The Carbon Mitigation Initiative
Second Annual Meeting
January 14-15, 2003
INTRODUCTION

Goal: The goal of the meeting is to understand progress to date and to produce a shared commitment to the objectives of Year-3 and beyond.
LAUNCH OF THE AGREEMENT


October 2000. BP and Ford Motor Company jointly announce the formation of the Carbon Mitigation Initiative (CMI) at Princeton University to develop new approaches to carbon management.

“CMI will focus on resolving the fundamental scientific, environmental, and technological issues that ultimately will determine public acceptance of carbon management strategies. It will search for strategies that: 1) will have the desired effect on atmospheric carbon and climate; 2) will be safe and reliable with limited environmental impact; and 3) will involve neither prohibitive economic costs nor prohibitive disruption of patterns of energy consumption.”

Recognizing the complexity and durability of the issues, both BP and Ford Motor Company make a ten-year commitment, with BP funding of $15,100,000 and Ford Fund funding of $5,000,000.

December 2000. Kickoff meeting is held in Princeton.
THE CHALLENGE
OF CARBON MANAGEMENT

The relentless increase of atmospheric carbon dioxide together with the trend of public opinion and scientific evidence points toward a future constrained by "the carbon problem". To solve the carbon problem, new technologies for the capture and storage of the carbon in fossil fuels must be implemented on a fantastic scale. The majority of the roughly one thousand billion tons of carbon* in the fossil fuels consumed over the 21st century will need to be actively redirected from the atmosphere and sequestered elsewhere.

*1000 Gt(C) ~ 500 ppmv
CMI Mission Statement

The vision of the CMI is to lead the way to a compelling and sustainable solution of the carbon and climate change problem. By combining the unique and complementary strengths of the CMI parties—one premier academic institution and two influential global companies—CMI participants seek to attain a novel synergy across fundamental science, technology development, and business principles that accelerates the pace from discovery, through proof of concept, to scalable application.
CMI Goals

CMI will focus on resolving the fundamental scientific, environmental, and technological issues that ultimately will determine public acceptance of carbon management strategies. CMI will establish which strategies:

• will have the desired effect on atmospheric carbon and climate;

• will be safe and reliable with limited environmental impact;

• will involve neither prohibitive economic costs nor prohibitive disruption of patterns of energy consumption.
“A sign about every quarter-mile” in the Canyons of the Ancients National Monument, Southwest Colorado.
$20,100,000 funding from BP and Ford.
BP: G. Hill

Ford: K. Hass

Directors:
S. Pacala
R. Socolow

Research Team Leaders:
R. Williams
M. Celia
J. Sarmiento
D. Bradford
M. Oppenheimer

External Advisory Board:
S. Benson
D. Hawkins
J. Holdren
D. Keith
F. Orr
R. Richels
Carbon capture projects explore the hydrogen-plus-electricity economy:

Low-cost routes to hydrogen production from natural gas and coal, with a first focus on membrane reactors.

Infrastructure requirements for hydrogen and carbon dioxide.
**Carbon Capture**

**Personnel**
- Consonni
- Benson
- Kreutz
- Vigano
- Larson
- Wang
- Law
- Xue
- Ogden
- Yang
- Ren
- Yuan
- Socolow
- Vanderbei
- Williams

**Core Research**
- $\text{H}_2$ production from fossil fuels with $\text{CO}_2$ sequestration (with Milan)
- Stabilization-driven strategies for staged commercialization – for electricity, $\text{H}_2$
- $\text{H}_2$ and $\text{CO}_2$ infrastructures (with DOE/FE, DOE/EE)

**Tools**
- Aspen and GS (Milan): plant engineering
- Markal: energy forecasting
- Combustion Laboratory

**Scouts**
- $\text{H}_2$ in IC engines, $\text{H}_2$ safety
- Polygeneration in China (with Tsinghua)
The Case for Hydrogen

1. Most of the century's fossil fuel carbon must be captured.

2. About half of fossil carbon, today, is distributed to small users – buildings, vehicles, small factories.

3. The costs of retrieval, once dispersed, will be prohibitive.

4. An all-electric economy is unlikely.

5. An electricity-plus-hydrogen economy is the most likely alternative.

6. Hydrogen from fossil fuels is likely to be cheaper than hydrogen from renewable or nuclear energy for a long time.
The Carbon Refinery

The importance of hydrogen for distributed uses leads to an energy system that:

–produces hydrogen centrally from fossil fuels, while capturing carbon
–distributes hydrogen to end users and carbon dioxide to storage sites through a new infrastructure
–uses hydrogen productively at end use

The coal power plant, the petroleum refinery, and the natural gas “refinery” converge at the Carbon Refinery.

