Carbon Capture and Sequestration
A Briefing by The CCSReg Project
Presentation Sponsored by Senator Robert P. Casey, Jr.

From Carnegie Mellon:
Granger Morgan, PI
Sean McCoy, Proj. Mgr.
Jay Apt
Sue Day
Paul Fischbeck
Edward Rubin
And Ph.D. students:
Lee Gresham
Olga Popova

From Vermont Law:
Michael Dworkin
Don Kreis
Over a dozen law students

From Van Ness Feldman:
Bob Nordhaus
Emily Pitlick
Ben Yamagata

From U. of Minnesota:
Elizabeth Wilson
Melisa Pollak
Several MS students

Details at: http://www.ccsreg.org
CO$_2$ is Not Like SO$_2$ or NO$_x$

Much of the CO$_2$ that gets emitted when we burn coal, oil and natural gas stays in the atmosphere for over 100 years. To stabilize the concentration of CO$_2$ in the atmosphere, the world needs to reduce emission by about 80%. A good analogy is a bathtub with a very large faucet and a very small drain. Unless the faucet gets closed way down the tub will continue to fill up.
Achieving an 80% Reduction...

• …in CO$_2$ emissions at a price we can afford is going to take a portfolio that includes:
  – Improved efficiency and conservation;
  – Nuclear;
  – Wind, hydro, and other renewables;
  – Cost effective energy storage;
  – Electrification of transport;
  – Carbon capture with deep geological sequestration, also know as (CCS); and,
  – Perhaps, direct air scrubbing.
Today the Bulk of…

The world's energy comes from coal, oil and natural gas.

In the U.S. today, we make about half of all our electricity from coal. The fraction is equal or greater in most of the world.

Whatever your views of fossil fuels, it is hard to see how we can shrink the blue part of the pie enough over the next 50 years to achieve the emission reduction that we need at an affordable cost.

That is why we have been working on CCS.
At Carnegie Mellon...

...Ed Rubin and his students and colleagues have worked extensively on technical performance and cost issues related to CCS.

Building on this work, Profs. Apt, Lave, Keith, Morel, and their students and colleagues have worked extensively on the economics of adoption.
While There Are Big Technical Challenges…

…issues of regulation are clearly critical to the future success of CCS. In 2007, we ran two workshops – the first here in Washington, DC in March.

Commissioned papers from:

- BP
- Bellona/Statoil
- RFF/IVL/CICERO
- UK Energy Research
- Australian GHG Office
- SwissRe
- Carnegie Mellon
- MIT
- Stanford
- NRDC
- PIK

Then in November 2007 at SwissRe near Zurich.
The CCSReg Project

These previous efforts laid the foundations for a project to develop a proposed regulatory framework for the U.S. for the deep geological sequestration (GS) of CO$_2$. The project assumes that new or modified legislative authority can be developed if needed.

CCSReg is a distributed effort anchored at Carnegie Mellon.

The project is supported by a $1.8-million grant from the Doris Duke Charitable Foundation with additional support from the Carnegie Mellon-NSF Climate Decision Making Center.
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We have allowed ample time for discussion after each brief presentation and for general Q&A and discussion at the end.
But, Before I Hand Off to Ed…

…let me answer the basic question:

"Why should we care about any of this right now before any significant amount of CCS is in place?"

ANSWER:

• 50% of our electricity comes from coal and there is no cost effective, or politically viable, way to get major emission reductions without CCS.

• As we'll explain in the talks that follow, today there is high uncertainty. If a comprehensive national framework is not developed now, to give regulatory certainty, the whole approach may become too expensive, financially risky, or difficult to adopt.

