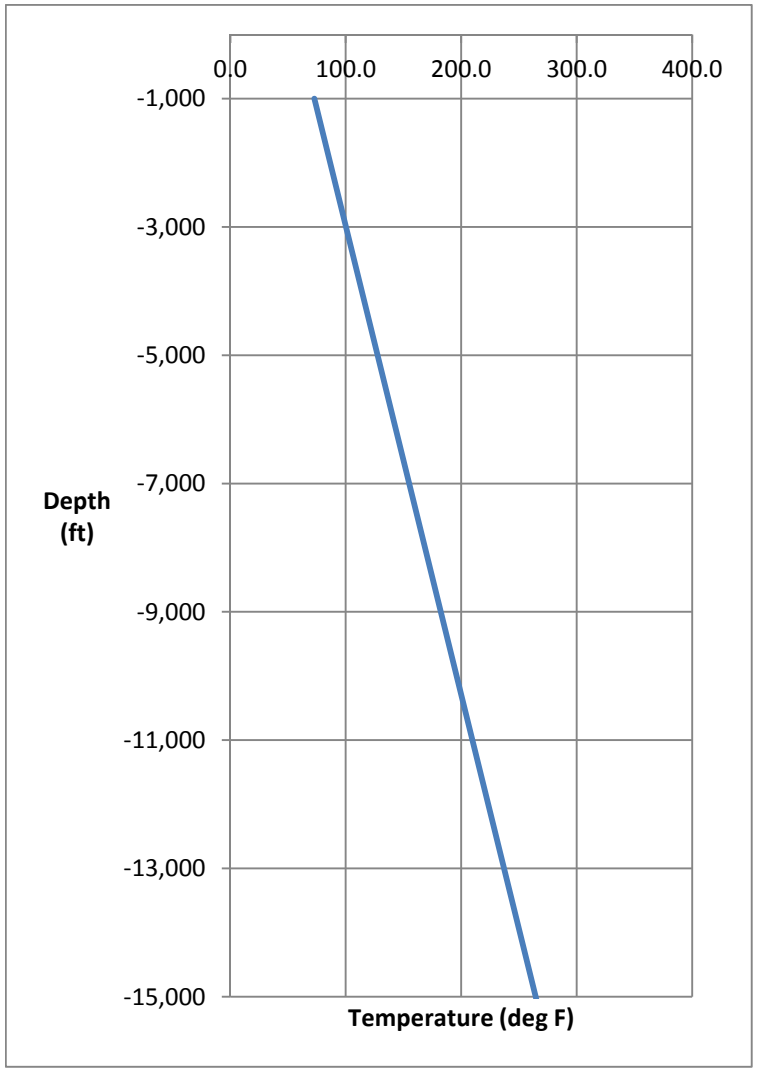
Geology

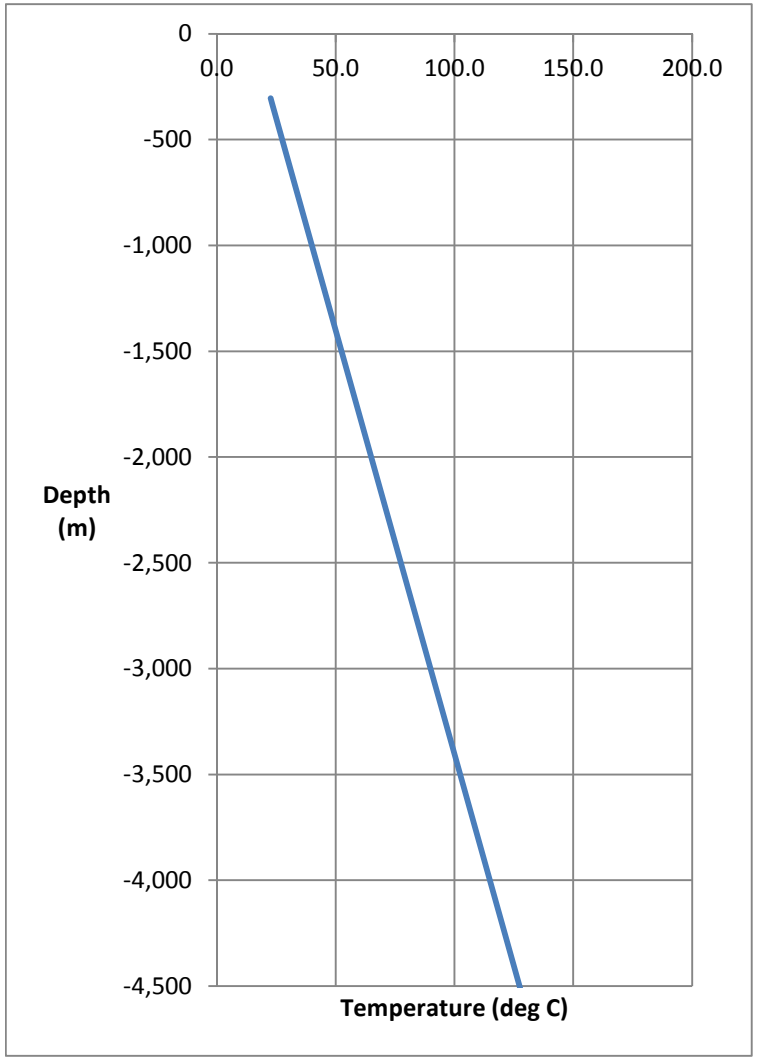
- **Subsurface consists of layers of rocks (formations) with each layer having different properties**
- **Key properties:**
  - Thickness (h) (thicker is better)
  - Porosity (ϕ) or fraction of total rock volume that is void space and can be occupied by fluids (higher is better)
  - Permeability (k) or tendency of rock to allow fluid to flow through it (higher is better)

Geology

- **Pressure generally increases with depth**
  - Lithostatic pressure (weight of rock)
    - 1 psi/ft
  - Fracture pressure (pressure needed to fracture rock)
    - Approximately 60% of lithostatic pressure
  - Hydrostatic pressure (weight of water/brine)
    - 0.464 psi/ft
- **Temperature generally increases with depth**
  - 1.37 deg F/100 ft
- **Salinity also tends to increase with depth**
  - Increase with depth not as systematic as temperature and pressure
  - Can be greater than salinity of ocean (30,000 ppm)
  - Underground sources of drinking water (USDWs) defined as less than 10,000 ppm
  - Fresh water is less than 500 - 1,000 ppm

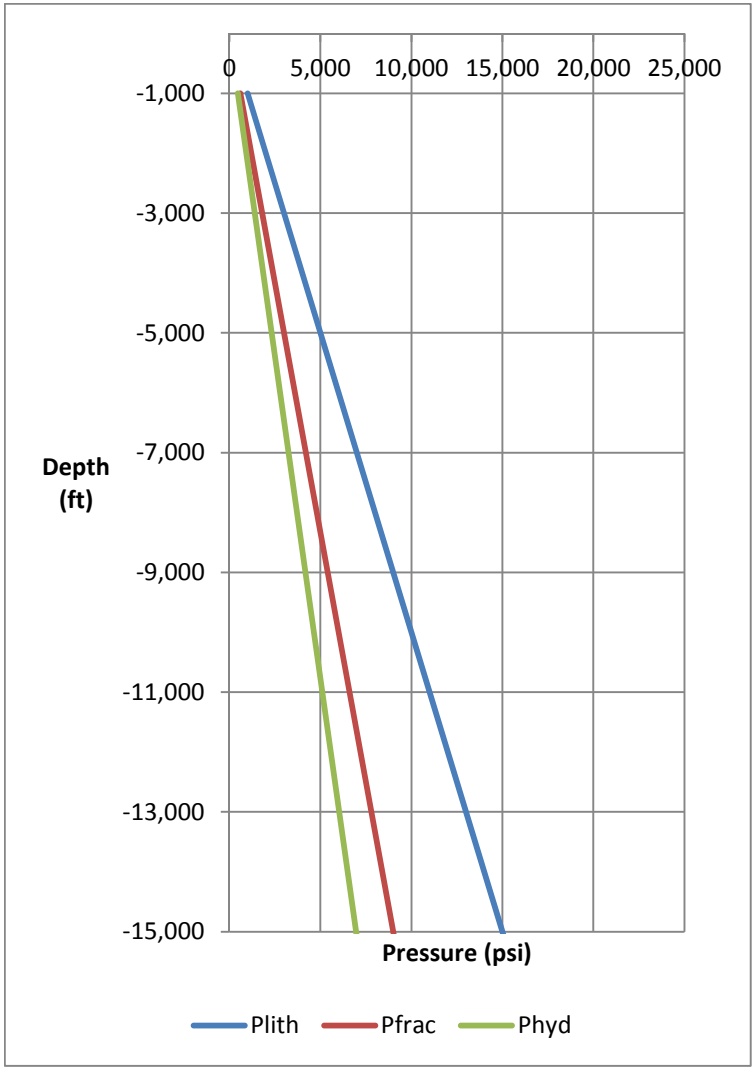
Temperature as Function of Depth

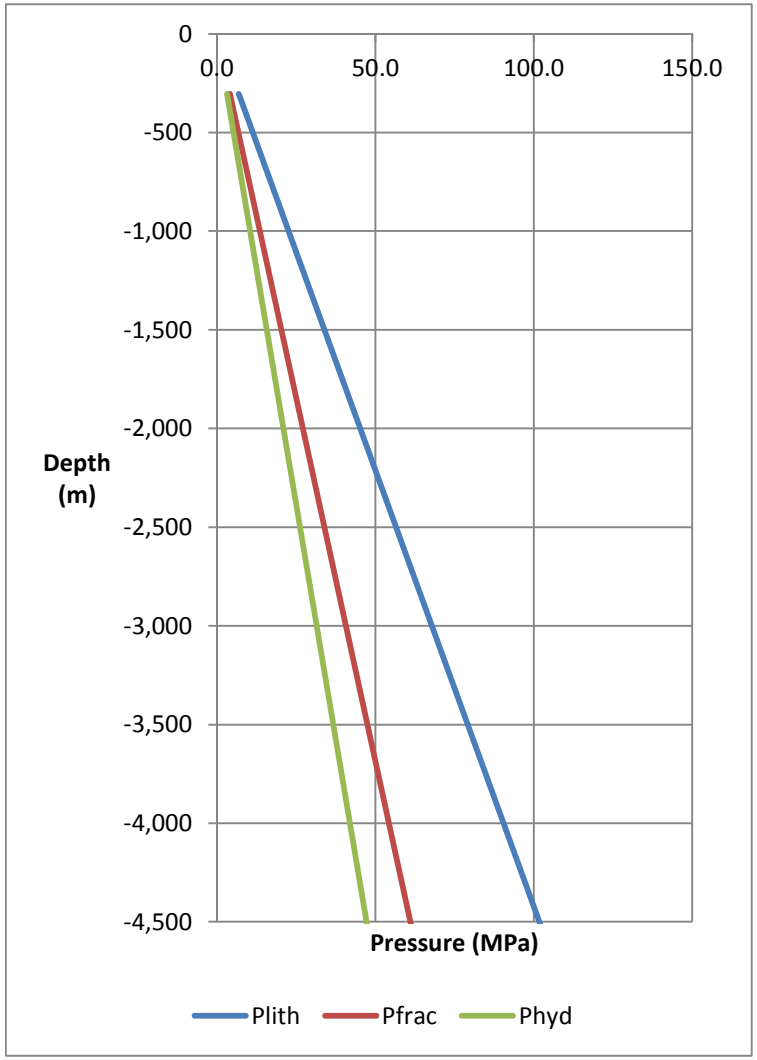




Source: NETL.

Pressure as Function of Depth





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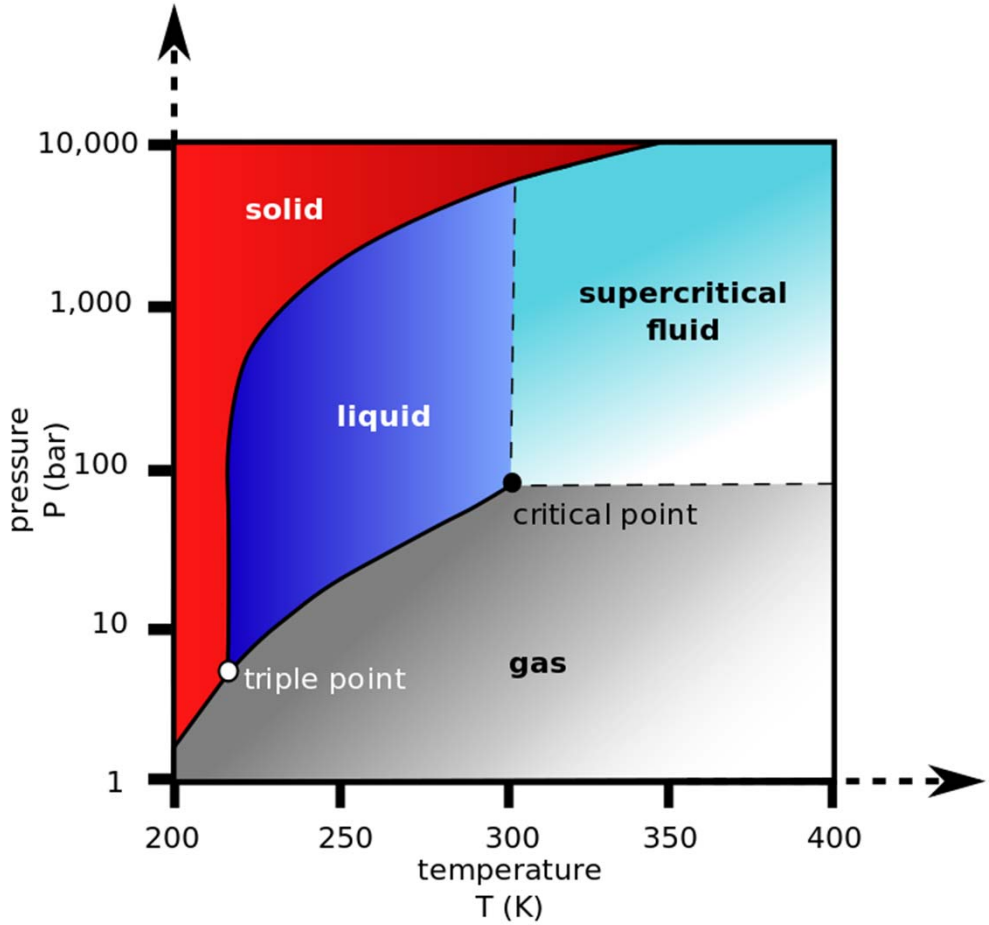
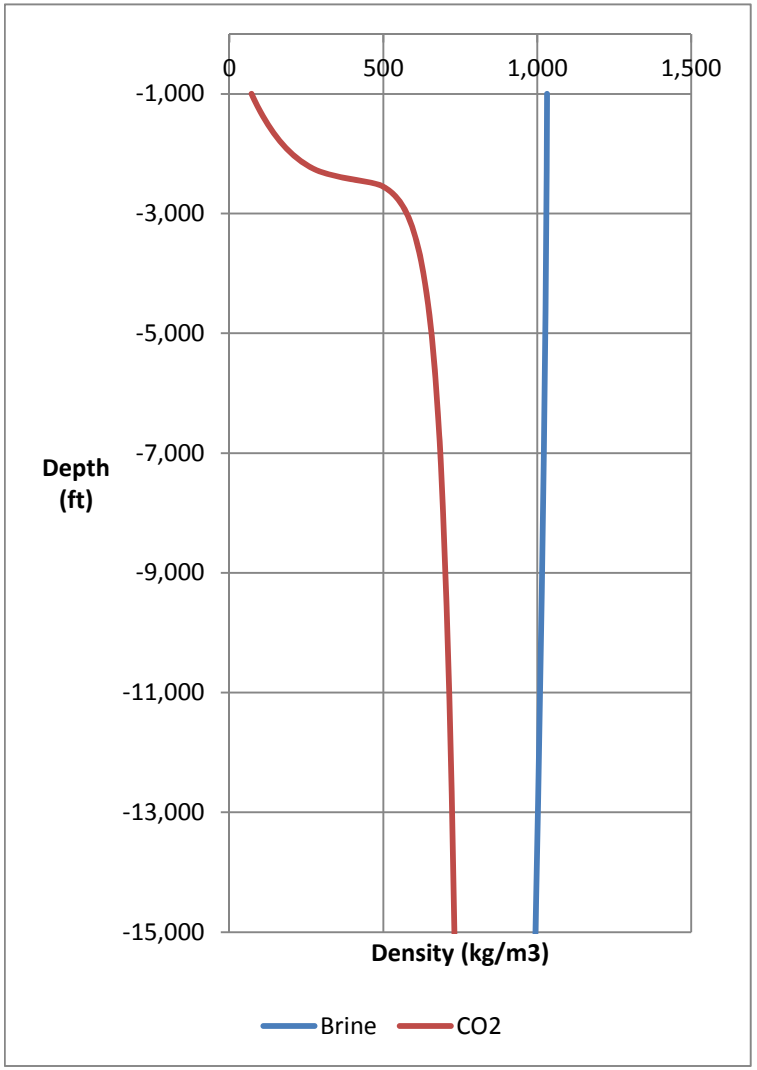
Properties of CO_2