The carbon refinery produces a variety of fuels and chemicals, exports electricity, and captures $\text{CO}_2$. Over time, a larger fraction of the product is $\text{H}_2$. 
Generic Production of Hydrogen, Electricity, and CO₂ from Fossil Fuels

Air Separation Unit → Oxygen Compressor → Compressed Oxygen

- Feedstock (natural gas, petroleum residuals, tar sands, coal, etc.)
- Fuel Reformer (Gasifier, partial oxidizer, steam reformer, etc.)
- Water-Gas Shift Reactor: CO + H₂O → H₂ + CO₂
- Gas Separation (solvent absorption + PSA, membrane, etc.)
- Electricity Production: combustion in air or O₂, electric power from steam or gas turbine

- Heat Recovery, Syngas Cleanup
- Hydrogen Compressor
- CO₂ Dryer/Compressor
- Supercritical CO₂ for sequestration (optional sulfur co-sequestration)
- CO₂ (+SO₂ optional)
- CO₂, H₂O, some H₂ (Purge gas/raffinate)

- Majority of H₂ (relatively pure)
- Hydrogen Pipeline: H₂ pipeline

(→ = Options)

Generic process figure 4 (1-15-01)
Conventional $H_2$ from Coal with Co-Sequestration of $CO_2$ and Sulfur-bearing Species (low-S coal)

• $CO_2$ capture and sequestration lowers efficiency by $\sim$3% and increases $H_2$ cost by $\sim$ 1.5 $/GJ.

(Cost of $CO_2$ pipeline transport and disposal used here is 0.4-0.6 $/GJ.)

• Co-sequestration has potential to lower $H_2$ cost by 0.25-0.75 $/GJ, depending on sulfur content of coal.

**Princeton Tasks**
- Polygeneration process design and cost modeling: DME, F-T liquids, methanol, H₂, syngas, chemicals, heat, electricity.
- Carbon sequestration analysis for near-term EOR and CBM; aquifer CO₂ storage for long term.
- Integrated strategic analysis.

**Tsinghua Tasks**
- Energy-data collection for Yanzhou and Jincheng.
- Coal-based polygeneration process design, simulation.
- Lifecycle environmental impact and cost analysis.
- Integrated strategic analysis.
- Outreach to Yanzhou Mining Group Ltd., Shanxi Jincheng Anthracite Coal Mining Group Ltd., and other decision makers.
Carbon storage

*Carbon storage projects* explore the safety, reliability and environmental impact of carbon storage in underground reservoirs:

Predictive models of CO2 leaking from an underground storage site as it moves toward the earth's surface, with an emphasis on chemistry in drinking-water aquifers and the unsaturated zone.

Experimental studies of the chemistry of CO2 at high pressure.

Exploratory studies of alternatives to underground storage (e.g., oceanic injection, carbonate production, enhanced biological sequestration).
Carbon Storage

**Personnel**

*Celia Altevogt*

*Jaffe Bruant*

*Myneni Duguid*

*Peters Gasda*

*Prevost Giammar*

*Scherer Li*

**Core Research**

**CO₂ Leakage Estimation**

Data from Alberta Basin (with AGS)

Critical Pathway: Existing Wells and Cement

Risks associated with CO₂ leakage into shallow ground water and soils

Geochemistry of CO₂-Brine-Rock Interactions

**Tools**

Extend Dynflow geomechanics code to include multi-phase, multi-component flow capabilities

Upscaling of micro-phenomena to large spatial scale

**Scouts**

Mammoth Mountain field studies of high- CO₂ soil gas impacts on vegetation
Existing Wells ("Artificial Penetrations") are Critical Leakage Pathways