• Our briefing notes lay out how to resolve these issues.
Schematic of a CCS System

Energy Conversion Process

- Carbonaceous Fuels
- Air or Oxygen

CO₂ Capture & Compress
- Post-combustion
- Pre-combustion
- Oxyfuel combustion

CO₂ Transport
- Pipeline
- Tanker

CO₂ Storage (Sequestration)
- Depleted oil/gas fields
- Deep saline formations
- Unmineable coal seams
- Ocean
- Mineralization
- Reuse

Useful Products
(Electricity, Fuels, Chemicals, Hydrogen)
Leading Candidates for CCS

• Fossil fuel power plants
  – Pulverized coal combustion (PC)
  – Natural gas combined cycle (NGCC)
  – Integrated coal gasification combined cycle (IGCC)

• Other large industrial sources of CO$_2$ such as:
  – Refineries, fuel processing, and petrochemical plants
  – Hydrogen and ammonia production plants
  – Pulp and paper plants
  – Cement plants

— Main focus is on power plants, the dominant source of CO$_2$ —
Many Ways to Capture CO$_2$

Choice of technology depends strongly on application
Post-Combustion Capture

Steam Turbine Generator

PC Boiler

Air Pollution Control Systems (NO\textsubscript{x}, PM, SO\textsubscript{2})

CO\textsubscript{2} Capture

Amine/CO\textsubscript{2} Separation

CO\textsubscript{2} to storage

Flue gas to atmosphere

Also applies to gas-fired power plants
Oxy-Combustion Capture

Steam Turbine Generator

PC Boiler

Air Pollution Control Systems (PM, SO₂)

Distillation System

CO₂ Compression

Steam

Electricity

Flue gas to atmosphere

Stack

CO₂ to storage

Coal

O₂

Air Separation Unit

Air

Flue gas recycle
Pre-Combustion Capture

- **Gasifier**
- **Quench System**
- **Shift Reactor**
- **Sulfur Removal**
- **CO₂ Capture**
- **Selexol/CO₂ Separation**
- **CO₂ Compression**
- **Combined Cycle Power Plant**
- **Air Separation Unit**
- **Flue gas to atmosphere**

Flowchart details:
- Air separation
- Quench system
- Shift reactor
- Sulfur removal
- CO₂ capture
- Selexol/CO₂ separation
- CO₂ compression
- Combined cycle power plant
-Flue gas to atmosphere
Status of CCS Technology

• Pre- and post-combustion CO$_2$ capture systems are commercial and widely used in industrial processes. Capture efficiencies are ~90%. Oxy-combustion systems are being developed and not yet commercial.

• Post-combustion capture also is employed at several gas-fired and coal-fired power plants to produce high-purity CO$_2$ for sale, but at scales small compared to a modern power plant (~40-50 MW).

• Integration of CO$_2$ capture, transport and geologic sequestration has been demonstrated in several large-scale (~1 Mt CO$_2$/yr) industrial applications (all outside the US), but not yet at an electric power plant at scale (≥3 Mt CO$_2$/yr). One U.S. power plant has integrated CCS at a pilot plant scale (~20 MW).
Examples of Post-Combustion CO$_2$ Capture at U.S. Power Plants

- **Bellingham Cogeneration Plant**
  
  (Bellingham, Massachusetts, USA)

- **Warrior Run Power Plant**
  
  (Cumberland, Maryland, USA)
Examples of Pre-Combustion CO$_2$ Capture at U.S. Industrial Sites

Petcoke Gasification to Produce H$_2$
(Coffeyville, Kansas, USA)

Coal Gasification to Produce SNG
(Beulah, North Dakota, USA)
Example of Oxy-Combustion CO$_2$ Capture System

30 MWt Pilot Plant (~10 MWe) at Vattenfall Schwarze Pumpe Station (Germany)
CO$_2$ Pipelines in the Western U.S.

~40 MtCO$_2$/yr transported

Source: USDOE/Battelle

Source: NRDC
Geological Formations in North America

Oil & Gas Fields

Deep Saline Formations
Geological Storage of Captured CO$_2$ with Enhanced Oil Recovery (EOR)
Geological Storage of Captured CO$_2$ in a Depleted Gas Reservoir

In Salah /Krechba  (Algeria)

Source: BP
Geological Storage of Captured CO$_2$ in a Deep Saline Formation

Sleipner Project (Norway)

Source: Statoil
Saline Formation Storage at the AEP Mountaineer Pilot Plant

Source: AEP, 2009
Trapping Mechanisms Provide Increasing Storage Security with Time

- Storage security depends on a combination of physical and geochemical trapping mechanisms.
- Over time, CO₂ trapping mechanisms increase the security of storage.
- Appropriate site selection and management are the keys to secure storage.