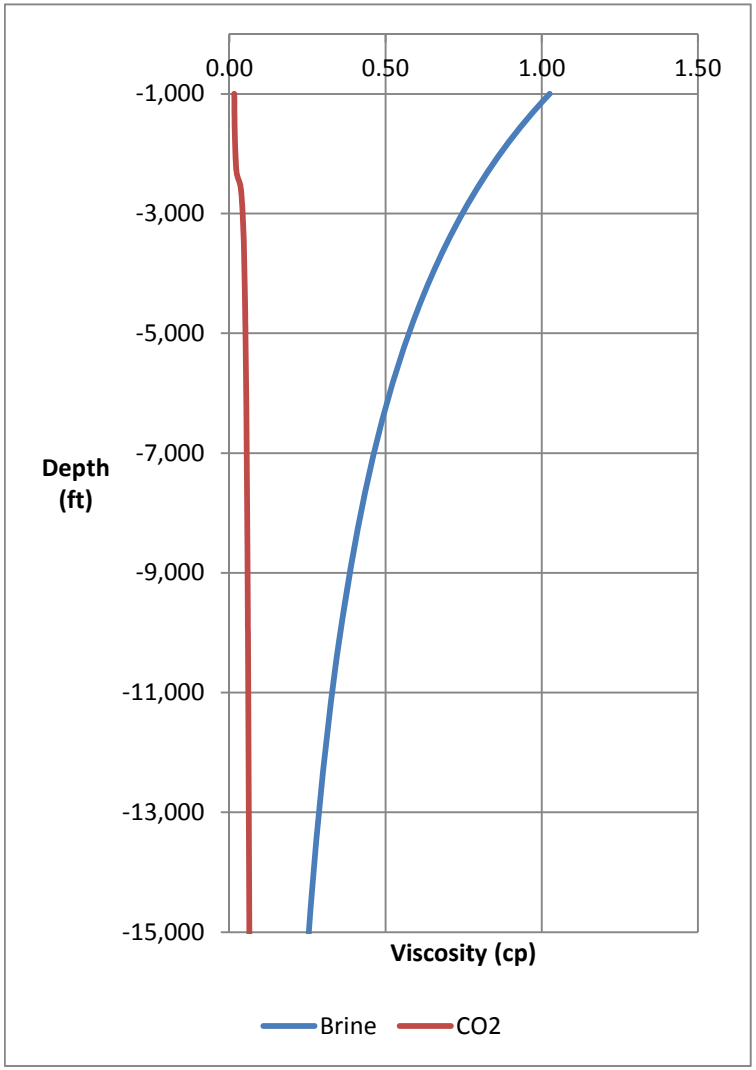


- **Critical point**
  - 7.38 MPa or 1,071 psi
  - 31.1 deg C or 88 deg F
- **Storage generally done when CO_2 is supercritical fluid**
- **CO_2 is supercritical at depths greater than 2,300 to 2,800 feet, approximately**

Source: Wikipedia, http://en.wikipedia.org/wiki/File:Carbon_dioxide_pressure-temperature_phase_diagram.svg
This diagram is in the public domain according to the licensing section of this website.

Density and Viscosity of CO_2 and Brine as Functions of Depth



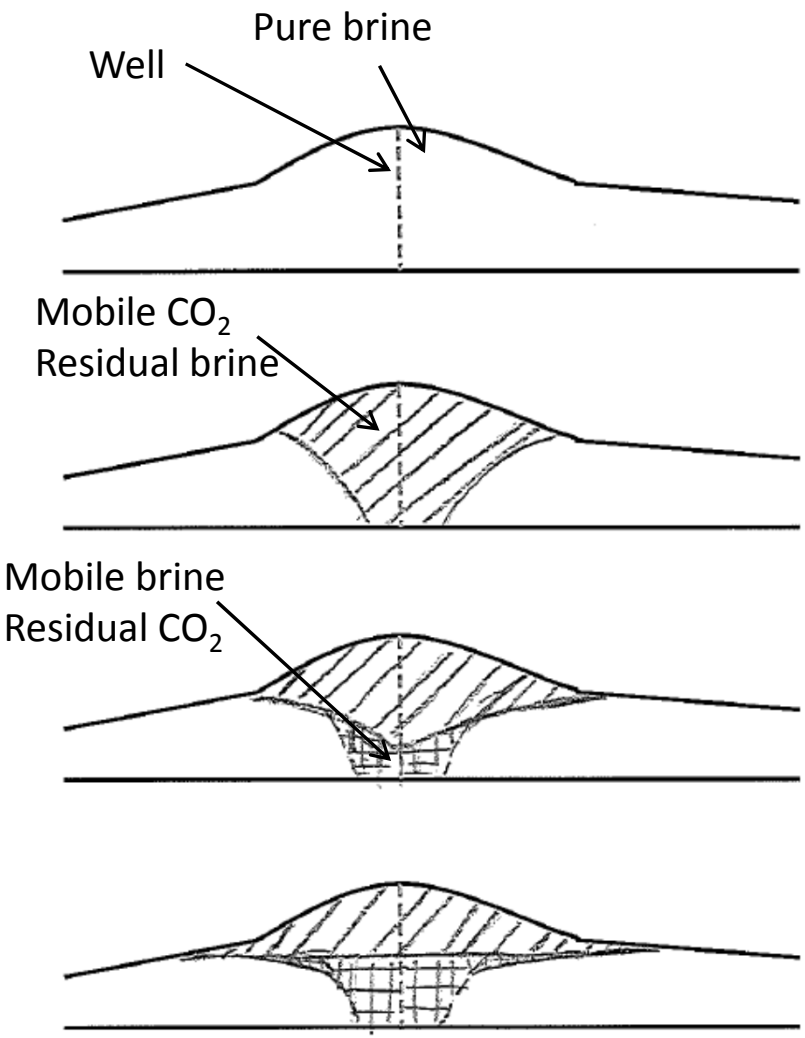


Source: NETL.

CO_2 Storage Concepts

- **CO_2 and brine flows follow Darcy's law for flow in porous media**
  - $\boldsymbol{q} = -\frac{\boldsymbol{k}}{\mu}\left(\boldsymbol{\nabla} p - \rho \boldsymbol{g}\right)$
  - where:
    - **q** = volumetric flux of fluid (vector) (m^3/m^2-s)
    - **k** = permeability tensor (m^2)
    - μ = viscosity (Pa-s or kg/m-s)
    - p = pressure (Pa or kg/m-s^2)
    - ρ = density of fluid (kg/m^3)
    - **g** = acceleration due to gravity (vector) (9.81 m/s2)

CO_2 Storage Concepts



Source: NETL.

- **Initially** only brine in formation

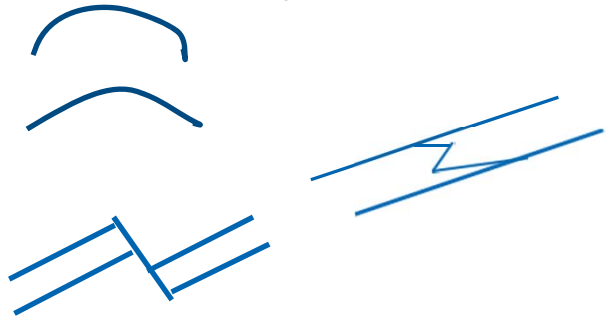
- **During injection**, CO_2 displaces brine
- Injection pressures drive fluid movement
- Residual, immobile brine remains as CO_2 migrates (10 to 30% of pore space)
- Elevated pressures extend well beyond CO_2 plume

- **After injection**, CO_2 moves up and out (buoyancy important for movement)
- Residual, immobile CO_2 remains as brine replaces CO_2 (10 to 30% of pore space)
- Pressure declines rapidly at first

- **After a long time**, CO_2 movement stops when constrained by structure or present at residual, immobile saturations
- Pressure declines slowly to ambient pressures

CO_2 Storage Concepts

- **Trapping mechanisms for CO_2**
  - Structural: Mobile CO_2 is prevented from migrating by cap rock or structural closures (immediate)
    - Dome (inverted bowl)
    - Anticline (folded paper)
    - Stratigraphic
    - Closure against a fault

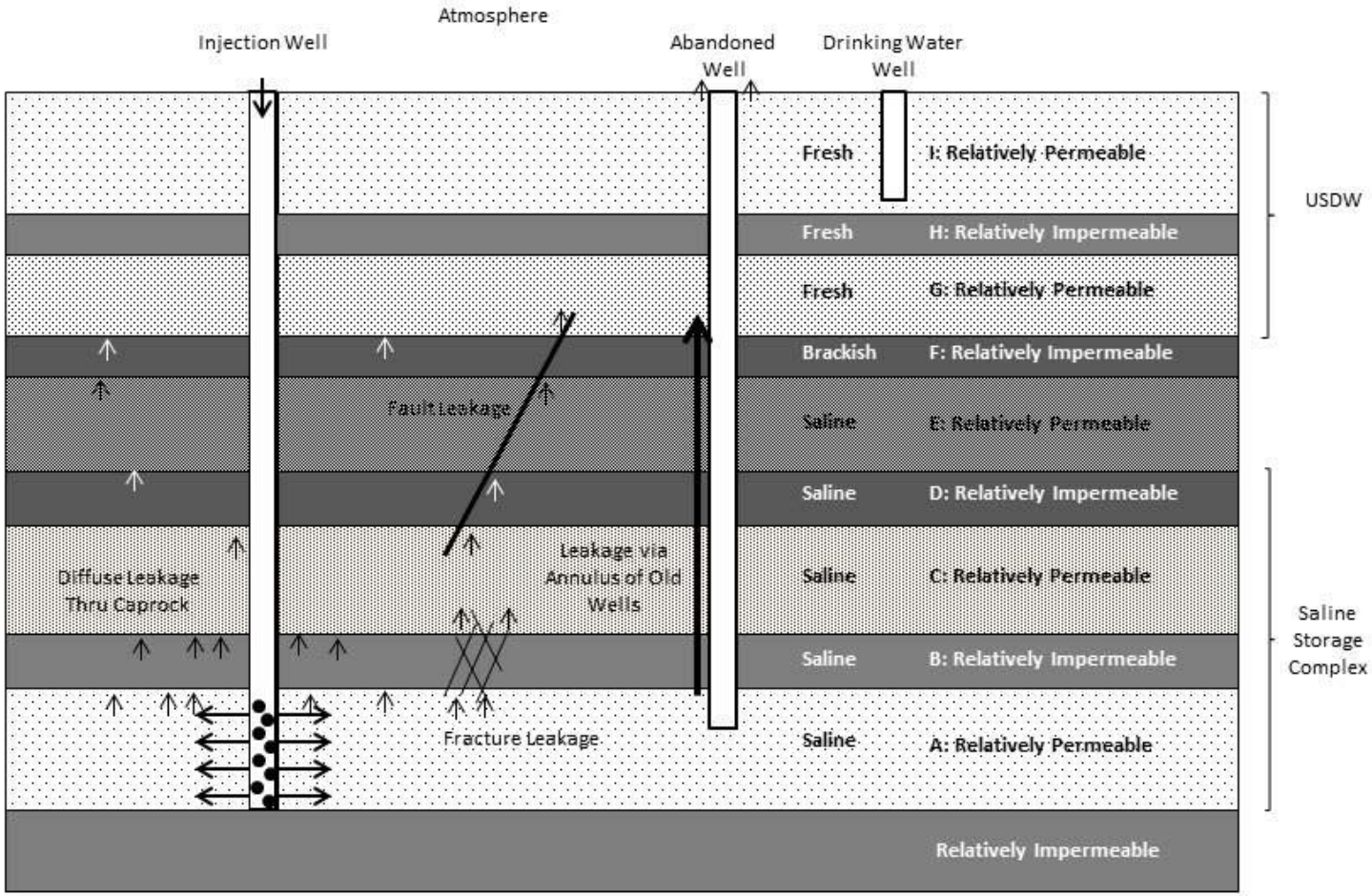


  - Capillary: CO_2 is immobilized by capillary forces (residual CO_2 saturation) (immediate to 5,000 years)
  - Dissolution: CO_2 dissolves in brine (100 to 10,000 years)
  - Mineralization: CO_2 reacts with chemicals in brine and rock to form precipitates (500 to 50,000 years)

Environmental Risks and EPA Regulations

- **Risks associated with CO_2 storage**
  - Pressure or buoyancy driven leakage of CO_2 from injection formation to USDW
    - CO_2 decreases pH (CO_2 is weak acid)
    - Decreasing the pH changes the water chemistry and can cause enhanced dissolution or precipitation of certain constituents, such as metals, but this is highly site specific
  - Pressure driven leakage of brine from injection formation to USDW
  - Leakage of CO_2 to atmosphere
  - Induced seismicity (low magnitude seismic events due to pressurization)
- **EPA regulations**
  - Class VI injection well regulations under Safe Drinking Water Act to protect USDWs
  - Subpart RR of Greenhouse Gas Reporting Rule under Clean Air Act to measure and report emissions of greenhouse gases (i.e., CO_2) to atmosphere
  - EPA regulations do not explicitly address induced seismicity

Environmental Risks

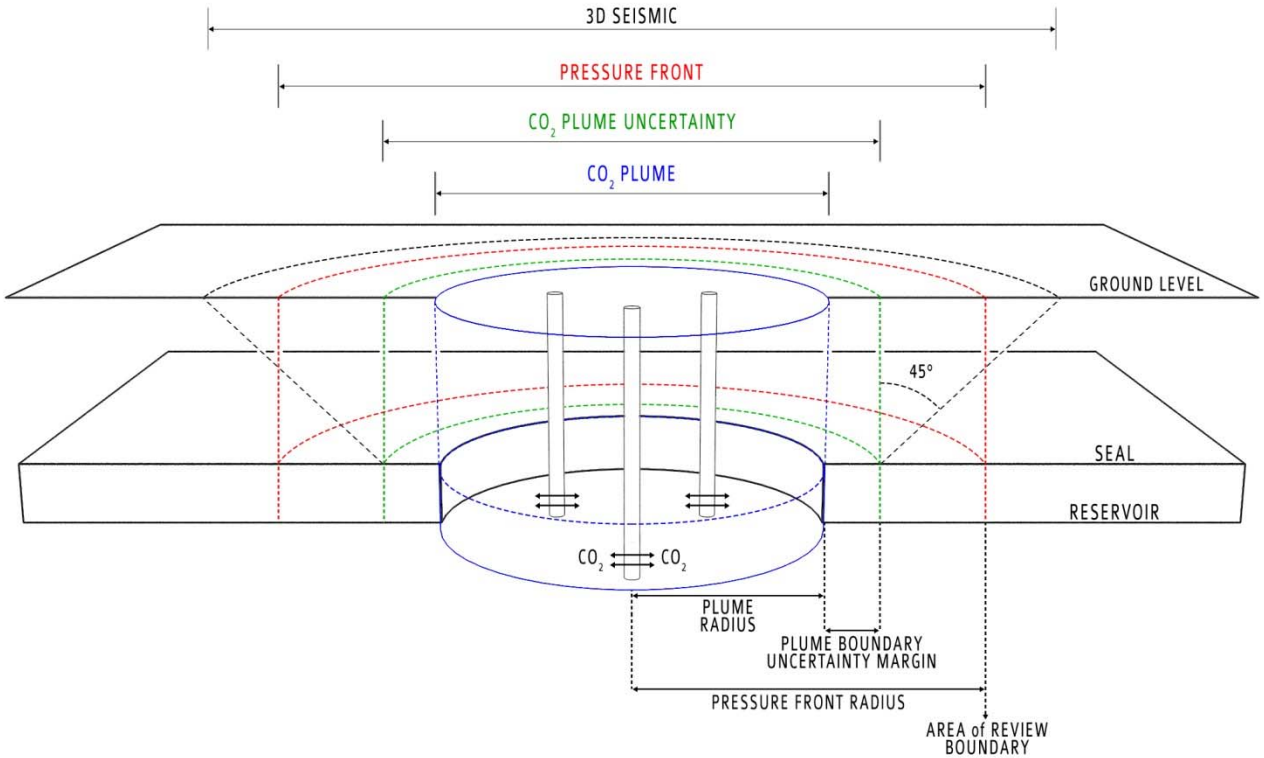


Source: NETL.

