Why Do CO$_2$ Storage?

- Mitigate climate change
- Clean coal technology
What is CO₂ Storage?

- Find a deep, relatively permeable, saline aquifer with a relatively impermeable cap rock
- Install deep injection wells
- Inject CO₂ into deep, saline formation

Source: NETL.
A Little Background Material

• Geology
• Properties of CO₂
• CO₂ storage concepts
• Environmental risks from CO₂ storage and regulations applicable to CO₂ storage
• Rudimentary design and cost considerations
Subsurface consists of layers of rocks (formations) with each layer having different properties

Key properties:
- Thickness ($h$) (thicker is better)
- Porosity ($\phi$) 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

Source: NETL.
Properties of CO₂

- Critical point
  - 7.38 Mpa or 1,071 psi
  - 31.1 deg C or 88 deg F
- Storage generally done when CO₂ is supercritical fluid
- CO₂ is supercritical at depths greater than 2,300 to 2,800 feet, approximately

This diagram is in the public domain according to the licensing section of this website.
Density and Viscosity of CO₂ and Brine as Functions of Depth

Source: NETL.
• CO₂ and brine flows follow Darcy’s law for flow in porous media

\[ q = -\frac{k}{\mu} (\nabla p - \rho g) \]

– where:

• \( q \) = volumetric flux of fluid (vector) (m³/m²-s)
• \( k \) = permeability tensor (m²)
• \( \mu \) = viscosity (Pa-s or kg/m-s)
• \( p \) = pressure (Pa or kg/m-s²)
• \( \rho \) = density of fluid (kg/m³)
• \( g \) = acceleration due to gravity (vector) (9.81 m/s²)
CO₂ Storage Concepts

- **Initially** only brine in formation
- **During injection**, CO₂ displaces brine
- Injection pressures drive fluid movement
- Residual, immobile brine remains as CO₂ migrates (10 to 30% of pore space)
- Elevated pressures extend well beyond CO₂ plume
- **After injection**, CO₂ moves up and out (buoyancy important for movement)
- Residual, immobile CO₂ remains as brine replaces CO₂ (10 to 30% of pore space)
- Pressure declines rapidly at first
- **After a long time**, CO₂ movement stops when constrained by structure or present at residual, immobile saturations
- Pressure declines slowly to ambient pressures

Source: NETL.
Trapping mechanisms for CO₂
- Structural: Mobile CO₂ is prevented from migrating by cap rock or structural closures (immediate)
  - Dome (inverted bowl)
  - Anticline (folded paper)
  - Stratigraphic
  - Closure against a fault
- Capillary: CO₂ is immobilized by capillary forces (residual CO₂ saturation) (immediate to 5,000 years)
- Dissolution: CO₂ dissolves in brine (100 to 10,000 years)
- Mineralization: CO₂ 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
Design and Cost of CO₂ Storage Project

- Concepts presented are from FE/NETL CO₂ Saline Storage Cost Model
  - 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 CO₂ injected
    - Maximum hourly or daily rate
    - Average rate per year
  - Duration of injection
- Critical design values
  - Area of the CO₂ 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

- CO₂ Plume Area
- CO₂ Plume Uncertainty Area
- Pressure Front Area

Source: NETL.
Estimating Areal Quantities

- **CO₂ Plume Area**

  \[ A_{pl} = \frac{q_{m-CO₂} \cdot T_{inj}}{\rho_{CO₂} \cdot h \cdot \phi \cdot e_{st}} \]

  where:
  - \(A_{pl}\) = CO₂ Plume Area (m²)
  - \(q_{m-CO₂}\) = annual average mass rate of CO₂ injection (kg/year)
  - \(T_{inj}\) = duration of the injection (years)
  - \(\rho_{CO₂}\) = density of CO₂ at reservoir temp. and press. (kg/m³)
  - \(h\) = thickness of formation (m)
  - \(\phi\) = porosity
  - \(e_{st}\) = storage coefficient
Estimating Areal Quantities

• CO₂ Plume Uncertainty Area
  
  \[ A_{pl-un} = A_{pl} \cdot a_{pl-un} \]

  where:
  
  • \( A_{pl-un} \) = CO₂ Plume Uncertainty Area (m²)
  • \( A_{pl} \) = CO₂ Plume Area (m²)
  • \( a_{pl-un} \) = CO₂ plume uncertainty factor (1.75)

• Pressure Front Area

\[ A_{pf} = A_{pl-un} \cdot a_{pf} \]

where:

• \( A_{pf} \) = Pressure Front Area (m²)
• \( A_{pl-un} \) = CO₂ Plume Uncertainty Area (m²)
• \( a_{pf} \) = pressure front multiplier (10)
Number of Active Injection Wells Needed