Source: S. Benson, LBNL

![Graph showing increasing storage security over time with different trapping mechanisms.](image)

Time since injection stops (years)
Still Missing

- Power plant demonstration project #1
- Power plant demonstration project #2
- Power plant demonstration project #3
- Power plant demonstration project #4
- Power plant demonstration project #5
- Power plant demonstration project #6
- Power plant demonstration project #7
- Power plant demonstration project #8
- Power plant demonstration project #9
- Power plant demonstration project #10
Proposed Projects in North America

- Map shows operating plus proposed or planned projects in the U.S. and Canada. They encompass power plants, industrial sources and research projects of widely varying scale.
Full-Scale Demonstration Projects Are Urgently Needed to . . .

- Establish the **reliability** and true **cost** of CCS in power plant applications
- Help resolve legal and regulatory issues regarding geological sequestration
- Address issues of public acceptance
- Reduce costs via learning-by-doing

- Financing large-scale projects remains a major hurdle;
- Despite announced plans and roadmaps, still not certain **when** or **where** we will see the first full-scale CCS power plant demo
Will Utilities Build Plants w/ CCS?

- Until a stable, predictable and substantial carbon market exists, CCS will require mandates or government support to encourage investment and deployment.

- Achieving economically viable options for investments in CCS plants is possible through a variety of policy options or combinations of policies:
  - A dynamic perspective is important.

- Operating decisions involve different economic factors that also must be considered, e.g.:
  - If built, will the CCS-plant operate?
  - Marginal costs and price of electricity
  - Generation costs of competing plants
  - Load factors for CCS plants uncertain
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Our Objective in the CCSReg Project…

… is to design a regulatory system that is safe, comprehensive, environmentally sound, affordable, internationally compatible and socially equitable.

Our focus in this presentation will be on the regulatory issues involved in moving CO₂ from the power plant to the injection site, and on all aspects of the life cycle of that site.
We Address Regulatory Needs Across the Lifecycle of a Sequestration Project

Legal access to and use of pore space

Liability and long-term stewardship

Need for an adaptive & comprehensive approach
We Believe That CCS Regulation…

…should be the responsibility of the following organizations:

- FERC & DOT for interstate CO$_2$ pipelines;
- EPA to oversee the licensing and operation of injection sites - with the option to delegate responsibility to states;
- A newly created independent Federal Geologic Sequestration Board housed administratively within the Department of Energy.
Minimize Use of Procedural Regulations

Regulations developed by:

- EPA for permitting the operation of GS Projects, and

- The Federal Geologic Sequestration Board for accepting GS sites into long-term stewardship and managing sites once they have entered long-term stewardship.

Should be performance based, and should consider the specific characteristics of the geologic properties of the formations into which CO$_2$ is being or has been injected.
Why a Take a Performance-Based Adaptive Approach

• To allow for potential migration of CO₂ in pore space:
  – Regulations should allow the regulator and site operator to modify details of the site monitoring plan, injection operations, and other regulated activities on the basis of the accumulated evidence as injection proceeds.

• To consider varying geological properties and GS site designs:
  – Regulatory requirements (including long-term stewardship) should be periodically reviewed and revised.
  – Reviews should consider accumulated experience with CCS projects operated in the United States and around the world.
Mechanism to Incorporate Learning Into the Regulatory Process

• We propose the creation of a CCS Technical Advisory Committee of the National Research Council that:

1. Will review accumulated evidence and make recommendations on the performance-based regulatory strategy used by the EPA to regulate GS after several (5-10) commercial-scale GS facilities (2 Mt CO$_2$/yr or more) have operated for at least five years.

2. Evaluate the cumulative experience from all domestic and foreign commercial-scale projects and assess whether fundamental changes to the structure of the GS regulatory framework are needed at least once every decade thereafter.
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Access to Pore Space

In much of the world (Europe, Australia, Canada, etc.), governments own most deep-subsurface resources and property rights. In much of the U.S., ownership rights are undefined.

This ambiguity might be resolved in several ways, many of which could make CCS economically infeasible. Our current thinking is that a federally coordinated solution is superior to a state-by-state solution, or resolution in the courts.
Resolution of Pore Space Access Issues is Complex
Some Routes Could Make CCS Costly and Difficult
We Propose a Solution...