Design and Cost of CO_2 Storage Project

- **Concepts presented are from FE/NETL CO_2 Saline Storage Cost Model**
  - Links to model on NETL website are at end of presentation
  - Includes costs of implementing and operating storage site
  - Includes costs of complying with Class VI injection well and Subpart RR
- **Basic design parameters**
  - Mass of CO_2 injected
    - Maximum hourly or daily rate
    - Average rate per year
  - Duration of injection
- **Critical design values**
  - Area of the CO_2 plume and pressure front
    - Calculated with numerical reservoir simulation models
    - Calculated using simplified engineering equations
  - Number of injection wells
    - Determined through reservoir simulation models
    - Calculated using simplified engineering equations

Areal Quantities Relevant to Design



- **CO_2 Plume Area**
- **CO_2 Plume Uncertainty Area**
- **Pressure Front Area**

Source: NETL.

Estimating Areal Quantities

- **CO_2 Plume Area**
  - $A_{pl} = \frac{q_{m-CO2} \cdot T_{inj}}{\rho_{CO2} \cdot h \cdot \phi \cdot e_{st}}$
  - where:
    - A_{pl} = CO_2 Plume Area (m^2)
    - $q_{m\text{-}CO2}$ = annual average mass rate of CO_2 injection (kg/year)
    - T_{inj} = duration of the injection (years)
    - ρ_{CO2} = density of CO_2 at reservoir temp. and press. (kg/m^3)
    - h = thickness of formation (m)
    - ϕ = porosity
    - e_{st} = storage coefficient

Estimating Areal Quantities

- **CO_2 Plume Uncertainty Area**
  - $A_{pl-un} = A_{pl} \cdot a_{pl-un}$
  - where:
    - A_{pl-un} = CO_2 Plume Uncertainty Area (m^2)
    - A_{pl} = CO_2 Plume Area (m^2)
    - a_{pl-un} = CO_2 plume uncertainty factor (1.75)
- **Pressure Front Area**
  - $A_{pf} = A_{pl-un} \cdot a_{pf}$
  - where:
    - A_{pf} = Pressure Front Area (m^2)
    - A_{pl-un} = CO_2 Plume Uncertainty Area (m^2)
    - a_{pf} = pressure front multiplier (10)

Number of Active Injection Wells Needed

- **Number of active injection wells**
  - $N_{injw} = q_{maxCO2proj}/\min(q_{mmaxf}, q_{mmaxw})$
  - where:
    - N_{injw} = number of active injection wells
    - $q_{maxCO2proj}$ = maximum daily mass rate of CO_2 that injection project needs to accommodate (design parameter) (tonne/day)
    - q_{mmaxf} = maximum rate of flow that formation can sustain from one injection well
    - q_{mmaxw} = maximum rate of flow that injection well tubing can sustain (based on well mechanics), estimated to be 3,660 tonnes/day

Number of Active Injection Wells Needed

- **Law and Bachu (1996) equation for maximum mass flow rate the formation can sustain**
  - $q_{mmaxf} = a_{LB} \cdot k \cdot h \cdot (p_{max} - p_{amb})/\mu_{CO2}$
  - where:
    - q_{mmax} = maximum mass rate of CO_2 flow that formation can sustain from a single injection well (tonne/day)
    - a_{LB} = Law and Bachu coefficient, 0.0208 (tonne/day-m-MPa)/(mD/cp)
    - k = permeability (mD)
    - h = thickness of formation (m)
    - p_{max} = maximum bottom hole injection pressure, 90% of fracture pressure (MPa)
    - p_{amb} = ambient pressure in the storage formation MPa)
    - μ_{CO2} = viscosity of CO_2 at reservoir temp. and press. (cp)

Example Calculations

- **Design parameters**
  - Annual CO_2 injection rate = 3.2 Mtonne/yr
    - Output from 420 MW subcritical PC power plant (net power) at 80% capacity factor and 90% CO_2 capture
  - Daily maximum injection rate = 10,960 tonnes/day
    - Assumes capacity factor of 80%
  - Duration of injection = 30 years

Example Calculations

- **Mount Simon3 formation in Illinois (good storage candidate)**
  - Depth to top of formation = 4,270 ft
  - Thickness = 1,000 ft, 305 m
  - Porosity = 12%
  - Permeability = 68.5 mD
  - Storage coefficient (flat or sloping) = 5.63%
  - Density of CO_2 in reservoir = 720 kg/m^3
  - Viscosity of CO_2 in reservoir = 0.0589 cp
  - Ambient pressure in formation = 15.3 MPa, 2,213 psi
  - Max. bottom hole inject. press. = 17.5 MPa, 2,538 psi
  - Ambient temperature in formation = 111 ^{o}F, 317 K

Example Calculations

- **Rose Run3 formation in Pennsylvania (poor storage candidate)**
  - Depth to top of formation = 13,800 ft
  - Thickness = 320 ft, 98 m
  - Porosity = 8%
  - Permeability = 1.6 mD
  - Storage coefficient (flat or sloping) = 4.71%
  - Density of CO_2 in reservoir = 727 kg/m^3
  - Viscosity of CO_2 in reservoir = 0.0629 cp
  - Ambient pressure in formation = 44.7 MPa, 6,490 psi
  - Max. bottom hole inject. press. = 52.0 MPa, 7,540 psi
  - Ambient temperature in formation = 251 ^{o}F, 395 K

Example Calculations

Parameter	Mount Simon3 (IL)	Rose Run3 (PA)
CO_2 Plume Area (mi^2)	25.0	139
CO_2 Plume Uncertainty Area (mi^2)	43.8	243
Pressure Front Area (mi^2)	438	2,430
Ratio of CO_2 Plume "Diameter" to Thickness	29.8	219
Number of Active Injection Wells	3	50

As points of reference:

- Area of Pittsburgh: 58.3 mi^2
- Area of Allegheny County: 745 mi^2

FE/NETL CO_2 Saline Storage Cost Model

Model Framework Based on EPA Class VI Regulations

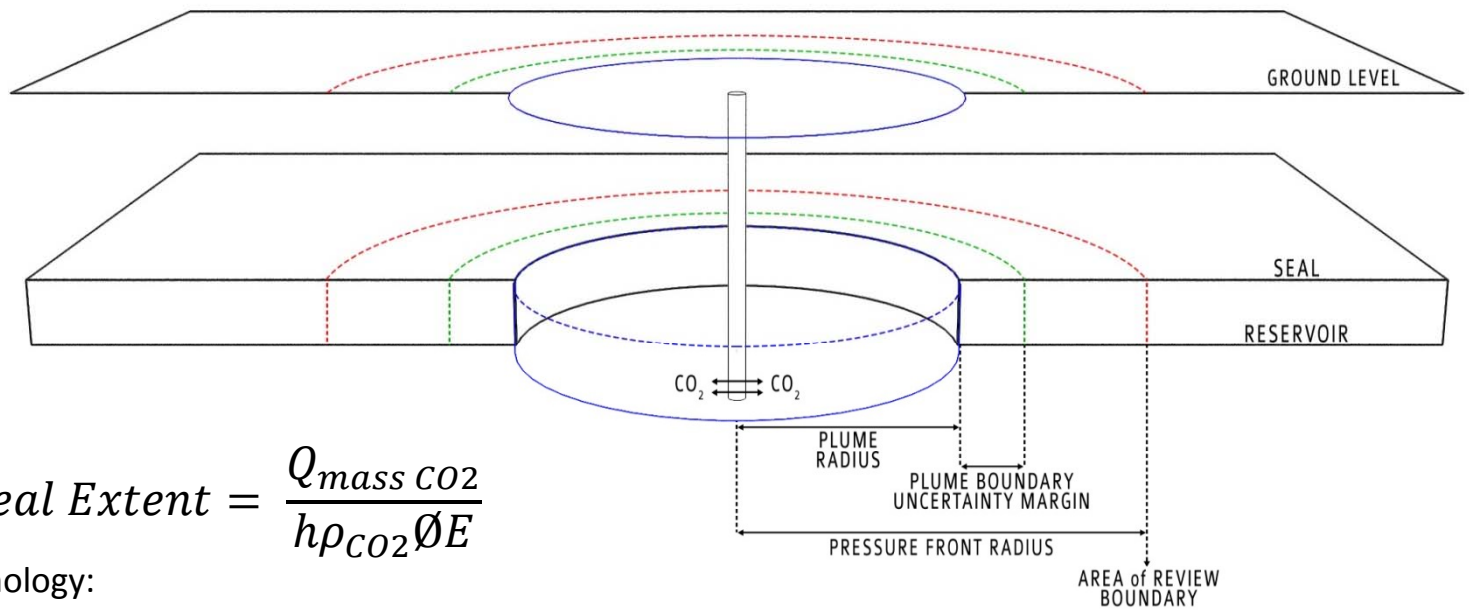
Regional Eval.	Site Selection & Char.	Permitting & Inj. Well Drilling	Operations	Post-Injection Monitoring	Long-Term Stewardship
	UIC Class VI Regulations				Developing State Regulations
			Class VI Permit		
0.5 to 1 year	3+ years	2+ years	30 to 50 years	10 to 50+ years	rest of civilization
gather existing data, develop several prospects	select a site, acquire new data (drill wells, shoot seismic), prepare permitting plans	permit awarded to drill injection wells, final approval to begin injection.	inject CO_2, drill monitoring wells & remediate existing wells as needed, MVA	monitor site, establish non-endangerment, close and restore site	another entity (e.g., a state) takes over
assemble acreage block (surface access/pore space)		Secure financial responsibility upon permit application; as required, pay into trust fund for financial responsibility			
	25% success rate assumed		pay $/tonne fees*		
negative cash flow			positive cash flow	negative cash flow	covered by fee paid during ops

* Per tonne cost associated with several cost items: long-term stewardship (state sets rate), insurance to cover emergency & remedial response (financial responsibility), a per/tonne "royalty" to pore space owner.

CO_2 Storage – Class VI Regulations

Regional Geologic Evaluation for Class VI Injection Permit

- **Minimum Criteria for Siting [40 CFR §146.83]**
  - Injection zone(s) of sufficient areal extent, thickness, porosity, and permeability for anticipated volume of CO_2.
  - Confining zone(s) of sufficient areal extent and free of transmissive faults and fractures.
  - May have to characterize additional confining zones



$$Areal\ Extent = \frac{Q_{mass\ CO2}}{h\rho_{CO2}\emptyset E}$$

Technology:
3-D (2-D) seismic & well control
Reservoir modeling: software & data

Source: NETL.

CO_2 Storage – Class VI Regulations

Site Characterization: Required Class VI permit information [40 CFR §146.82]

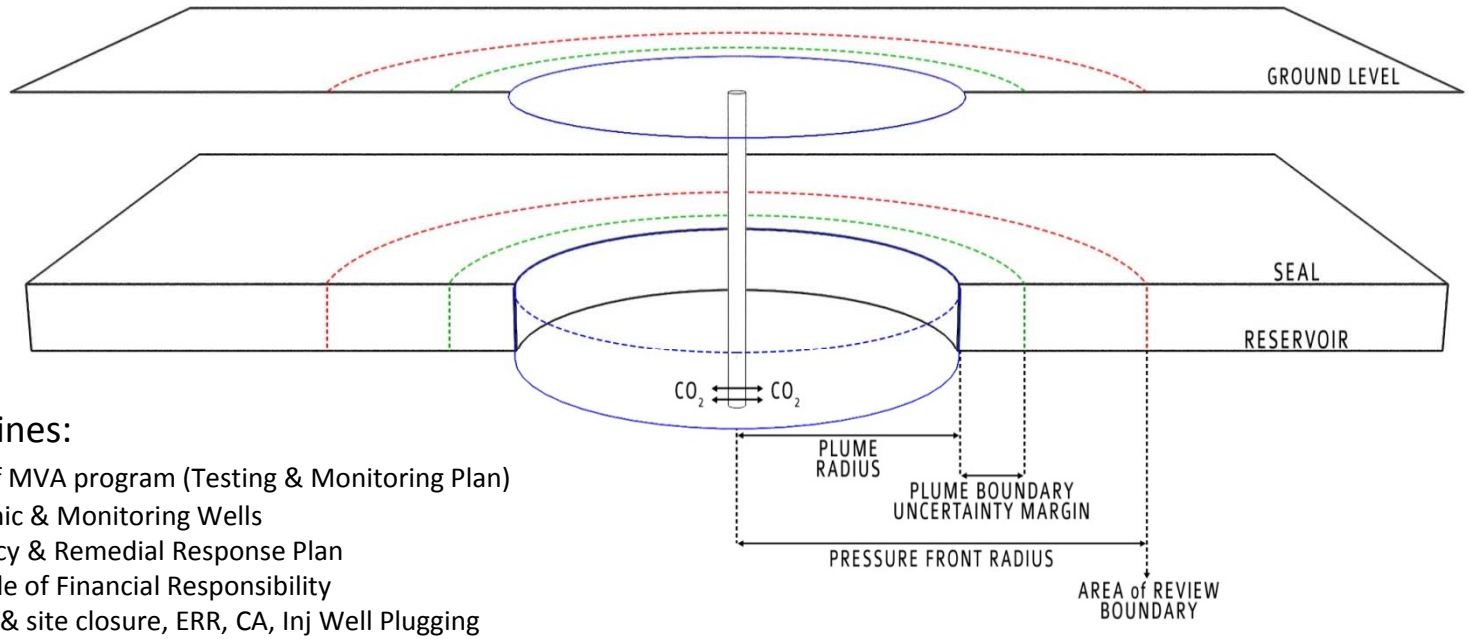
Prior to issuance of a permit…the Director shall consider the following:

- Map of proposed inject well and its AoR (only information of public record required to be plotted)
  - Post all injection, producing, abandoned, plugged wells; dry holes, deep stratigraphic boreholes; water wells.
  - State or EPA approved subsurface clean-up sites.
  - Surface bodies of water, springs, mines (surface & subsurface), quarries,
  - State, Tribal and territorial boundaries, roads,
  - Structures intended for human occupancy
  - Faults if known or suspected
- Info on geologic structure, hydrogeologic properties of storage site and overlying formations
  - Maps and cross-sections of AoR
  - Faults if known or suspected that may transect injection zone: location, orientation, properties, possibly interfere with containment
  - Depth, areal extent, thickness, mineralogy, porosity, permeability and capillary pressure of injection and confining zone(s)
    - Geology/facies change based on field data (cores, outcrop data, seismic, well logs, names & lithologic descriptions)
  - Geomechanical information within confining zone(s): fractures, stress, ductility, rock strength, in situ fluid pressures.
  - Seismic history: presence and depth of seismic sources, determination that seismicity will not interfere with containment
  - Geologic/Topographic maps & cross-sections illustrating regional geology, hydrogeology and the geologic structure of the local area.
- Tabulation of all wells within AoR
  - Which penetrate the injection or confining zones(s)
  - Description of each well's type, construction, date drilled, location, depth, completion/plugging record, additional info required by Director.
- Maps and stratigraphic cross-sections of all USDWs, water wells, and springs within AoR
  - Vertical and lateral limits, direction of water movement if known and position relative to injection zone.
- Baseline geochemical data on subsurface formations, including all USDWs in AoR.
- Proposed operating data for proposed geologic sequestration site.
  - Avg/Max daily rate/volume/mass and total anticipated vol/mass of CO2 stream
  - Avg/Max injection pressure
  - Source(s) of CO_2
  - Analysis of chemical and physical characteristics of CO_2 to be injected

CO_2 Storage – Class VI Regulations

Area of Review and Corrective Action [40 CFR §146.84]

- **Area of Review (AoR) region around project where USDWs may be endangered**
- **Perform following actions to delineate AoR and ID all wells that require corrective action (CA):**
  - Use computational methods modeling that accounts for the physical and chemical properties of all phases of the injected CO_2 stream
    - Director may require reactive transport or geomechanical modeling
  - Predict the projected lateral and vertical migration of CO_2 plume and formation fluids until plume movement ceases, until pressure differentials sufficient to endanger USDWs no longer present, or end of fixed time determined by Director
    - Incorporate data acquired during site characterization
    - Account for reservoir and seal heterogeneities; migration via faults and/or fracture zones
  - ID all penetrations and underground mines that may penetrate the confining zone(s).

