Goal: The goal of the meeting is to understand progress to date and to produce a shared commitment to the objectives of Year-4 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.
Near McElmo Dome, Colorado  (from David Hawkins, NRDC)

“A sign about every quarter-mile” in the Canyons of the Ancients National Monument, Southwest Colorado.
Carbon Mitigation Initiative
at Princeton, 2001-2010

Carbon Capture

Carbon Storage

Carbon Science

Carbon Policy

$21,150,000 funding from BP and Ford.
BP:  
G. Hill

Ford:  
K. Hass

Directors:  
S. Pacala  
R. Socolow

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

External Advisory Board:  
S. Benson  
D. Hawkins  
J. Holdren  
D. Keith  
F. Orr  
R. Richels
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

Tools
Earth System Model
Automated Trace Gas Samplers

Core Research
Calculate Stabilization Emissions
Predict Future of Natural Sink
Measure Natural Sinks, Including via O₂/N₂ and Ar/N₂ Measurements
Predict Climate Change Impacts
Improve Carbon and Climate Models

Scouts
Iron Fertilization
Glacial/Interglacial
Deep injection
Ecological Sequestration
Climate Change and Wind Energy
Science Highlights 2003

1. New observational and data-based estimates of terrestrial and ocean carbon sink size and variability confirm previous estimates.

2. New data indicate that polar oceans were stratified during the last glacial period, supporting the hypothesis that decreased evasion of CO2 from the deep ocean had a cooling influence on climate.

3. Data from polar oceans provide the first evidence that natural iron variations produce changes in marine biological productivity, possibly influencing CO2 uptake.

4. A new state-of-the-art climate model with an interactive land model has been completed and is running initial simulations.

5. Analysis of Wisconsin forests since the 1960’s indicate growth rates have decreased with rising CO2 levels, undermining the theory that carbon dioxide’s fertilizing effect on land plants would increase CO2 uptake in the future.
Uncertainty About the Future of the Land Sink Compared to Stabilization Emissions

![Graph showing the relationship between the future of the land sink and stabilization emissions.](image)
Cumulative Emissions Reductions Necessary to Stabilize at 500 PPM

Fossil Carbon Emissions Reductions

Year

CO2 Fertilization Sink
Land Use Sink
Foreword

America, Why I Love Her

John Waynet's
Forest Growth Decline

Observed Change in Growth Rate

Number of Observations

Zero CO2 Fertilization Prediction
Conclusions

- Growth in forests in the north-central US has slightly but significantly decreased over the last 35 years.
- State-of-the-art ecosystem models of CO$_2$ fertilization are false for this region.
- When added to observed down-regulation and evidence from new global carbon budgets, this result provides additional cause for skepticism about the predicted future benefits of CO$_2$ fertilization.
- The IPCC should give equal time to models with no CO$_2$ fertilization, or risk endorsing integrated assessments that recommend too little early mitigation of fossil carbon emissions.
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

<table>
<thead>
<tr>
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<tr>
<td>Williams</td>
<td>Celik</td>
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<td>Yuan</td>
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*Milan: Consonni, Chiesa, Vigano*

*Tsinghua: Li, Ren*

## Core Research

- $\text{H}_2$ production from fossil fuels with CO$_2$ sequestration (with Milan)
- Polygeneration of electricity, $\text{H}_2$, synfuels (with Tsinghua)
- $\text{H}_2$ and CO$_2$ infrastructures (DOE)
- $\text{H}_2$ and DME combustion

## Scouts

$\text{H}_2$ use beyond transportation

## Tools

- Aspen Plus and GS (Milan): plant design
- Markal: energy forecasting
- Combustion Laboratory
Research Highlights for 2003

• Hydrogen production from coal with CO₂ capture shows costs are comparable for membrane and conventional separation. Key issues: byproduct electricity, syngas cooling, co-capture of sulfur.

• Polygeneration (electricity + synfuels + H₂) modeling highlights opportunities via once-through liquid-phase synthesis reactors. Superiority of indirect to direct liquefaction is communicated at high level in China.

• Costing of H₂ infrastructures to link large-scale production and decentralized use clarify pace of transition in cities, requirements for system storage.

• Combustion mechanisms for H₂ and dimethyl ether (DME) are studied.
A Glimpse of the Future: Coal Gasification is More Than Halfway to Coal with CO2 Capture

The Wabash River
Coal Gasification Repowering Project
**Benchmark: IGCC Electricity with CO₂ Capture**

- **Cost:** 6.4 ¢/kWh (at carbon tax of 93 $/tonne C), efficiency: 34.8% (HHV). (70 bar gasifier with quench cooling; plant scale: 368 MWₑ)

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**Diagram Description:**
- **O₂-blown coal gasifier**
- **Air separation unit**
- **Heat recovery steam generator**
- **High temp. WGS reactor**
- **Low temp. WGS reactor**
- **Quench + scrubber**
- **Regeneration, Claus, SCOT**
- **Solvent regeneration**
- **CO₂ drying + compression**
- **Supercritical CO₂ to storage**
- **Coal slurry**
- **Air**
- **Formed syngas streams:**
  - H₂ _and_ CO₂-rich syngas
  - CO₂-lean exhaust gases
  - Saturated steam
  - H₂S _physical absorption_
  - Lean/rich solvent
  - CO₂ _physical absorption_
  - Lean/rich solvent
  - H₂-rich syngas
  - Syngas expander

---

GHGT-6 conv. electricity, CO2 sec. (9-25-02)
H₂ Production: Add H₂ Purification/Separation

- Replace syngas expander with PSA and purge gas compressor.
Conventional $H_2$ Production with $CO_2$ Capture