- **Number of active injection wells**
  \[ N_{\text{injw}} = \frac{q_{\text{maxCO2proj}}}{\min(q_{\text{mmaxf}}, q_{\text{mmaxw}})} \]
  - where:
    - \( N_{\text{injw}} = \) number of active injection wells
    - \( q_{\text{maxCO2proj}} = \) maximum daily mass rate of CO\(_2\) that injection project needs to accommodate (design parameter) (tonne/day)
    - \( q_{\text{mmaxf}} = \) maximum rate of flow that formation can sustain from one injection well
    - \( q_{\text{mmaxw}} = \) 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: 19
Number of Active Injection Wells Needed

- Law and Bachu (1996) equation for maximum mass flow rate the formation can sustain

\[ q_{mmax} = a_{LB} \cdot k \cdot h \cdot (p_{max} - p_{amb})/\mu_{CO2} \]

- 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)
  - \( \mu_{CO2} \) = 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 Simon formation in Illinois (good storage candidate)
  - Depth to top of formation = 4,000 ft
  - Thickness = 1,000 ft, 305 m
  - Porosity = 12%
  - Permeability = 55 mD
  - Storage coefficient (flat or sloping) = 5.63%
  - Density of CO$_2$ in reservoir = 645 kg/m$^3$
  - Viscosity of CO$_2$ in reservoir = 0.0534 cp
  - Ambient pressure in formation = 14.4 MPa, 2,090 psi
  - Max. bottom hole inject. press. = 16.5 MPa, 2,390 psi
Example Calculations

- Rose Run formation in Pennsylvania (poor storage candidate)
  - Depth to top of formation = 14,000 ft
  - Thickness = 450 ft, 137 m
  - Porosity = 8%
  - Permeability = 1.6 mD
  - Storage coefficient (flat or sloping) = 4.71%
  - Density of CO$_2$ in reservoir = 728 kg/m$^3$
  - Viscosity of CO$_2$ in reservoir = 0.0631 cp
  - Ambient pressure in formation = 45.5 MPa, 6,500 psi
  - Max. bottom hole inject. press. = 52.8 MPa, 7,660 psi
## Example Calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mount Simon (IL)</th>
<th>Rose Run (PA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Plume Area (mi²)</td>
<td>27.9</td>
<td>98.5</td>
</tr>
<tr>
<td>CO₂ Plume Uncertainty Area (mi²)</td>
<td>48.9</td>
<td>172.3</td>
</tr>
<tr>
<td>Pressure Front Area (mi²)</td>
<td>489</td>
<td>1723</td>
</tr>
<tr>
<td>Ratio of CO₂ Plume Diameter to Thickness</td>
<td>31.5</td>
<td>131</td>
</tr>
<tr>
<td>Number of Active Injection Wells</td>
<td>3</td>
<td>22</td>
</tr>
</tbody>
</table>

As points of reference:
- Area of Pittsburgh: 58.3 mi²
- Area of Allegheny County: 745 mi²
## CO₂ Storage Project Phases

<table>
<thead>
<tr>
<th>Regional Eval.</th>
<th>Site Selection &amp; Char.</th>
<th>Permitting &amp; Inj. Well Drilling</th>
<th>Operations</th>
<th>Post-Injection Monitoring</th>
<th>Long-Term Stewardship</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>UIC Class VI Regulations</td>
<td></td>
<td>Class VI Permit</td>
<td>Developing State Regulations</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>rest of civilization</td>
</tr>
<tr>
<td>0.5 to 1 year</td>
<td>3+ years</td>
<td>2+ years</td>
<td>30 to 50 years</td>
<td>10 to 50+ years</td>
<td>another entity (e.g., a state) takes over</td>
</tr>
<tr>
<td>gather existing data, develop several prospects</td>
<td>select a site, acquire new data (drill wells, shoot seismic), prepare permitting plans</td>
<td>permit awarded to drill injection wells, final approval to begin injection.</td>
<td>inject CO₂, drill monitoring wells &amp; remediate existing wells as needed, MVA</td>
<td>monitor site, establish non-endangerment, close and restore site</td>
<td></td>
</tr>
<tr>
<td>assemble acreage block (surface access/pore space; $50/acre + per tonne royalty)</td>
<td>Secure financial responsibility upon permit application; as required, pay into trust fund for financial responsibility if selected; perform on covered tasks.</td>
<td>pay $/tonne fees*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25% success rate assumed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>negative cash flow</td>
<td></td>
<td>positive cash flow</td>
<td>negative cash flow</td>
<td>covered by fee paid during ops</td>
<td></td>
</tr>
</tbody>
</table>

* Default assumptions are $0.07/tonne for long-term stewardship, $0.75/tonne for insurance to cover emergency & remedial response during injection/PISC, and $0.25/tonne “royalty” to pore space owner.