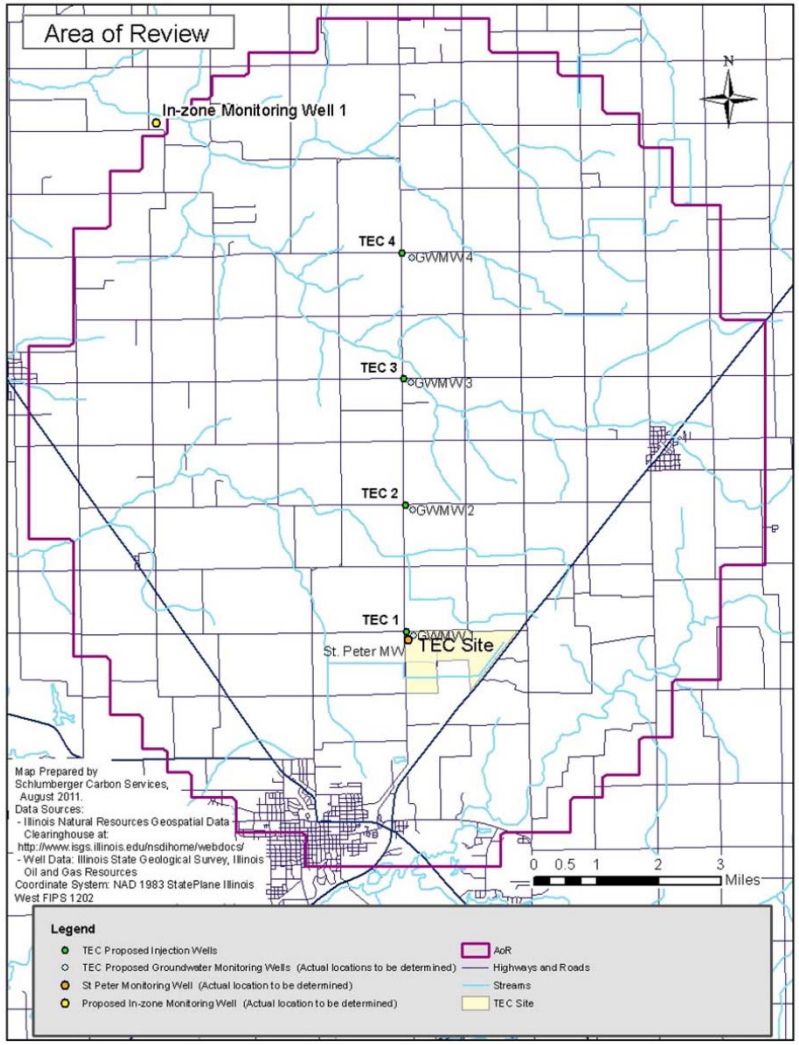


AoR Defines:

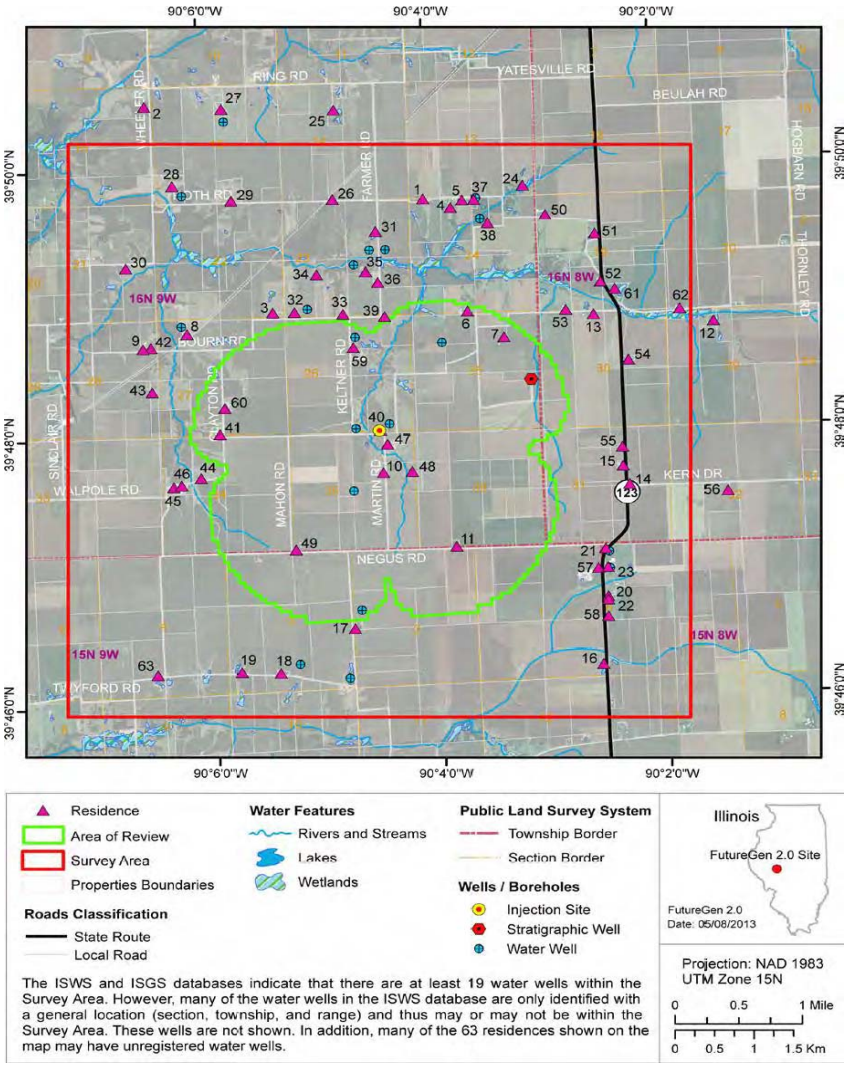
- Extent of MVA program (Testing & Monitoring Plan)
  - Seismic & Monitoring Wells
- Emergency & Remedial Response Plan
- Magnitude of Financial Responsibility
  - PISC & site closure, ERR, CA, Inj Well Plugging

Source: NETL.

CO_2 Storage – Area of Review (AoR)



Tenaska Taylorville Energy Center (TEC)



FutureGen 2

CO_2 Storage – Class VI Regulations

Geologic Systems & Series		Wells	Producing Reservoirs				Nat Gas Storage	Geologic Unit	Driller's Term
			Oil	O&G	Gas	CBM			
Perm								Dunkard Gp	
Penn	U	2,921	105	54	192	33		Monongahela Gp	
								Conemaugh Gp	
	M							Allegheny Fm	
	L							Pottsville Gp	
Miss	U	1,620	100	64	290		16	Mauch Chunk Gp	Princeton, Ravencliff, Avis, Maxton, Little Lime, Blue Monday
	M	11,738	238	234	476			Greenbrier Gp	Big Lime, Keener, Big Injun
	L	15,314	78	114	300			Price Gp	Squaw, Weir
		6,700	79	74	189			Berea Ss	
Devonian	U	26,684	201	522	1,294		8	Hampshire FM	Gantz, 50', 30', Gordon, Gordon Stray, 4th, 5th, Bayard, Speechley Balltown, Bradford, Riley, Benson, Alexander, Elk
								"Chemung Gp"	
								Brallier Fm	
	M	15,324	33	72	207			Harrell Shale	
								Mahantango Fm	
		486	0	27	123			Marcellus Fm	
		5,142	2	8	129			Onondaga Ls	
	L						10	Oriskany Ss	
								Helderberg Gp	
Silurian	U	243	1	0	22			Salina Fm	
								Newburg Ss	
								Williamsport Fm	
	M							McKenzie Fm	
								Rochester Shale	
		574	0	0	12			Keefer Ss	
								Rose Hill Fm	
	L	62	0	0	24			Tuscarora Ss	
Ordovician	U	143	12	6	30			Juniata Fm	
								Oswego FM	
								Reedsville Shale	
								Trenton Gp	
	M	22						Black River Gp	
								St. Paul Gp	St Peter Ss
	L	6						Beekmantown Gp	Rose Run, Copper Ridge
Cambrian	U	10						Conococheague Fm	
	M							Elbrook Fm	
	L							Waynesboro Fm	
								Tomstown Dol	
								Chilhowee Gp	
								Catoctin Fm	
Pre-Cambrian		11						Crystalline Rock	

Confining Unit	Sequestration Target	Organic Shale	Coal -bearing Interval	Basement

Appalachian Basin - WVa

Corrective Action

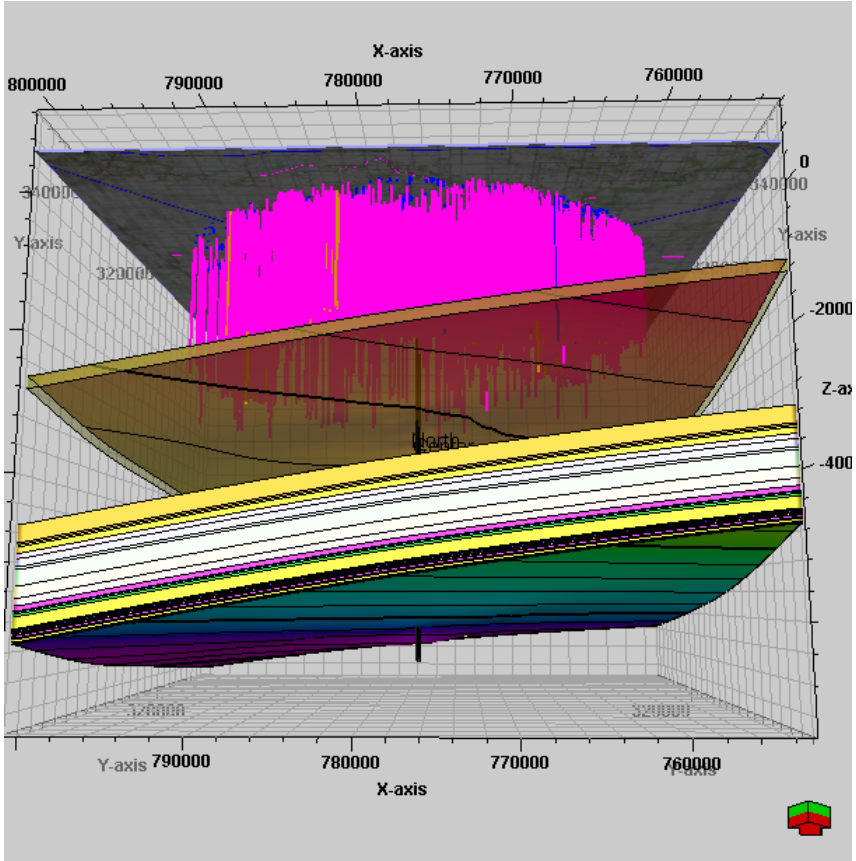
- List all wells in AoR that may penetrate the confining zone(s).
  - Ability to locate old wells
- Determine which wells are plugged in a manner to prevent movement of fluids into or between USDWs.
- In WVa 88% of wells Devonian or shallower.
- Several sequestration targets deeper than Devonian.
- Data on old wells – cement quality
  - Plugging Permit for old wells
  - Cement Bond Log available
  - Remediation necessary?

West Virginia CCS Working Group final report. Found at: http://www.dep.wv.gov/executive/Documents/WVCCS%20Working%20Group%20Final%20Report%20-%20June%2030,%202011.pdf

CO_2 Storage – Class VI Regulations

Tenaska TEC

- Shallow oil production less than 2,500 ft
- Only four wells penetrate the St. Peter Sandstone



Tenaska Energy Center Class VI Permit Application. Technical Report Figures. Found at: http://www.epa.gov/Region5/water/uic/tec/pdfs/tec-permit-appl-figures-2011-09.pdf

CO_2 Storage – Class VI Regulations

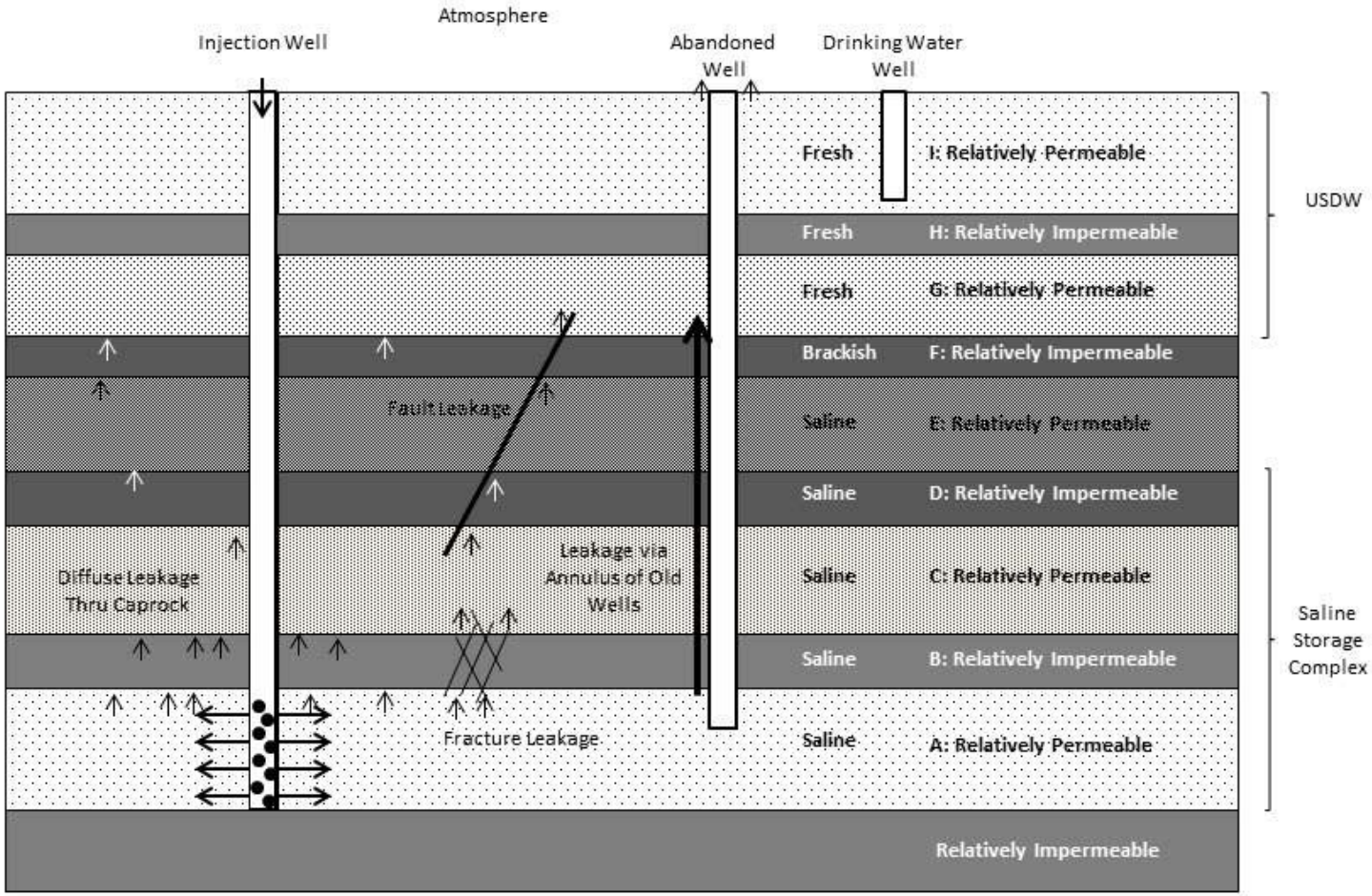
Site Characterization:

Prior to issuance of a permit…the Director shall consider the following:

- Proposed pre-operational formation testing program:
  - to obtain an analysis of the chemical and physical characteristics of the injection zone(s) and Confining Zones(s) and
  - that meet the requirements at 40 CFR §146.87 [Logging, sampling, and testing prior to injection well operations]
- Proposed stimulation program:
  - a description of stimulation fluids to be used and
  - a determination that stimulation will not interfere with containment
- Proposed procedure to outline steps necessary to conduct injection operations
- Schematics or other appropriate drawings of the surface and subsurface construction details of the well
- Injection well construction procedures that meet the requirements of 40 CFR§146.86 [Injection well construction requirements]
- Proposed **AREA OF REVIEW AND CORRECTIVE ACTION PLAN** that meet the requirements of 40 CFR §146.84 [Area of review and corrective action]
- A demonstration, satisfactory to the Director, that the applicant has met the financial responsibility requirement under 40 CFR §146.85 [**FINANCIAL RESPONSIBILITY**]
- Proposed **TESTING AND MONITORING PLAN** required by 40 CFR §146.90 [Testing and monitoring requirements]
- Proposed **INJECTION WELL PLUGGING PLAN** required by 40 CFR §146.92(b) [40 CFR §146.92 Injection well plugging]
- Proposed **POST-INJECTION SITE CARE AND SITE CLOSURE PLAN** required by 40 CFR §146.93(a) [40 CFR §146.93 Post-injection site care and site closure]
- At the Director's discretion, a demonstration of an alternative post-injection site care timeframe required by 40 CFR §146.93(c)
- Proposed **EMERGENCY AND REMEDIAL RESPONSE PLAN** required by 40 CFR §146.94(a) [40 CFR §146.94 Emergency and remedial response]
- A list of contacts, submitted to the Director, for those States, Tribes and Territories identified to be within the area of review of the Class VI project based on information provided map of applicable AoR [40 CFR §146.82(a)(2)]
- Any other information requested by the Director

Permit Awarded – permission to drill CO_2 injection well <u>but can not begin injection operations</u>

CO_2 Storage – Class VI Regulations



Primary purpose of UIC regulations – protect USDW

- Potential pathways for migration of CO_2 from storage

Source: NETL.