...large-scale development of geologic sequestration (GS) of CO$_2$ will require federal legislation that establishes a regulatory framework for authorizing injection of CO$_2$ into deep geologic pore space on federal and private lands.

The policy brief outlines the form that framework should take.
Recommendations for Managing Access to and Use of Pore Space

• Work within EPA's Underground Injection Control (UIC) program

• Issuance of a UIC injection permit expressly grants a GS project developer the legal right to inject and sequester CO$_2$ within the boundaries specified by the permit.

• UIC permitting should provide public notice and a significant but finite period for:
  1. filings by, and comparative consideration of, alternative GS projects that might be precluded or substantially impaired by the grant of the initial application; and,
  2. filings by mineral rights owners (and other pore space users) notifying the UIC permitting agency of conflicting uses of the pore space during permit process.
Recommendations to Manage Access to and Use of Pore Space… (Cont.)

- If material impairment of a non-GS use is demonstrated, the GS project should be permitted only in accordance with:
  1. a contractual resolution of the preexisting interest;
  2. a modification of the project that avoids the impairment; or,
  3. a finding by the UIC permitting agency that the GS project is of such public importance as to justify condemnation of the preexisting interest, with appropriate compensation if necessary.
Recommendations to Manage Access to and Use of Pore Space… (Cont.)

• Federal legislation should limit the trespass liability of project developers operating pursuant to a valid UIC permit—use of pore space should give rise to a trespass claim only when injection and migration of CO₂ materially impairs a current or imminent use.

• Legislation should not preempt state mineral rights laws, except where necessary to ensure that mineral exploration and production activities will not cause leakage of sequestered CO₂ or compromise the integrity of GS site.
# Briefing Agenda

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Magnitude and Timing of Risks in Sequestration Projects

• Hazards associated with sequestration projects include:
  – CO$_2$ escape to the atmosphere;
  – Local damage to human health and the environment;
  – Impairment of subsurface resources.

• Liability is the financial risk associated with these hazards; there are also liabilities associated with monitoring, verification, and accounting (MVA) activities post-closure.

• We are operating under the assumption that the risks associated with the hazards above decreases with time.
Liability for Sequestration Projects

- Companies will design and operate projects to minimize their exposure to these liabilities, and
- Major insurance companies are offering or expect to offer policies to address many of these liabilities through the post-injection phase of a project.

- However, less conventional mechanisms involving government, will be needed to manage these liabilities as part of long-term stewardship.
A Number of…

…alternative approaches are available to address issues of liability. We considered the strengths and limits of each as we developed our policy brief in this area.
We Propose a Solution…

Large-scale, commercial deployment of CCS requires: workable liability rules for geologic sequestration (GS), and a program for long-term stewardship of closed sequestration sites. This policy brief reviews current liability rules for personal injury, property damage, and trespass claims arising out of GS operations, options for any necessary changes in those rules, and recommends a federally administered long-term stewardship program.
Recommendations on Liability & Long-Term Stewardship:

• Operating commercial GS projects should remain subject to liability rules under otherwise applicable state and federal law and should rely on the private insurance market, or mutual insurance, for risk management.

• A federal program operated by a Federal Geologic Sequestration Board ("FGSB") should be created to oversee the long-term stewardship of adequately closed injection projects.

• The FGSB should be an "independent agency," but housed within an existing federal agency for purposes of administration. It should administer, and be financed by, a revolving fund that is based upon risk-based assessments on GS projects during their operating life.
Recommendations on Liability & Long-Term Stewardship…(Cont.)

• Once an injection project is completed and regulators determine that the project meets established standards and does not present unreasonable health, safety, or environmental risks, it should be transferred to the federal long-term stewardship program along with all liability and responsibility for compensation.

• Any necessary remediation or compensation payments during the stewardship phase should be the responsibility of the FGSB, and should be disbursed from the revolving fund. The FGSB could also make the fund available for emergency remediation of sites not yet covered by the long-term stewardship program (with the prior requirement that the FGSB will recover costs of remediation from the project operator or other parties).
Recommendations on Liability & Long-Term Stewardship…(Cont.)