ABANDONED WELLS: ALBERTA BASIN

- Number of wells on the y-axis.
- Year abandoned on the x-axis, ranging from 1883 to 1999.
- The bars represent the number of wells abandoned each year, with significant peaks in 1949 and 1994.
3D Computational Test Problem: Well Leakage

- **CO₂ injection** = 20 kg/s = $Q_{in}$

- **Seal**:
  - $k = 10^{-16}$ m$^2$
  - $n = 0.10$

- **Aquifers**:
  - $k = 10^{-13}$ m$^2$
  - $n = 0.10$
Carbon science

*Carbon science projects* explore the consequences of large-scale carbon management:

- Earth system modeling of the impact of alternative mitigation options on greenhouse gases and climate.
- Analysis of abrupt changes in the carbon and climate system.
- Shipboard measurements of the $O_2/N_2$ ratio of air to estimate natural CO$_2$ sequestration by the land biosphere and oceans.
## Carbon Science

### Personnel
- Bender
- Morel
- Pacala
- Sarmiento
- Sigman
- Caspersen
- Denkenberger
- Ho
- Jacobson
- Malyshev
- Mignone
- Roy
- Shevliakova

### Core Research
- Calculate Stabilization Emissions
- Predict Future of Natural Sink
- Measure Natural Sinks via $O_2/N_2$ and $Ar/N_2$
- Predict Climate Change Impacts

### Tools
- Earth System Model
- Automated Trace Gas Samplers

### Scouts
- Iron Fertilization
- Glacial/Interglacial
- Deep injection
- Ecological Sequestration
- Climate Change and Wind Energy
Growth Rate of Carbon Reservoirs
Conclusions for the Global Sink

• Much (and probably most) of the global missing sink is caused by land use change.
• IPCC modeling studies probably overestimate the current contribution of $\text{CO}_2$ fertilization.
• The missing sink is likely to shrink in the future, making the carbon problem more difficult to solve.
Carbon policy

*Carbon policy projects* explore the economics of large-scale sequestration:

The economics of leaky containment and the discounting of future damages.

Incentives bearing on shifts in technological regimes.
Carbon Policy

**Personnel**

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<td>Oppenheimer</td>
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*students, Penn State

**Core Research**

- Economic instruments and other policies to promote carbon management (integrated assessments)
- Optimal magnitudes and timing of mitigation
- Benchmarking “dangerous interference with the climate system,” e.g., impacts on cryosphere

**Tools**

- Modified versions of the RICE Model
- MiniCAM (PNL) and Merge (EPRI) Integrated Assessment models

**Scouts**

- Innovative international allowance trading scheme
- Carbon cycle modeling in integrated assessments (Workshop, May 2002)
- Models of learning by doing
How strong is the case for starting now?

DON’T. Wait a generation. General learning will clarify risks and benefits, add options.

DO. Learning later that action is urgent and then trying to catch up could be costly.

Early action carries low costs, low risks.

- Already commercialized technologies
- Willing fossil fuel companies

Optimal growth models quantify the value of early activity.
The Size of the Sequestration Business

A benchmark market price for CO$_2$ emission or storage in a mature sequestration regime might be:

$100$ per ton of carbon 

$= \frac{12}{44} = \frac{M_C}{M_{CO2}}$ 

$= $27 per ton of CO$_2$ 

$= $12 per barrel of oil 

~8 barrels per ton of C, 7 bbl/ton 

Rent: Subtract the storer’s cost from $12 per barrel.

1 Gt(C)/yr, the unit of discourse for climate change mitigation, is then **12 billion dollars**. 

Sequestration scale might be 1-2 units in 2050.

The oil and gas industry paid twice: C out and C back in?
Integration

Storage

Economics

Science

Capture

OLD STRUCTURE

“Scouts”

Ford

BP
Reshaping the Program in Year 3

The reshaping, toward greater integration:
  Allows us to make a distinctive contribution

Is confirmed by recent events

Must preserve the core program

Was scheduled for Year 3 at Year 0

Will be the topic later today