CO_2 Storage – Class VI Regulations

Release Scenario	Likelihood (annual)
Pipeline Events	
Pipeline Rupture	1 in 200 (0.5%)
Pipeline Puncture	1 in 100 (1.0%)
Storage Site Events	
Wellhead Equipment Rupture	6 in 100,000 (0.006%)
CO2 Injection Well Leak	3 in 100,000 (0.003%)
Other Well Leak	7 in 100 (7.0%)
Rapid Leakage through Caprock	2 in 10 billion (0.00000002%)
Slow Leakage through Caprock	4 in 100,000 (0.004%)
Release through Existing, Induced Faults	2 in 100 million (0.000002%)

- **Emergency and Remedial Response [40 CFR §146.94]**
- Address movement of injection and/or formation fluids that may endanger USDWs
- Jewett, Texas FG risk modeling:
  - Estimated total damages valued between \$8.5 (50th percentile) to \$18.6 million (95th percentile)
  - \$0.17 to \$0.37 per tonne (50 Mt CO_2 modeled for storage)

Global CCS Institute. Found at: http://www.globalccsinstitute.com/publications/valuation-potential-risks-arising-model-commercial-scale-ccs-project-site

CO_2 Storage – FutureGen 2 ERR Estimate

Activity or Event	Est Cost (million$)
Post-Injection USDW Contamination	
Acidification due to migration of CO2	0.305
Toxic metal dissolution and mobilization	5.865
Displacement of groundwater with brine due to CO2 injection	0.270
Post-Injection Failure Scenarios (Acute)	
Upward migration through CO2 injection well	3.343
Upward migration through deep oil and gas wells	2.111
Upward migration through undocumented, abandoned, or poorly constructed wells	2.111
Post-Injection Failure Scenarios (Chronic)	
Upward migration as a result of the gradual failure of the confining zone(s)	5.865
Release through existing faults due to effects of increased pressure	5.865
Release through induced faults due to effects of increased pressure	6.10
Upward migration through CO2 injection well	0.821
Upward migration through deep oil and gas wells	0.411
Upward migration through undocumented, abandoned, or poorly constructed wells	0.411
Other	
Catastrophic failure of confining zone(s)	6.10
Failure of confining zone(s) or well integrity due to seismic event	6.10

- Emergency & Remedial Response: $45.678 million valuation of events for FutureGen2
- Estimate $100 million policy, $250,000 deductible, annual premium between $625,000 & $825,000
  - $0.57 to $0.75 per tonne based on cost of premium paid during operations.

FutureGen Alliance UIC Permit Application. Supporting Documentation
Found at: http://www.epa.gov/r5water/uic/futuregen/pdfs/futuregen-permitapp-201303.pdf

CO_2 Storage – Financial Responsibility

Estimates for Financial Responsibility – Wyoming Carbon Sequestration Working Group Tied to EPA's Categories for Financial Responsibility		
Million $		EPA
22	Extensive relief well & water treatment mitigation	Emergency & Remedial Response
15	Water Quality contamination during the fluid phase – Drinking water replacement	
	A single large release to the surface – relief well mitigation	
	Chronic low-level releases to surface – relief well mitigation	
10	Entrained contaminant releases – pumpback and treatment systems	
	Storage rights infringement – relief well mitigation	
5	Modified surface topography – structural damages	
5	Accidents or unplanned events – surface clean-up	
57	Total	
2	Well plugging & abandonment (3 inj ection wells, 3 monitoring well per injection well)	Injection Well P&A
2	Facilities/Pipeline D&D/Abandonment	
2	Surface disturbance reclamation	
6	Total	
9	Post-injection monitoring (15 yrs)	PISC & Site Closure
1	Post-injection inspection and maintenance	
2	Contractor contingencies for site closure & reclamation (15%)	
1	Field Management	
1	Unknowns for site closure & reclamation (10%)	
16	Total	
	Corrective Action – remediate old wells	Corrective Action
77	Total for Financial Responsibility	

Wyoming CCS Working Group

- Wyoming work prior to EPA release of Class VI rules
- Wyoming's cost based on sequestering 60 Mt over an area of 9 mi^2 (0.15 mi^2/Mt_{CO2})
- EPA cost modeling assumes that storage projects will have to remediate ~10% of the older well with AoR.
- Corrective action can be taken as the plume grows
- Wyoming did not estimate a cost for corrective action.
- EPA estimates ~ $700K to remediate old O&G wells and groundwater wells.
- Suggests $1.25 - $1.30/$Mt_{CO2}$ sequestered for Financial Responsibility

FutureGen 2: 22 Mt_{CO2} stored

- Corrective Action $0.623 Million
- Inj & Mon Well P&A $2.723
- PISC $18.32
- Site Closure $3.402
- ERR $45.678

Wyoming CCS Working Group report to the Legislature found at: http://deq.state.wy.us/out/downloads/1%20FinalReport081909.pdf
FutureGen 2.0 Alliance UIC Permit Application. Financial Responsibility information found at: http://www.epa.gov/r5water/uic/futuregen/pdfs/futuregen-permitapp-201303.pdf

CO_2 Storage – Injection Well

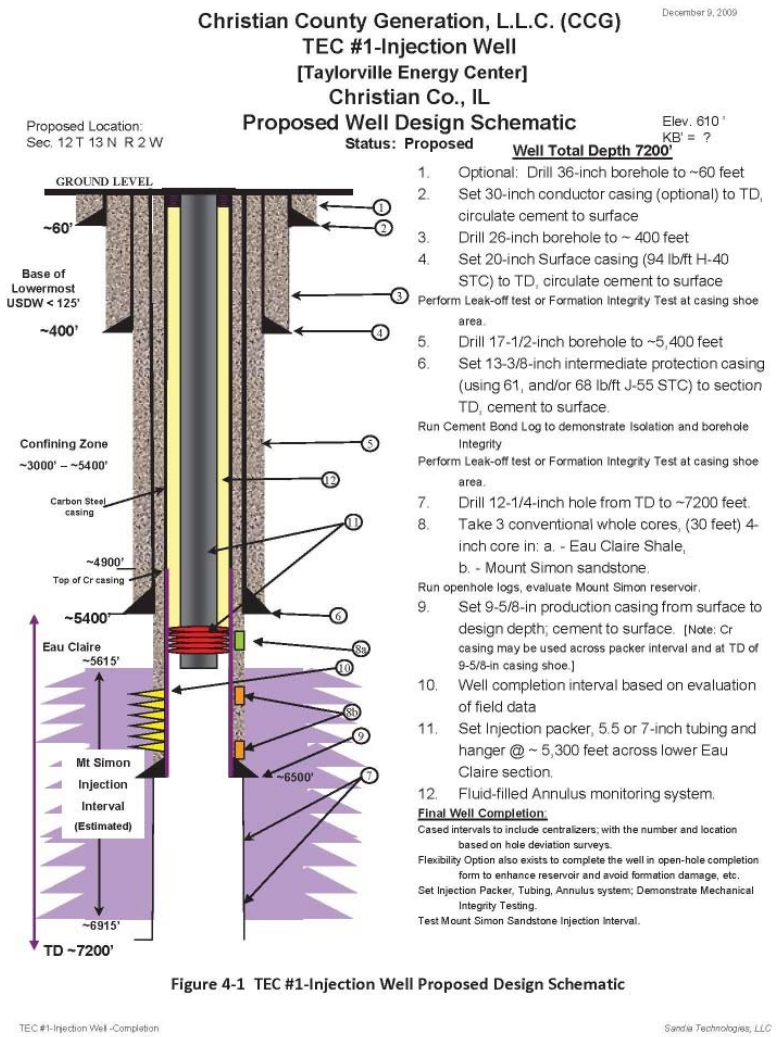


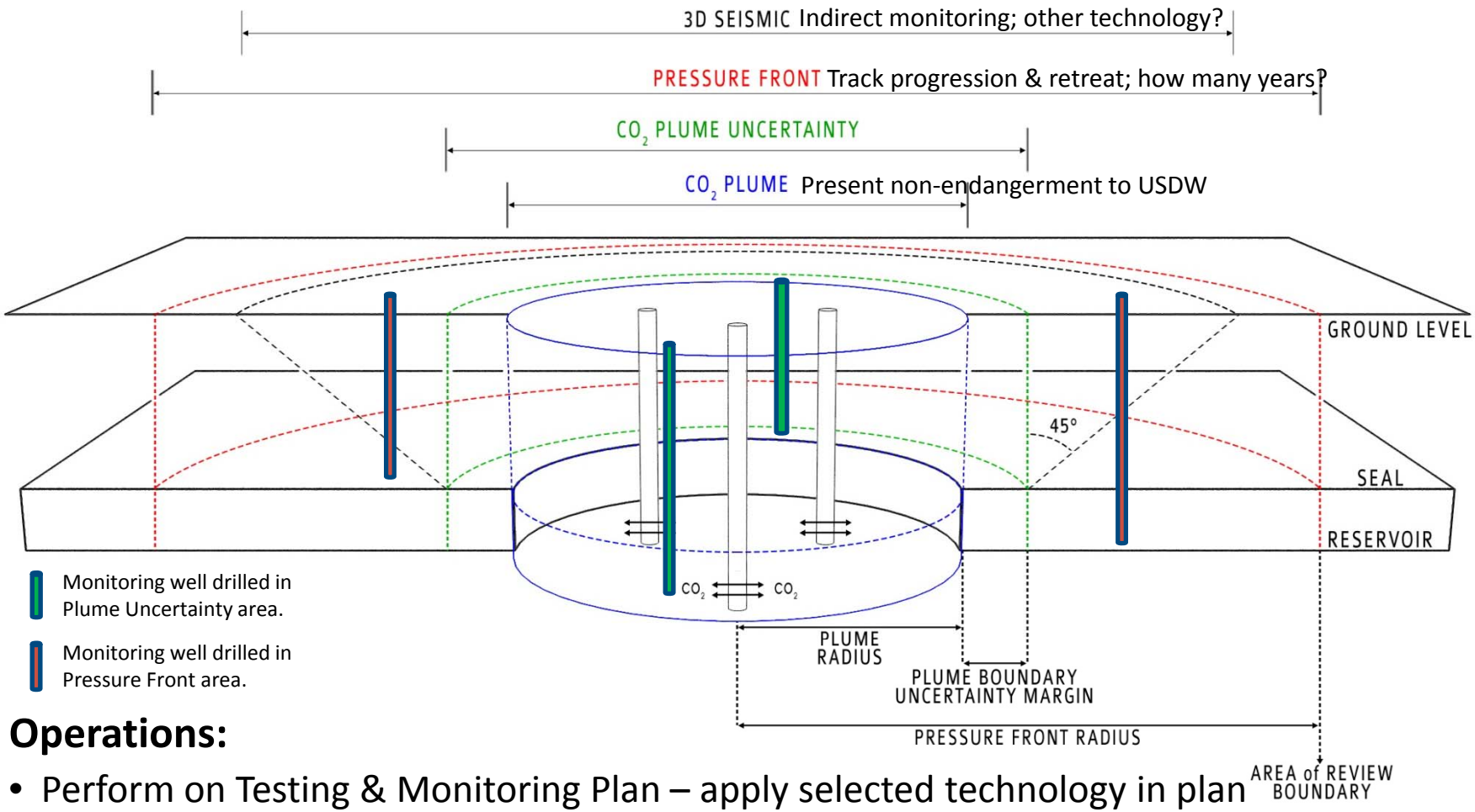
Figure 4-1 TEC #1-Injection Well Proposed Design Schematic

Injection Well Construction [40 CFR §146.86]

- Prevent movement of fluids into/between USDWs
- Permit use of workover and testing tools
- Continuous monitoring of annulus between tubing and casing
- Surface casing set below lowest USDW
  - Cement back to surface
- At least one long string casing from injection zone to surface
  - Cement back to surface
- Injection through tubing and packer
- Material must be suitable for environment of operations
- Two step process
  - Award permit to drill injection well
  - Authorized to begin injection

Tenaska Energy Center Class VI Permit Application. Technical Report Figures. Found at: http://www.epa.gov/Region5/water/uic/tec/pdfs/tec-permit-appl-figures-2011-09.pdf

CO_2 Storage – Operations



Operations:

- Perform on Testing & Monitoring Plan – apply selected technology in plan
- Perform corrective action per AoR-Corrective Action plan
- Submit Monitoring, Recording and Verification plan per Subpart RR regulations

Source: NETL.

CO_2 Storage – Operations

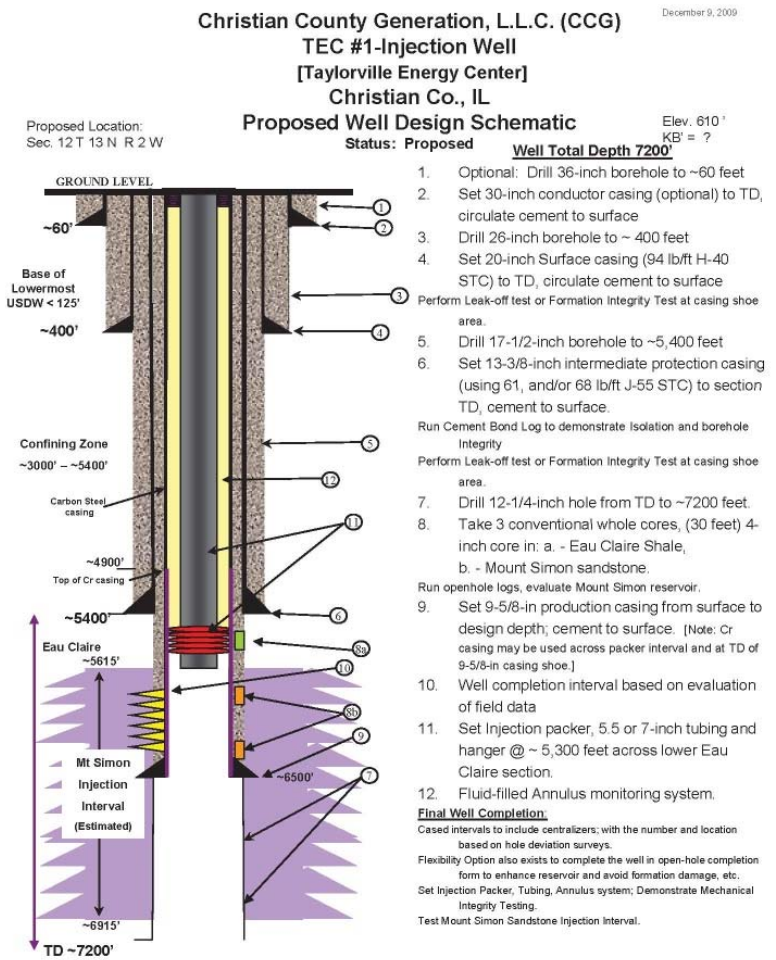


Figure 4-1 TEC #1-Injection Well Proposed Design Schematic

Operations: Monitoring Injection Well [40 CFR § 146.88]

- Continuous monitoring equipment on wellhead
- Corrosion monitoring of casing and tubing material
- Annual demonstration of external mechanical integrity
- Pressure fall-off test of injection zone(s) at least once every 5 years.