- Depending on the timing of general federal CCS legislation, it may be necessary to establish a stop-gap federal indemnity program for the stewardship phase of "first-mover" projects. Those projects should ultimately be covered by the stewardship program outlined in this brief.
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This Brief Argues That:

- Commercial deployment of CCS may require construction of a large CO$_2$ pipeline system.
- To build out this system, the U.S. will need to create a workable regulatory framework.
- Considerations – no access to federal siting authority, patchwork of state laws and regulations.
It Further Argues That…

- Existing CO$_2$ pipeline system is small.
- Built for enhanced oil recovery (EOR).
- EOR system is unlikely to be sufficient to support the infrastructure build out necessary for large-scale commercial deployment of CCS.
- Likely property rights requirements: access to a federal siting process, federal eminent domain authority, and a streamlined permitting process for projects on federal lands—especially multi-state projects and some intrastate projects.
- Economic regulation hurdles: resolve and address the shape of any rules on transportation rates and access and whether pipelines will need to serve as common carriers.
Recommendations on Pipelines:

• Create an "opt-in" federal regulatory regime that provides the Federal Energy Regulatory Commission (FERC) with authority to consider and grant or deny applications for federal siting permits for new CO$_2$ pipelines built to transport CO$_2$ for purposes of permanent sequestration. The federal siting permit should provide the pipeline with federal eminent domain authority.

• Once new CO$_2$ pipelines with federal siting permits are operational they should be subject to non-discriminatory access and rate regulation. Prescriptive cost-of-service rate regulation is not necessary.
Recommendations on Pipelines…(Cont.)

- Retain the current system of state siting and economic regulation for existing CO$_2$ pipelines.
- Subject new CO$_2$ pipelines to the current system unless they opt into the federal regulatory regime by filing for and obtaining a federal siting permit.
- Streamline the permitting process for CO$_2$ pipeline projects on federal lands.
- Utilize the existing pipeline safety regulatory framework to ensure safe operation of all CO$_2$ pipelines.
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Greenhouse Gas Accounting for CCS

For carbon capture and sequestration (CCS) to be an effective climate change mitigation tool, captured CO$_2$ must be *effectively sequestered & accounted for* under a greenhouse gas (GHG) emission reduction program.

This will require knowing:
- how much CO$_2$ is captured
- How much is transported
- How much is injected
- How much energy is used
- If there is any leakage, how much escapes to the atmosphere.

*Inventory accounting*

*Emissions accounting*
Recommendations for Inventory Accounting

Make sure that captured CO\textsubscript{2} reaches its intended destination in a sequestration facility.

Three separate commercial entities

Capture $\rightarrow$ Transport $\rightarrow$ Sequestration

Operators of each stage of a CCS project should be required to measure and report the mass of CO\textsubscript{2} handled, including the amount captured, exported, imported, and injected.
Recommendations on Emissions Accounting

Under a GHG emission reduction program each stage of a CCS project should be a covered entity - required to report emissions

GS projects should be covered entities regardless of size or emissions rate, and sequestered CO₂ should be treated as avoided emissions rather than as offsets.
Recommendations on Monitoring for GHG Accounting

Routine monitoring

- Protects health and the environment, and demonstrates that CO2 is safely contained
- Site-specific, performance-based, and incorporates the lessons learned from the first hand-full of carefully monitored commercial-scale projects
- Subsurface monitoring methods.

Monitoring for GHG accounting

- Quantifies potential leakage emissions to the atmosphere
- Should be required ONLY IF routine monitoring finds that CO2 has migrated through the confining formation
- Surface monitoring methods
Recommendations on Monitoring for GHG Accounting…(Cont.)

If a loss of containment is detected, GS project operators should be required to undertake a monitoring program to quantify emissions from the site.

- Regulators should establish performance standards identifying the level of leakage a monitoring program should be designed to detect.

- If a satisfactory monitoring program cannot be implemented at the site (due to technological or other factors), the operator should submit allowances to cover a set fraction (e.g., 0.1% to 1%) of the total amount of CO₂ sequestered at the site.

Male et al., 2009, Environmental Earth Sciences
Recommendations for GHG Accounting in Long-Term Stewardship

An emissions allowance reserve program should be created to address possible emissions during the long-term stewardship phase.

- GS project operators should be required to deposit emissions allowances equal to some small fraction (e.g., less than 0.5%) of their annual injection quantity into a pooled fund, which would be used to cover leakage from all GS projects during long-term stewardship.