Source: NETL.
CO₂ Storage – Class VI Regulations

Regional Geologic Evaluation for Class VI Injection Permit

- Minimum Criteria for Siting [§146.83]
  - Injection zone(s) of sufficient areal extent, thickness, porosity, and permeability for anticipated volume of CO₂.
  - Confining zone(s) of sufficient areal extent and free of transmissive faults and fractures.
  - May have to characterize additional confining zones.

\[
Areal Extent = \frac{Q_{mass \: CO₂}}{h\rho_{CO₂} \Phi E}
\]

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

Source: NETL.
CO₂ Storage – Class VI Regulations

Site Characterization: Required Class VI permit information [§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 CO₂
  – Analysis of chemical and physical characteristics of CO₂ to be injected
Area of Review and Corrective Action [§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 CO₂ stream
    - Director may require reactive transport or geomechanical modeling
  - Predict the projected lateral and vertical migration of CO₂ 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.
CO₂ Storage – Area of Review (AoR)

Tenaska Taylorville Energy Center (TEC)  FutureGen 2

The ISWS and ISGS databases indicate that there are at least 19 water wells within the Survey Area. However, many of the water wells in the ISWS database are only identified with a general location (section, township, and range) and thus may or may not be within the Survey Area. These wells are not shown. In addition, many of the 03 residences shown on the map may have unregistered water wells.
CO$_2$ Storage – Class VI Regulations

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?

Appalachian Basin - WVa

CO₂ Storage – Class VI Regulations

Tenaska TEC

• Shallow oil production less than 2,500 ft
• Only four wells penetrate the St. Peter Sandstone
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 §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 §146.86 [Injection well construction requirements]

- Proposed AREA OF REVIEW AND CORRECTIVE ACTION PLAN that meet the requirements of §146.84 [Area of review and corrective action]

- A demonstration, satisfactory to the Director, that the applicant has met the financial responsibility requirement under §146.85 [FINANCIAL RESPONSIBILITY]

- Proposed TESTING AND MONITORING PLAN required by §146.90 [Testing and monitoring requirements]

- Proposed INJECTION WELL PLUGGING PLAN required by §146.92(b) [§146.92 Injection well plugging]

- Proposed POST-INJECTION SITE CARE AND SITE CLOSURE PLAN required by §146.93(a) [§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 §146.93(c)

- Proposed EMERGENCY AND REMEDIAL RESPONSE PLAN required by §146.94(a) [§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 [§146.82(a)(2)]

- Any other information requested by the Director

Permit Awarded – permission to drill CO₂ injection well but can not begin injection operations
Primary purpose of UIC regulations – protect USDW

- Potential pathways for migration of \( \text{CO}_2 \) from storage

Source: NETL.
## CO₂ Storage – Class VI Regulations

<table>
<thead>
<tr>
<th>Release Scenario</th>
<th>Likelihood (annual)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pipeline Events</strong></td>
<td></td>
</tr>
<tr>
<td>Pipeline Rupture</td>
<td>1 in 200 (0.5%)</td>
</tr>
<tr>
<td>Pipeline Puncture</td>
<td>1 in 100 (1.0%)</td>
</tr>
<tr>
<td><strong>Storage Site Events</strong></td>
<td></td>
</tr>
<tr>
<td>Wellhead Equipment Rupture</td>
<td>6 in 100,000 (0.006%)</td>
</tr>
<tr>
<td>CO₂ Injection Well Leak</td>
<td>3 in 100,000 (0.003%)</td>
</tr>
<tr>
<td>Other Well Leak</td>
<td>7 in 100 (7.0%)</td>
</tr>
<tr>
<td>Rapid Leakage through Caprock</td>
<td>2 in 10 billion (0.000000002%)</td>
</tr>
<tr>
<td>Slow Leakage through Caprock</td>
<td>4 in 100,000 (0.004%)</td>
</tr>
<tr>
<td>Release through Existing, Induced Faults</td>
<td>2 in 100 million (0.000002%)</td>
</tr>
</tbody>
</table>

- **Emergency and Remedial Response [§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 CO₂ modeled for storage)
# CO₂ Storage – FutureGen 2 ERR Estimate

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

- **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
CO₂ Storage – Financial Responsibility