Tenaska Energy Center Class VI Permit Application. Technical Report Figures. Found at: http://www.epa.gov/Region5/water/uic/tec/pdfs/tec-permit-appl-figures-2011-09.pdf

CO_2 Storage – Operations

Operations:

Testing and Monitoring [40 CFR §146.90]

- Periodic monitoring above the confining zone(s)
  - Loc/Number of monitoring wells base on site characterization work
  - Monitoring frequency and spatial distribution per baseline data
- Testing & monitoring to track CO_2 plume and pressure front.
  - Direct methods in the injection zone…
  - Indirect methods (e.g. seismic, electrical, gravity, or electromagnetic surveys and/or down-hole CO2 detection tools)…unless…such methods are not appropriate.
- Director may require surface air monitoring &/or soil gas monitoring (Subpart RR)
  - Per Subpart RR, upon award of Class VI permit have 180 days to submit MRV plan
- EPA guidance:
  - Methods for plume and pressure-front tracking:
    - In situ fluid pressure; indirect geophysical; ground water geochemical; computational
  - Primary, Secondary and Potential Technologies

CO_2 Storage – Monitoring Wells

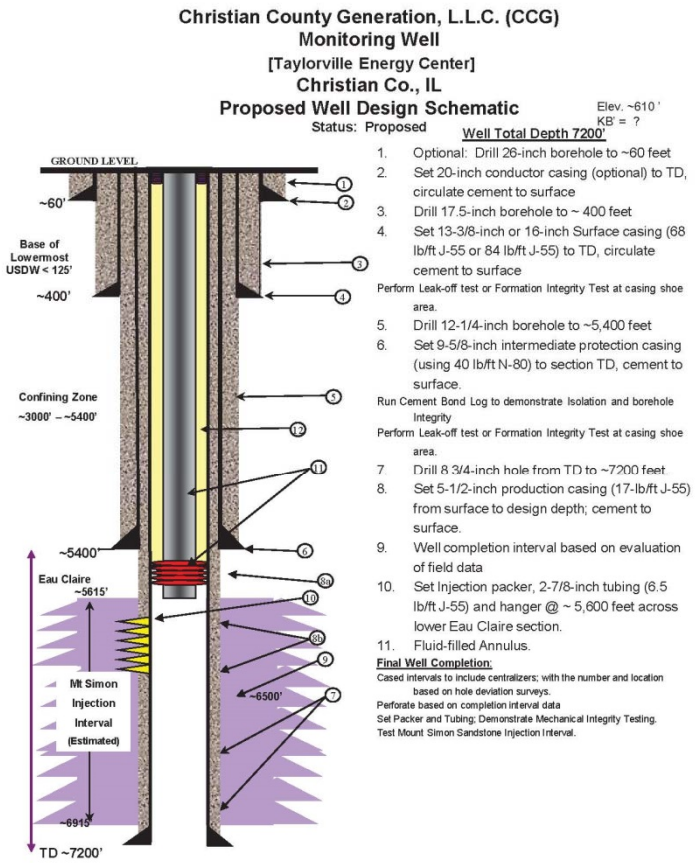


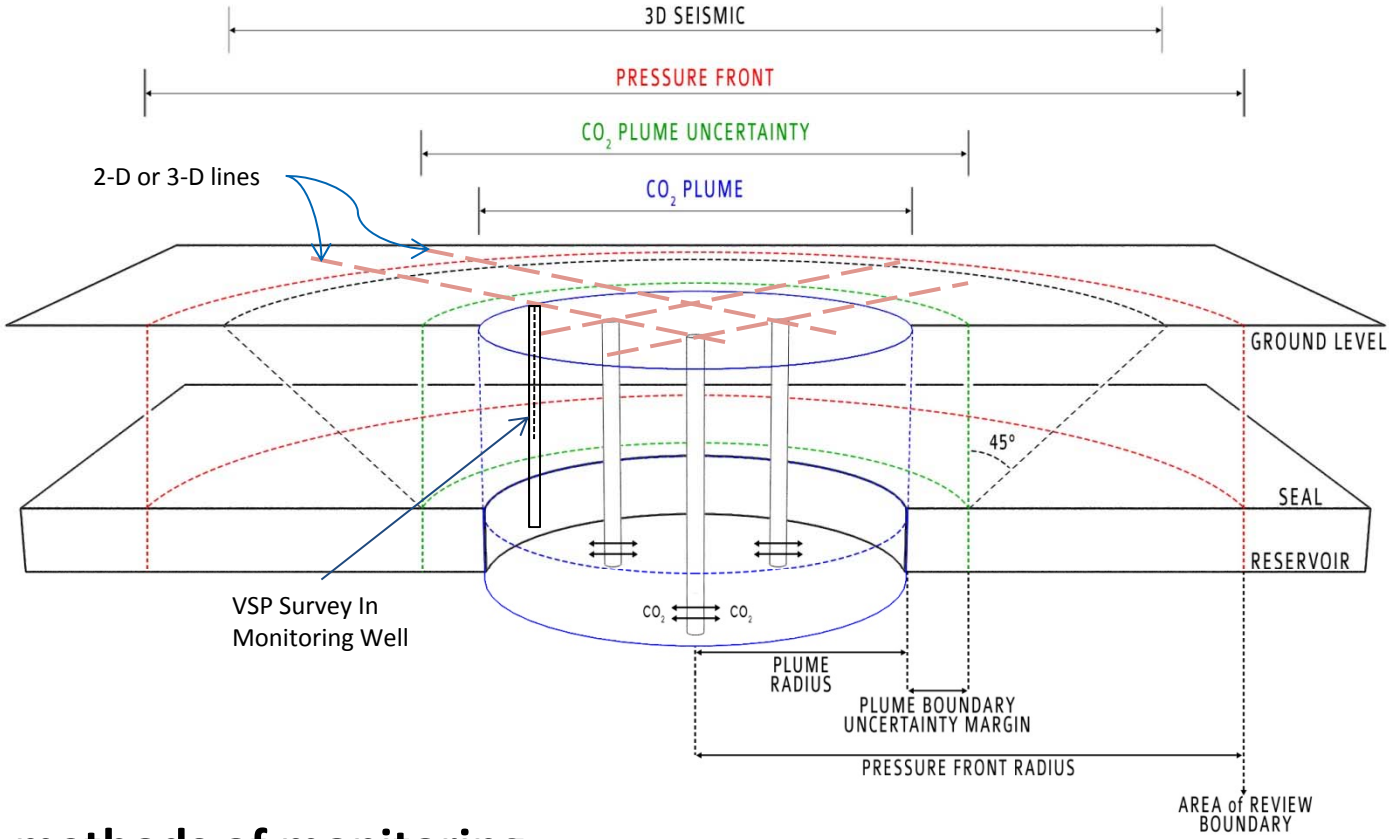
Figure 4-3 In-zone Monitoring Well Proposed Design Schematic

Operations: Monitoring Wells-Direct [40 CFR § 146.90]

- In-reservoir monitoring
  - Pressure monitoring
  - Geochemical sampling
- Above confining zone(s) monitoring
  - Groundwater quality
  - Geochemical changes
- Dual completions where possible
  - Well materials compatible with environment or completion
- EPA recommends (guidance)[1]
  - monitoring USDWs
  - Consider installing/operation more than the minimal number of monitoring wells
  - More extensive and frequent monitoring from beginning of operations

Tenaska Energy Center Class VI Permit Application. Technical Report Figures. Found at: http://www.epa.gov/Region5/water/uic/tec/pdfs/tec-permit-appl-figures-2011-09.pdf

CO_2 Storage - Monitoring



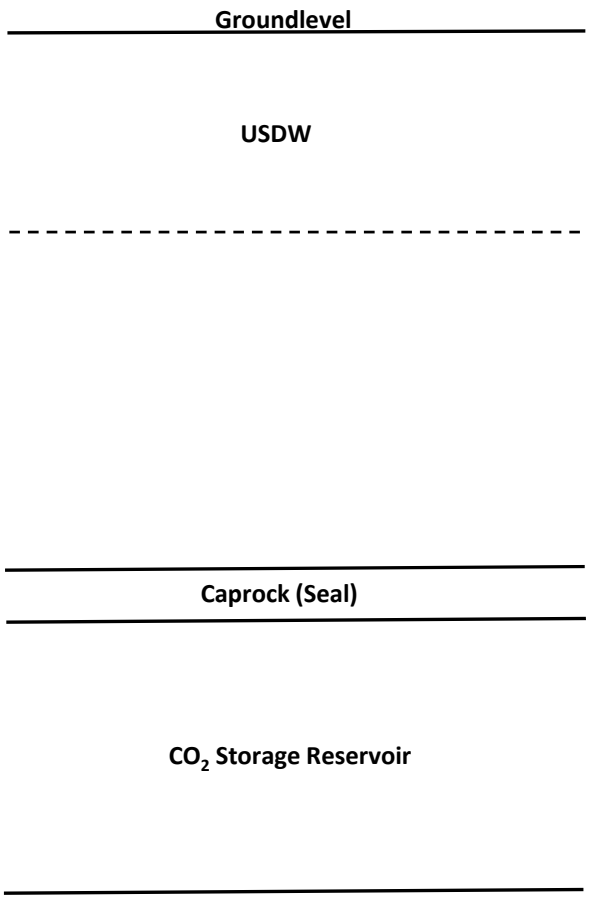
Indirect methods of monitoring

- Seismic, electrical, gravity, or electromagnetic surveys and/or downhole CO_2 detection tools
- Unless Director determines, based on site geology, that such methods are not appropriate

Source: NETL.

CO_2 Storage - Monitoring

40 CFR §146.90: Testing & Monitoring
40 CFR §146.93: Post-injection site care and site closure



The Director may require surface air monitoring and/or soil gas monitoring… Upon award of Class VI permit, have 180 days to file MRV plan under Subpart RR regulations. Class VI testing and monitoring plan can be accepted as suitable For MRV plan.

Periodic monitoring of the ground water quality and geochemical changes above the confining zone(s) that may be a result of CO_2 movement through the confining zone(s) or additional identified zones including:

1. Location & number of monitoring wells based on specific information about the geologic sequestration project, …
2. The monitoring frequency & spatial distribution of monitoring wells based on baseline geochemical data that has been collected and on any modeling results in the AoR

Testing & Monitoring to track the extent of the CO_2 plume and the presence/absence of elevated pressure (pressure front) by using:

1. Direct methods in the injection zone; and,
2. Indirect methods (seismic, electrical, gravity, EM surveys &/or open-hole CO_2 detection tools), unless Director determines, based on site-specific geology that such methods are not appropriate.

Post-injection site care plan can change MVA/MRV program conducted during injection operations but must meet objective of tracking plume and pressure front position. Shorter time frame possible with sufficient data.

CO_2 Storage – Class VI Regulations

Post-injection site care (PISC) and site closure [40 CFR §146.93]

- **Plan submitted on application for Class VI permit to include:**
  - Pre and Post Injection pressure differential in injection zone(s)
  - Predicted position of CO2 plume and pressure front at site closure (in AoR plan)
  - PISC monitoring location, methods and frequency of monitoring/sampling
  - Schedule of reporting data
  - Timeframe for PISC to establish non-endangerment
  - Update plan when injection operations cease or show why original plan still valid.
- **Monitor to show position of CO_2 plume and pressure front**
  - Continue MVA plan from operations or modify
- **Monitoring continues until non-endangerment established and Director agrees**
  - Default period for PISC is 50 years
  - Can get approval for less time but if non-endangerment is not demonstrable…
  - Can make an early demonstration of non-endangerment

CO_2 Storage – Class VI Permit Application

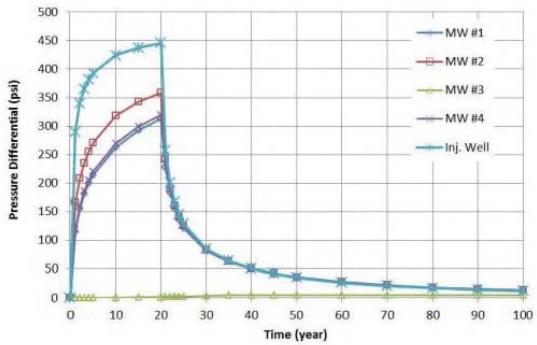


Figure 7.1. Simulated Pressure Differential Versus Time at Monitoring Well Locations

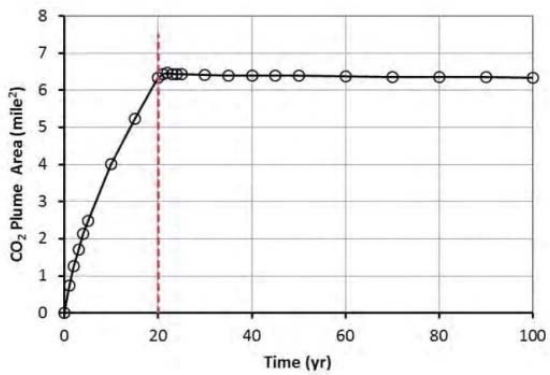
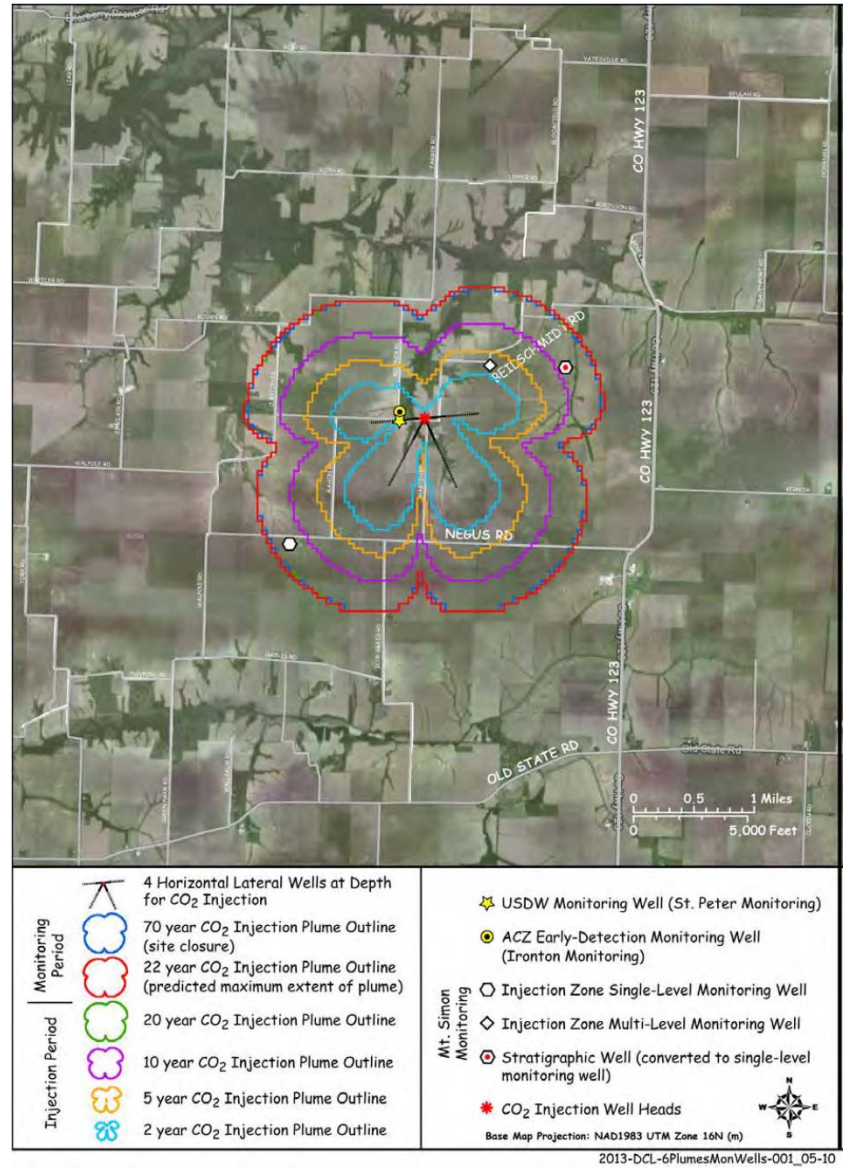


Figure 7.2. Simulated Plume Area over Time (the vertical dashed line denotes the time CO_2 injection ceases)

The physical trapping mechanisms that will facilitate the sequestration of the injected CO_2 are discussed in Section 3.1.2 in Chapter 3.0. No geochemical trapping mechanisms were modeled and such reactions are not expected to occur during the time frame of this project.