- The fund should be managed by the federal entity responsible for long-term stewardship.
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<thead>
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Transitioning from EOR to GS of CO\textsubscript{2}

- CO\textsubscript{2}-flood Enhanced Oil Recovery (EOR) is widely practiced in the United States and results in permanent sequestration of CO\textsubscript{2}.
- EOR is attractive because:
  - Operators have over 30-years of commercial experience with EOR.
  - It can slow declining domestic oil production.
  - Regulations surrounding EOR are generally clear.
  - The infrastructure built today for EOR could compliment development of saline aquifer sequestration in future (e.g. CO\textsubscript{2} pipelines).
Growth in CO$_2$-Flood EOR

Data: 2008 Oil & Gas Journal EOR Survey
U.S. EOR Projects in 2008

~50 Mt CO$_2$/y Sequestered

Data from Oil & Gas Journal, 2008
How is EOR Different from Sequestration in Saline Aquifers?

<table>
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<tr>
<th>Step</th>
<th>EOR</th>
<th>GS</th>
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<td>1. CO₂ is delivered via pipeline</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>2. 'New' CO₂ is mixed with recycled CO₂</td>
<td>✔</td>
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<td>3. CO₂ stream injected into the reservoir through an injection well</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>4. Oil is produced that is mixed with CO₂ and water through a production well</td>
<td>✔</td>
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<tr>
<td>5. Oil &amp; CO₂ are separated</td>
<td>✔</td>
<td></td>
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<tr>
<td>6. CO₂ is compressed and recycled</td>
<td>✔</td>
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<tr>
<td>7. Subsurface monitoring to demonstrate CO₂ containment</td>
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Recommendations on EOR

• EOR and GS projects are different and should be treated differently under a regulatory framework:
  – EOR projects operating today primarily for oil recovery, employing wells subject to the current applicable UIC rules, should not be subject to regulations governing geologic sequestration projects;
  – EOR projects initially permitted for oil recovery that wish to convert to sequestration of CO₂ and obtain credit for injected CO₂ should be required to meet performance standards applicable to geologic sequestration projects.
# Briefing Agenda

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Producing Model Legislative Language

While the policy briefs lay out the basic ideas that we believe should govern the regulation of CCS, we are presently working to take things the next step and actually produce draft legislative language.

We do not harbor any illusions that the Congress would adopt and pass such a piece of legislation in the form we produce it.

However, we think it may prove useful to have a more specific worked out example of what we think is needed.
Model Legislative Language...(Cont.)

The bill we are drafting consists of five separate titles:

TITLE I—CARBON DIOXIDE PIPE LINES

TITLE II—ADAPTIVE PERFORMANCE BASED APPROACH TO CCS REGULATION

TITLE III—LICENSING AND OPERATION OF INJECTION SITES

TITLE IV—LONG-TERM STEWARDSHIP OF CLOSED INJECTION SITES

TITLE V—ACCOUNTING FOR SEQUESTERED CARBON DIOXIDE
Model Legislative Language…(Cont.)

We are close to completing a first draft of this legislative language.

We have two requests:

1. If you would be willing to lend a hand in helping us to refine our language, we'd like to talk.

2. If you would like to receive a copy of the draft when we have it completed, please leave a card with Sue Day, or send e-mail to Sean McCoy at stmccoy@andrew.cmu.edu
Bottom Line:

While there are technical challenges, today resolving the regulatory uncertainties is at least as important.

Designing a comprehensive national regulatory framework is complicated and challenging...

...that is why we have put together an interdisciplinary team of engineers and lawyers who've worked on this issue for the last two years.

We believe that the framework that we have developed, and will soon convert to legislative language, boils down the issues to something manageable, and should point the way to resolving the issues.
Publications and Project are Available on the Project Website
It is time for the US to move past the hype on CCS and start building some commercial-scale facilities!
Acknowledgments

• This work is made possible by support from
  – The Doris Duke Charitable Foundation (Grant 2007117) to Carnegie Mellon University, Department of Engineering and Public Policy for the project, "Regulation of Capture and Deep Geological Sequestration of Carbon Dioxide".
  – The National Science Foundation through the Center for Climate Decision Making at Carnegie Mellon University (SES-0345798).