- $H_2$ cost: 7.5 $/GJ (HHV) (at carbon tax of 38 $/tonne C, electricity 4.6 ¢/kWh).
  [70 bar gasifier with quench cooling; plant scale: 1210 MW$_{th}$ $H_2$ (HHV)]
Carbon Mitigation from the Perspective of Combustion: Flamefront Instabilities

- Relevance: transition to turbulence and detonation; engine knock; explosion hazard
- Instability aggravated with increasing pressure, but diminished with propane addition

Equivalence ratio: 0.80
Pressure: 5 atm
Carbon Mitigation from the Perspective of Combustion: Dimethyl Ether (DME) as Diesel Fuel

- Diesel engine testing: reduced emissions of CO, NO$_x$, formaldehyde, particulates, and unburned hydrocarbons (UHC)

- Ignition temperature experimentally determined

- Detailed and reduced reaction mechanisms developed. Simulation agrees with experiment
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
Luet
Rodonjic

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 Dynaflow 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
Research Highlights for 2003

• Refocus of the below-ground group.
• Experiments to assess the potential for cement failure in wells are underway.
• Analytical solutions for determining the characteristics of CO$_2$ injection plumes, and to estimate leakage rates through abandoned wells.
• Geochemical experiments have shown that pressure has only minimal effects on mineral dissolution in deep aquifers.
New Focus for Carbon Storage

Core Research

Potential for CO₂ Leakage From Existing Wells Focusing on Cement

1. Analysis of field collected cement samples (Teapot Dome).
2. Laboratory experiments on cement in the presence of CO₂.
3. Numerical models for the areas surrounding the interface between sequestration reservoir and well.
4. Fast reservoir models for basin scale risk analysis.

Scouts

Mathematics of injected CO₂
Research Highlights for 2003

• Refocus of the below-ground group.
• Experiments to assess the potential for cement failure in wells are underway.
• Analytical solutions for determining the characteristics of CO$_2$ injection plumes, and to estimate leakage rates through abandoned wells.
• Geochemical experiments have shown that pressure has only minimal effects on mineral dissolution in deep aquifers.
Corrosion of Cement in Carbonated Brine

Unreacted

Reacted cement sample (50°C)

Unreacted zone

Reacted zone

6mm
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

Bradford        Li
Oppenheimer     Naevdal
Donner          Naik
Greenblatt      Wagner
Kim

Penn State: Keller
IIASA: Riahi
PNNL: Edmonds

Core Research

Costs and benefits of “wedge” technologies
Optimal magnitudes and timing of mitigation
Benchmarking “dangerous interference with the climate system,” e.g., impacts on cryosphere
Innovative international allowance trading scheme

Scouts

Carbon cycle modeling in integrated assessments (Workshop, May 2002)
Models of learning by doing

Tools

Modified versions of the RICE
MiniCAM (PNL) and Merge (EPRI)
Research Highlights for 2003

• Four integrated assessment models tailored for our use are operational.
• New economic analyses indicate that delaying mitigation of CO₂ emissions by decades could make avoiding specific climate thresholds prohibitively expensive.
• Experiments with our integrated assessment models estimate the costs of stabilizing atmospheric CO₂ at less than twice the preindustrial level.
What is the size of the stabilization wedge?

Notes:

- Carbon emissions exclude land use changes.
- The projections differ with the assumptions made about the future economic growth & energy technologies.
- The required carbon taxes in 2100 range between 150 and 600 $/tC.
- MERGE projections are biased close to the terminal conditions (2080 onwards).
What would be the size of each of slices for the stabilization wedge?

The size of each of the slices depends crucially on the assumptions on future economic growth and technological changes in energy technologies.
CMI 2003

Integration: Stabilization Wedge

- Economics & Policy
- Science
- Technology Capture Storage

“Scouts”
The Stabilization Wedge

Easier CO2 target \( \approx 750 \) ppm

Tougher CO2 target \( \approx 500 \) ppm

Business As Usual
Seven “Slices” Fills the Wedge

It is irresistible to divide the wedge into seven equal parts. We call these “slices.”
What is a “slice”?  

A “slice” is an activity reducing the rate of carbon build-up in the atmosphere that grows in 50 years from zero to 1.0 Gt(C)/yr.

Cumulatively, a slice redirects the flow of 25 Gt(C) in its first 50 years. This is 2.5 trillion dollars at $100/t(C).

A “solution” to the Greenhouse problem should have the potential to provide at least one slice.
Filling the Wedge

The discussion moves to choosing among alternate ways of filling the wedge.

- Coal to Gas
- Natural Sinks
- Efficiency
- Renewables
- CCS
- Nuclear
Questions Organizing Year 4 and Beyond

Science

What is a safe level for CO₂ in the atmosphere?
How much CO₂ can be emitted if we are to stabilize at any given level?
What are the unintended environmental consequences of mitigation options?

Capture

What are the critical enabling technologies that are ready for commercialization in the near term?
Given that most of the stabilization wedge must be built in developing countries, what technological options are most promising for the developing world?
What is the relationship between cost and capacity for the various mitigation options?
Questions Organizing Year 4 and Beyond

Storage
- How likely are CO\textsubscript{2} storage reservoirs to leak?
- How risky are leaks at basin-scales or larger?
- How can we best mitigate leakage risk?

Economics and Policy
- What is the economic cost of stabilization?
- What are the most efficient economic instruments to accomplish it?
- What is the relationship between economic efficiency and practicality of implementation?
- What is the cost of waiting?
- What political options are most feasible and which are most likely?

Outreach