FutureGen2 – storage proposal:

AoR = area of CO_2 Plume at 22 years

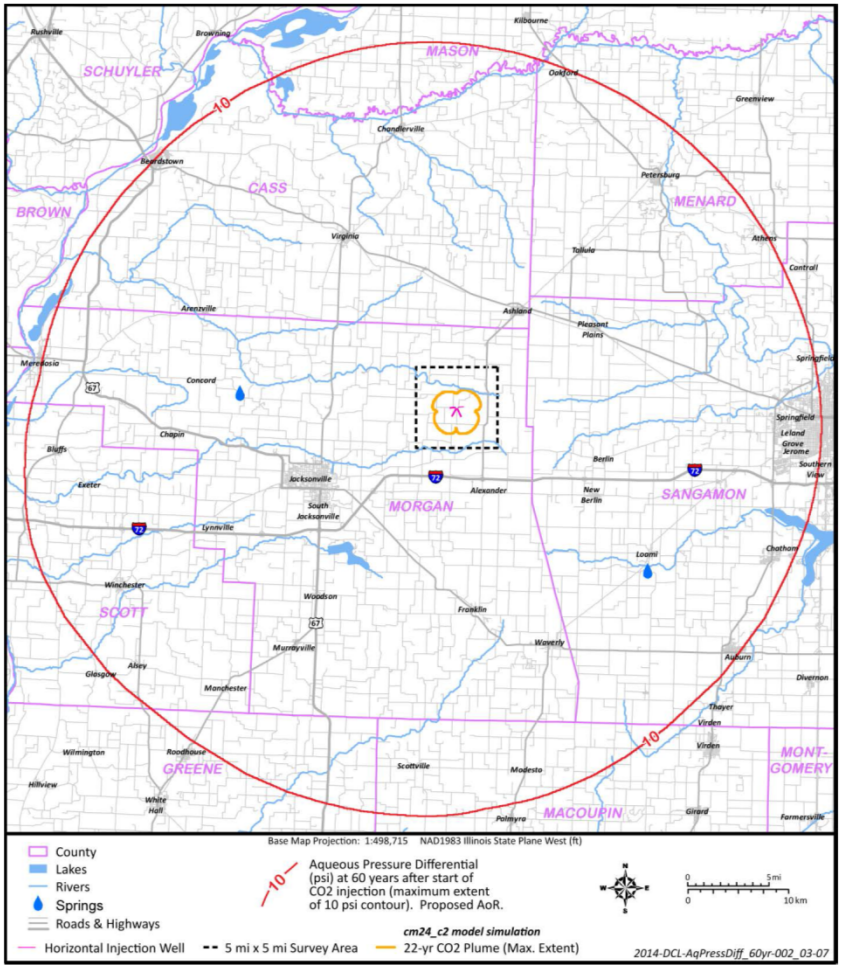
1.1 Mt CO_2 inj/yr – 22 Mt CO_2

50 years planned post-injection site care

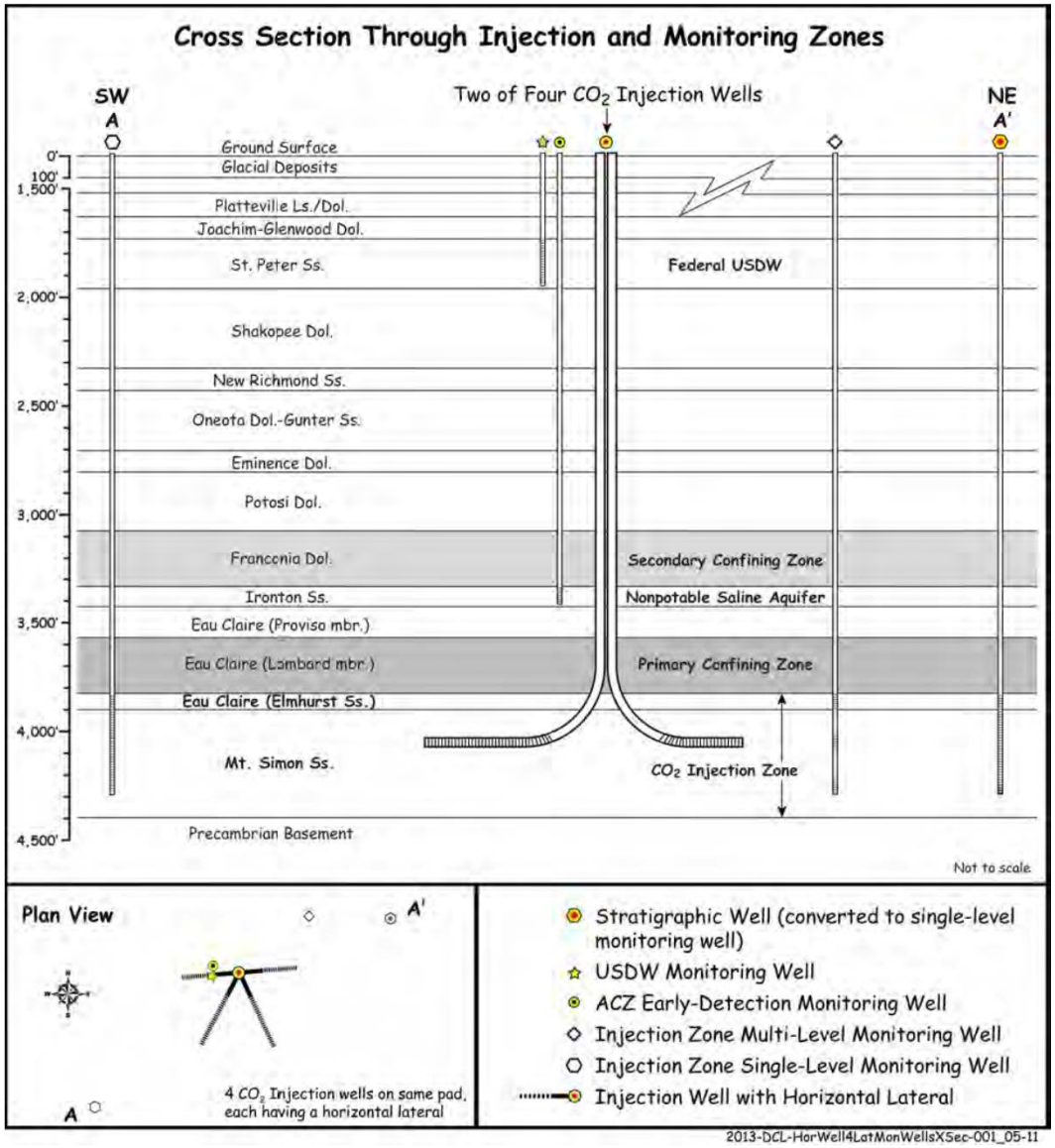
CO_2 Storage – Class VI Permit

FutureGen 2.0

- Proposed AoR based on area covered by CO2 plume after 22 years – max extent of plume.[1]
  - Clover shape outline in center of map
- Deep USDW and pressure of Mt. Simon presents infinite AoR
- Permitted AoR defined by Δ10 psi in Mt. Simon.[2]
  - Red line
- Plume radius ~38.6 km (28 mi)
  - 4,687 km2 (2,463 mi2)
- PISC for 50 years



CO_2 Storage – Class VI Permit



FutureGen2

- Horizontal injection – 4 laterals
- 5 monitoring wells
  - 1 in reservoir
  - 1 multi completed
  - 1 above primary seal
  - 1 in deep USDW (St. Peter Ss)
  - 1 strat well converted to monitoring
- Injection zone = Mt. Simon
- Primary seal = Eau Clair
- Secondary seal = Franconia Dol.
  - No monitoring well immediately above this seal

FutureGen Alliance UIC Permit Application. Supporting Documentation
Found at: http://www.epa.gov/r5water/uic/futuregen/pdfs/futuregen-permitapp-201303.pdf

CO_2 Storage – Class VI Permit
Financial Responsibility – FutureGen 2.0

Estimate of ERR Costs - FutureGen 2.0 Application[1]	$ Million
Post-Injection USDW Contamination	
Acidification due to migration of CO_2	0.305
Toxic metal dissolution and mobilization	5.865
Displacement of GW w/brine due to CO_2 injection	0.270
Post-Injection failure scenarios (acute)	
Upward migration through CO_2 injection well	3.343
Upward migration through deep oil and gas wells	2.111
Upward migration through old wells	2.111
Post-Injection failure scenarios (chronic)	
Upward migration w/slow failure of the confining zone(s)	5.865
Release through existing faults due to increased pressure	5.865
Release through induced faults due to increased pressure	6.100
Upward migration through CO_2 injcetion well	0.821
Upward migration through deep oil and gas wells	0.411
Upward migration through old wells	0.411
Other	
Catastrophic failure of confining zone(s)	6.100
Failure of confinment due to seismic event	6.100
Total	**45.678**

Covered Activity - by issued Permit[2]	$ Million
Corrective Action	0.62
Plugging Injection Wells	2.70
Post-Injection Site Care	18.30
Site Closure	3.40
Emergency & Remedial Response	26.70
Total	**51.72**

- Early planning recommended $100 million policy to cover estimated ERR liabilities valued at $45.678 million. Possible policy parameters:
  - $250,000 deductible
  - $625,000 to $825,000 annual premium
  - $0.57 to $0.75 per tonne CO_2 injected
- With Issued Class VI permit:
  - Trust Fund for Financial Responsibility
  - ERR covered by Trust Fund
  - Change ERR from expense to investment

CO_2 Storage

FutureGen 2.0

- Sept. 2010: DOE commits $1B funding for FutureGen 2.0 [1]
- March 2013: Class VI permit application to EPA [2]
  - Site selected, characterized, plans prepared and permit application submitted in 4th year of project.
- March 31, 2014: EPA completes technical evaluation and issues draft decision
- May 7, 2014: Public Hearing
- August 29, 2014: Issue Permit
  - Permit with authorization to drill injection wells in 5th year of project.

Plant		3 to 5 Year Capital Expenditure Period					Begin CCS	30 years of Operations							
Transportation				3 year Capital Expenditure Period				30 years of Pipeline Operations							
Storage	Regional Evaluation	Site Characterization			Permitting & Inj Well Drill			30 years of Operations (MVA)				50 years for PISC & Site Closure			
Year	1	2	3	4	5	6		7	8	35	36	37	38	86	87

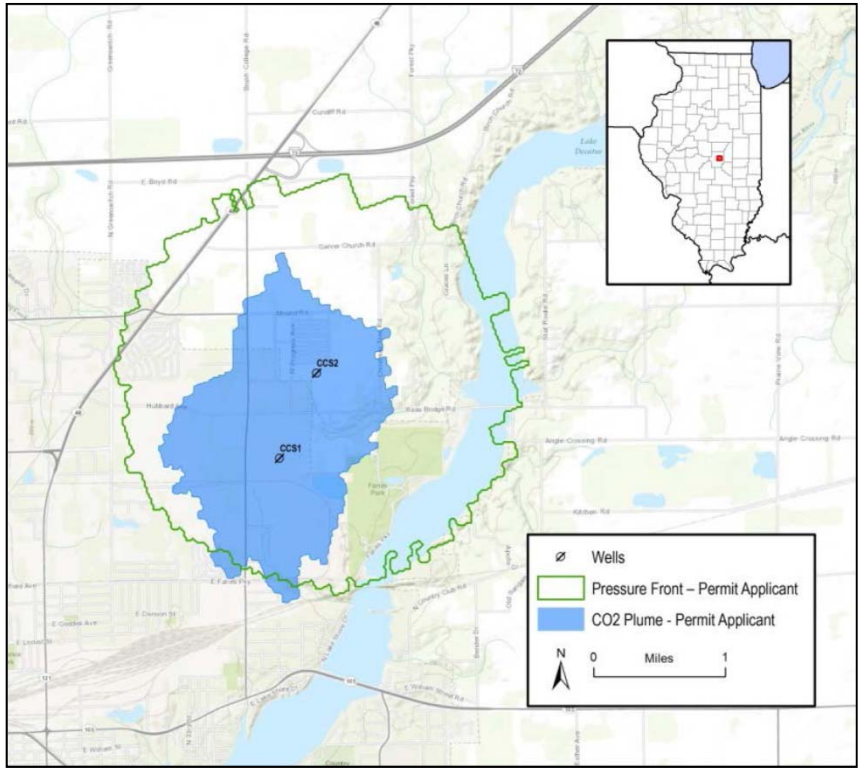
Table, Exhibit 2-1, page 11, from QGESS: carbon Dioxide Transport and Storage Costs in NETL Studies. DOE/NETL-2014-1653
Found at: http://www.netl.doe.gov/research/energy-analysis/quality-guidelines-qgess

CO_2 Storage – Class VI Permit

ADM Decatur, Illinois[1]

- CCS#2 Class VI permit – final decision issued September 23, 2014
- Inject 1.1 Mt CO2 /yr for 5 years
  - 5.5 Mt CO2 stored
- AoR radius ~3.2 km (32.2 km^2)
  - 1.9 mi (12.4 mi^2)
- PISC for 10 years
- Financial Responsibility: Corporate guarantee for all covered activities
- ADM total assets in U.S. = $30,674 million