Tied to EPA’s Categories for Financial Responsibility

<table>
<thead>
<tr>
<th>Million $</th>
<th>EPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>Extensive relief well &amp; water treatment mitigation</td>
</tr>
<tr>
<td>15</td>
<td>Water Quality contamination during the fluid phase – Drinking water replacement</td>
</tr>
<tr>
<td></td>
<td>A single large release to the surface – relief well mitigation</td>
</tr>
<tr>
<td></td>
<td>Chronic low-level releases to surface – relief well mitigation</td>
</tr>
<tr>
<td>10</td>
<td>Entrained contaminant releases – pumpback and treatment systems</td>
</tr>
<tr>
<td></td>
<td>Storage rights infringement – relief well mitigation</td>
</tr>
<tr>
<td>5</td>
<td>Modified surface topography – structural damages</td>
</tr>
<tr>
<td>5</td>
<td>Accidents or unplanned events – surface clean-up</td>
</tr>
<tr>
<td>57</td>
<td>Total</td>
</tr>
<tr>
<td>2</td>
<td>Well plugging &amp; abandonment (3 injection wells, 3 monitoring well per injection well)</td>
</tr>
<tr>
<td>2</td>
<td>Facilities/Pipeline D&amp;D/Abandonment</td>
</tr>
<tr>
<td>2</td>
<td>Surface disturbance reclamation</td>
</tr>
<tr>
<td>6</td>
<td>Total</td>
</tr>
<tr>
<td>9</td>
<td>Post-injection monitoring (15 yrs)</td>
</tr>
<tr>
<td>1</td>
<td>Post-injection inspection and maintenance</td>
</tr>
<tr>
<td>2</td>
<td>Contractor contingencies for site closure &amp; reclamation (15%)</td>
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<tr>
<td>1</td>
<td>Field Management</td>
</tr>
<tr>
<td>1</td>
<td>Unknowns for site closure &amp; reclamation (10%)</td>
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<tr>
<td>16</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>Corrective Action – remediate old wells</td>
</tr>
<tr>
<td>77</td>
<td>Total for Financial Responsibility</td>
</tr>
</tbody>
</table>

### 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 mi² (0.15 mi²/MtCO₂)
- 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/MtCO₂ sequestered for Financial Responsibility

FutureGen 2: 22 MtCO₂ 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](http://deq.state.wy.us/out/downloads/1%20FinalReport081909.pdf)
CO₂ Storage – Injection Well

**Injection Well Construction [§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

---

Figure 4-1 TEC #1-Injection Well Proposed Design Schematic
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.
CO₂ Storage – Operations

Operations: Monitoring Injection Well

- 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.

Figure 4-1 TEC #1-Injection Well Proposed Design Schematic
CO$_2$ Storage – Operations

Operations:

Testing and Monitoring [§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 CO$_2$ 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
CO₂ Storage – Monitoring Wells

Operations: Monitoring Wells-Direct

- 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)
  - monitoring USDWs
  - Consider installing/operation more than the minimal number of monitoring wells
  - More extensive and frequent monitoring from beginning of operations

Indirect methods of monitoring

- Seismic, electrical, gravity, or electromagnetic surveys and/or downhole CO₂ detection tools
- Unless Director determines, based on site geology, that such methods are not appropriate

Source: NETL
CO₂ Storage - Monitoring

§146.90: Testing & Monitoring

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.

§146.93: Post-injection site care and site closure

Periodic monitoring of the ground water quality and geochemical changes above the confining zone(s) that may be a result of CO₂ 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 CO₂ 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 CO₂ 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.
**CO₂ Storage – Class VI Regulations**

**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**
Post-injection site care (PISC) and site closure [§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 CO2 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 Regulations

FutureGen2 – Post-Injection Site Care:
20 years injection – 22 Mt CO2
50 years planned post-injection site care

FutureGen Alliance UIC Permit Application. Supporting Documentation
CO$_2$ Storage – Class VI Regulations

Tenaska TEC: Pressure Front = 78,793 ac. (30 yrs); 23.12 ac. (proj yr 45)
Plume Area = 11,294 ac. (30 yrs); 11,603 ac. (proj yr 45)
CO₂ Storage

NETL Four Basin Study – Transportation & Storage Costs

- Williston Basin Storage for ND Plants
- Powder River Basin Storage for MT Plants
- Illinois Basin Storage for Midwest Plants
- East Texas Basin Storage for TX Plants

• 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.
## CO₂ Storage
### NETL Four Basin Study – Transportation & Storage Costs

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Pipeline configuration:
- 3.2 million tonnes per year transported
- 100 km (62 mi) 12 inch pipeline with 1 boost pump
- 2,200 psig inlet and 1,200 psig outlet pressure
CO₂ 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

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<th>State</th>
<th>Deep Saline Formation Storage (Million Metric Tons)</th>
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CO$_2$ Storage

Acknowledgements

NETL Strategic Center for Coal
- Sean Plasynski – Director Strategic Center for Coal
- Jared Ciferno – Director Office of Coal & Power R&D
- Traci Rodosta – Technology Manager – Carbon Storage
- John Wimer – Director Office of Program Performance & Benefits (OPPB)
- Chuck Zelek – Director Benefits Division (OPPB)

Contractors (ESPA)
- Booz Allen Hamilton
- Advanced Resources International
- MRI Global