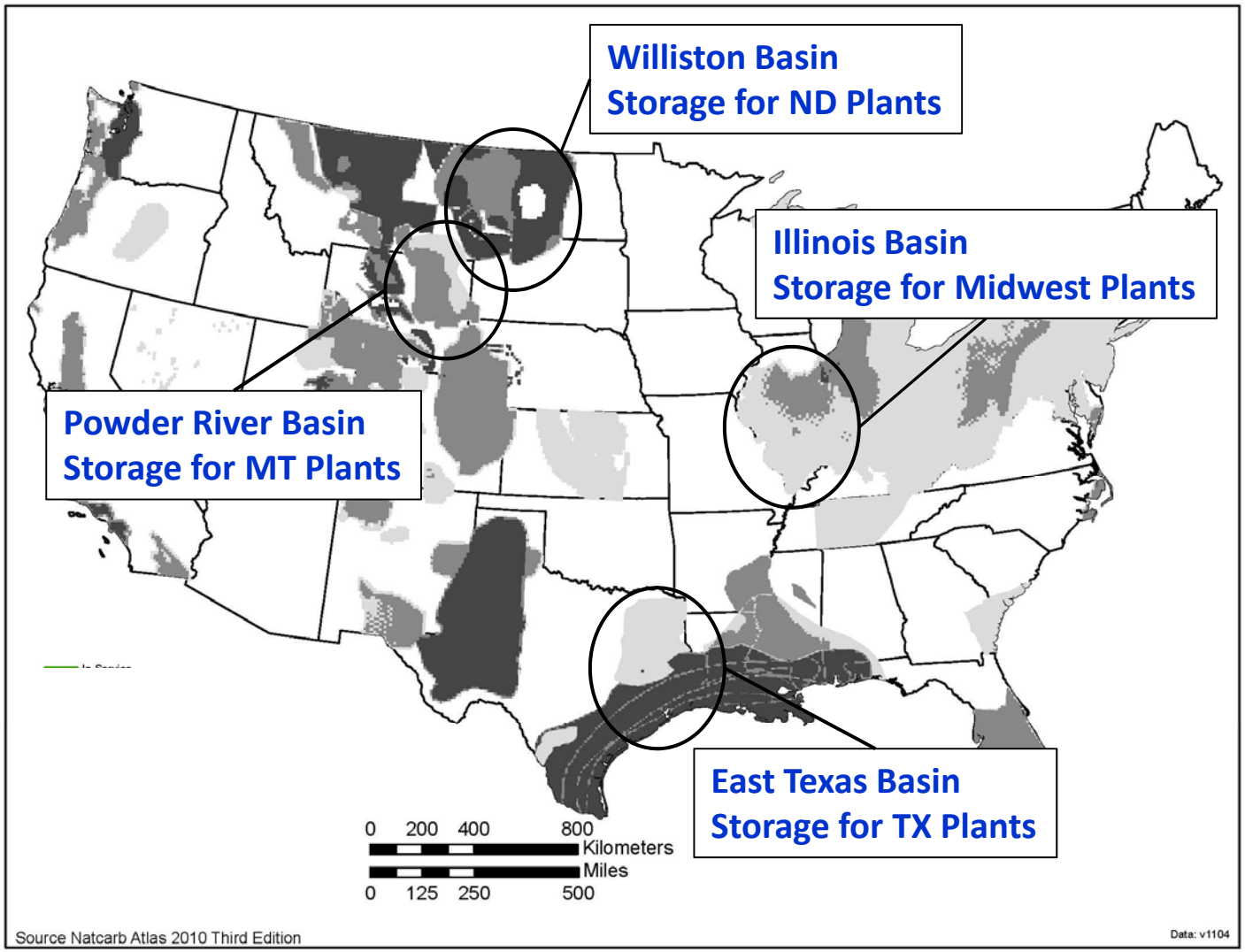
Covered Activity - by issued Permit	$ Million
Corrective Action	0.23
Plugging Injection Wells	0.59
Post-Injection Site Care	6.43
Site Closure	0.54
Emergency & Remedial Response	30.79
Total	**38.58**



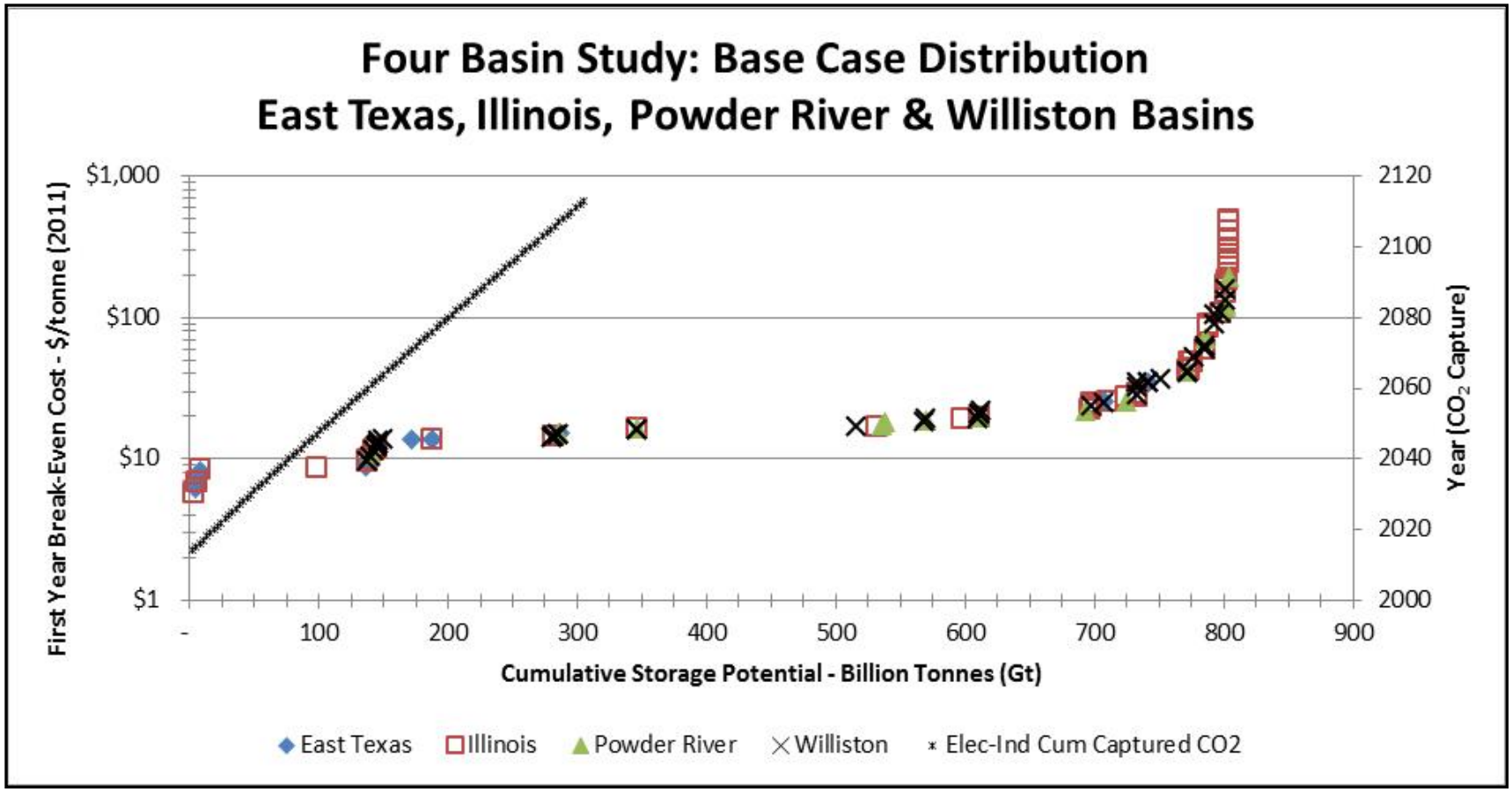
1 – Slide data found in ADM Class VI permit documents: http://www.epa.gov/region05/water/uic/adm/index.htm

CO_2 Storage

NETL Four Basin Study – Transportation & Storage Costs



CO_2 Storage



- Cumulative storage potential cost supply curve
- This storage potential is a resource that has yet to be proven. This will be done by site characterization and operations.

CO_2 Storage

NETL Four Basin Study – Transportation & Storage Costs

Plant Location	Basin	Transport (2011$/tonne)	Base Case Storage (2011$/tonne)	Total T&S (2011$/tonne)	T&S Value for System Studies (2011$/tonne)
Midwest	Illinois	2.24	8.69	10.93	11
Texas	East Texas		8.83	11.07	11
North Dakota	Williston		13.95	16.19	16
Montana	Powder River		21.81	24.05	24

Pipeline configuration:

- 3.2 million tonnes per year transported
- 100 km (62 mi) 12 inch pipeline with 1 booster pump
- 2,200 psig inlet and 1,200 psig outlet pressure

CO_2 Storage Potential

CO_2 Storage Potential – Atlas IV

- **This is a resource estimate**
- **Needs to be proven**
  - Site Characterization
  - Operations
- **Storage Coefficients**
  - Low = 0.4%
  - High = 5.5%
  - Regional Values
  - Project specific will have higher values
    - Core data
    - Wireline data (logging)
    - modeling

	State	Deep Saline Formation Storage Million Metric Tons	
		Low Estimate	High Estimate
1	Texas	333,400	4,584,250
2	Louisiana	149,360	2,053,760
3	Montana	120,710	1,653,720
4	North Dakota	103,220	120,070
5	Wyoming	87,430	1,202,200
6	Mississippi	45,450	624,940
7	New Mexico	32,120	441,650
8	Colorado	30,860	424,330
9	California	30,070	413,490
10	Washington	29,930	411,570
	Appalachian, Illinois & Michigan Basins		
15	Michigan	14,620	58,490
16	Indiana	14,370	85,440
18	Illinois	8,490	115,330
20	Pennsylvania	6,900	27,620
21	West Virginia	4,480	17,930
23	Ohio	3,970	15,900
24	New York	1,700	6,820
25	Kentucky	1,350	9,450

The United States 2012 Carbon Utilization and Storage Atlas, 4th Edition. Found at: http://www.netl.doe.gov/research/coal/carbon-storage/atlasiv

CO_2 Storage Lecture

Acknowledgements

NETL Strategic Center for Coal

Sean Plasynski – Director Strategic Center for Coal

John Wimer – Director Office of Coal & Power R&D

Traci Rodosta – Technology Manager – Carbon Storage

Kristin Gerdes – Director Office of Program Performance & Benefits (OPPB)

Chuck Zelek – Director Benefits Division (OPPB)

Contractors (ESPA)

Booz Allen Hamilton

Advanced Resources International

MRI Global

QUESTIONS

Links to Cost Models

- **Link to FE/NETL CO_2 Saline Storage Cost Model**
  - http://www.netl.doe.gov/research/energy-analysis/analytical-tools-and-data/co2-saline-storage
- **Link to FE/NETL CO_2 Transport Cost Model**
  - http://www.netl.doe.gov/research/energy-analysis/analytical-tools-and-data/co2-transport

CO_2 Storage Lecture

Appendix A:

- **Summary notes on Class VI and Subpart RR regulations**

Appendix A:
Class VI Injection Well Regulations

- Class VI injection wells are part of USEPA's Underground Injection Control (UIC) Program
- UIC Program is authorized under the Safe Drinking Water Act
- Primary intent of Class VI injection well regulations is to protect underground sources of drinking water (USDWs); preventing injected CO_2 from reaching atmosphere is secondary effect of regulations
- Class VI is the main regulatory framework for CO_2 storage; Subpart RR complements the Class VI regulations, but imposes lesser requirements
- Operator must obtain a Class VI permit for each injection well and the permit application requires the submittal of several documents

Appendix A:
Class VI Injection Well Permitting Process

- **Permitting process can be divided into 6 phases which are used to define structure of FE/NETL CO_2 Saline Storage Cost Model**
- **Phase 1: Regional evaluation and site selection – identify a candidate site using readily available geologic data**
- **Phase 2: Site characterization**
  - Perform detailed characterization of site (strat wells, seismic surveys, other field work)
  - Design storage system (develop geologic model of site, design injection system, perform reservoir simulations of injection system, design monitoring program)
  - Based on reservoir simulations, delineate CO_2 plume area and Area of Review (AoR), which is the maximum extent of elevated pressures
  - Identify operating and abandoned wells in AoR
  - Secure surface access rights and pore space rights
  - Prepare documents for Class VI permit

Appendix A:
Class VI Injection Well Permitting Process

- **Phase 3: Obtain Class VI permit**
  - Finalize five plans needed for Class VI permit
    - AoR and Corrective Action: Document delineates location of CO_2 plume and AoR based on reservoir simulations. All operating and abandoned wells that penetrate seal or cap rock are identified in this plan. The plan also describes the process for testing and properly plugging old wells that may not have been correctly plugged (i.e., corrective action or CA).
    - Testing & Monitoring: Document presents suite of technology to be used to confirm location of CO_2 plume and pressure front, assure injection well integrity as well as assure non-endangerment. Plan should include direct and in-direct measurement of the reservoir and overlying strata. Plan includes monitoring of near surface environments.
    - Injection Well Plugging: Document presents methods and technologies to assure injection wells are plugged when injection stops.
    - Post-Injection Site Care (PISC) and Site Closure: Document presents suite of technologies to be used after injection ceases to confirm location and (presumably) stability of CO_2 plume and track decline in reservoir pressure to ambient pressure before injection.
    - Emergency and Remedial Response (ERR): Document presents program for responding to leakage of CO_2 and/or formation fluids from the storage reservoir.

Appendix A:
Class VI Injection Well Permitting Process

- **Phase 3: Obtain Class VI permit**
  - Secure Financial Responsibility instruments
    - Instrument is intended to provide funds for USEPA or state to complete the following tasks should the operator fail to do so: CA, injection well plugging, PISC and site closure, and ERR
    - Example instruments are self insurance (for large, well funded operators), trust funds, escrow accounts, insurance
    - Instrument must be secured before permit application with possibility for short pay-in period (3 years) to fully fund trust fund or escrow account
    - Note: Fully funding trust fund or escrow account early in project has the effect of moving costs for CA, injection well plugging, PISC and site closure, and ERR to the beginning of the project which can increase financing costs; these costs typically occur later (for some costs, much later) in the storage project

Appendix A:
Class VI Injection Well Permitting Process

- **Phase 3: Obtain Class VI permit**
  - Submit required plans for injection wells and demonstration of Financial Responsibility to regulatory authority (USEPA or state if state has primacy)
    - Respond to USEPA or state requests for more info and/or clarification
    - Public review
  - USEPA or state provides approval to drill injection wells
  - Operator drills, tests and completes injection wells
    - Incorporate new well data with data submitted with plans
    - If new data indicates significant disagreement with data in plans, then operator will have to revise and re-submit plans
    - Submitted and approved plans appended to permit
  - USEPA or state approves injection
    - Permit awarded for life of operations and PISC
    - Operator has 180 days to submit Monitoring, Reporting, and Verification (MRV) Plan for compliance with Subpart RR

Appendix A:
Class VI Injection Well Permitting Process

- **Phase 4: Operations**
  - Perform work as described in submitted plans
    - Frequency of data sampling and application of technology described in Testing and Monitoring Plan
  - Submit review of AoR at least every five years
    - Delineate position of CO_2 plume and pressure front
    - Condition of injection wells
    - Any other changes discovered since last review
    - Permit can be modified, revoked, reissued, or terminated at this time
  - Annual review of financial responsibility instrument
    - Review of nominal cost of covered activities
    - USEPA or state determines if there are sufficient funds available and, if not, a need to increase funding
    - Permit can be modified per new instruments or revoked for insufficient coverage
  - Injection operations cease
    - Plug injection wells according to Injection Well Plugging Plan
    - Submit injection well plugging report

Appendix A:
Class VI Injection Well Permitting Process

- **Phase 5: Post-Injection Site Care and Site Closure**
  - Primary concern is return of elevated reservoir pressure to ambient pressures before injection
  - Perform work as described in PISC and Site Closure Plan
    - Frequency of data sampling and application of technology described in Plan
    - Can be same as during operations or different
  - Default period of 50 years
    - Operator can request shorter time period for PISC when injection ceases based on data acquired during operations
  - Closure is obtained when USEPA or state establishes non-endangerment of USDWs
    - Monitoring wells are plugged, other monitoring devices removed along with surface equipment
    - Site closure report submitted
    - Class VI permit released
    - Financial Responsibility instruments released

Appendix A:
Class VI Injection Well Permitting Process

- **Phase 6: Long-term stewardship**
  - USEPA does not have authority to transfer liability
  - Several states have passed legislation regarding long-term stewardship responsibilities

Appendix A:
Subpart RR Regulations

- Subpart RR is part of the Greenhouse Gas Reporting Rule which is authorized under the Clean Air Act
- Subpart RR is a reporting and monitoring requirement for Class VI injection wells
- Intent of Subpart RR is to obtain information on mass of CO_2 entering storage site, mass of CO_2 being injected and mass of CO_2 being emitted from various pathways to allow CO_2 mass balance calculations to be performed

Appendix A:
Subpart RR Regulations

- **All Class VI injection wells must comply**
- **Monitoring, Reporting and Verification (MRV) Plan:**
  - Submit within 180 days of Class VI permit
  - Shallow subsurface (e.g., soil gas, groundwater) and surface monitoring
  - Surface equipment leakage monitoring
  - Operator defines specific areas of concern to monitor
- **MRV reporting requirements:**
  - Mass of CO_2 received by source
  - Mass of injected CO_2 and, if applicable, mass of produced CO_2
  - Mass of CO_2 emitted from surface equipment
  - Mass of CO_2 emitted to the surface from other pathways
  - Prescribed use of mass balance equations
- **Much of the material needed for MRV Plan may already be included in Testing & Monitoring Plan submitted for Class VI permit**