

# Overview CO<sub>2</sub> Sequestration Science & Technology in the U.S.

**B. Peter McGrail**  
**Pacific Northwest National Laboratory**  
**Richland, Washington USA**

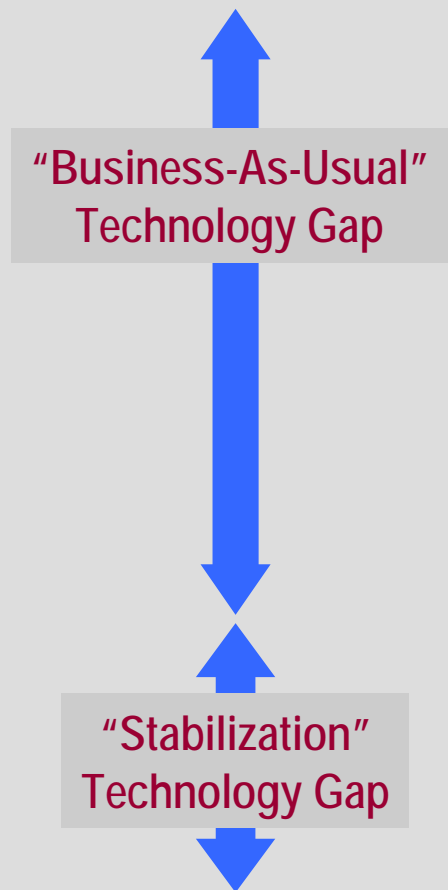
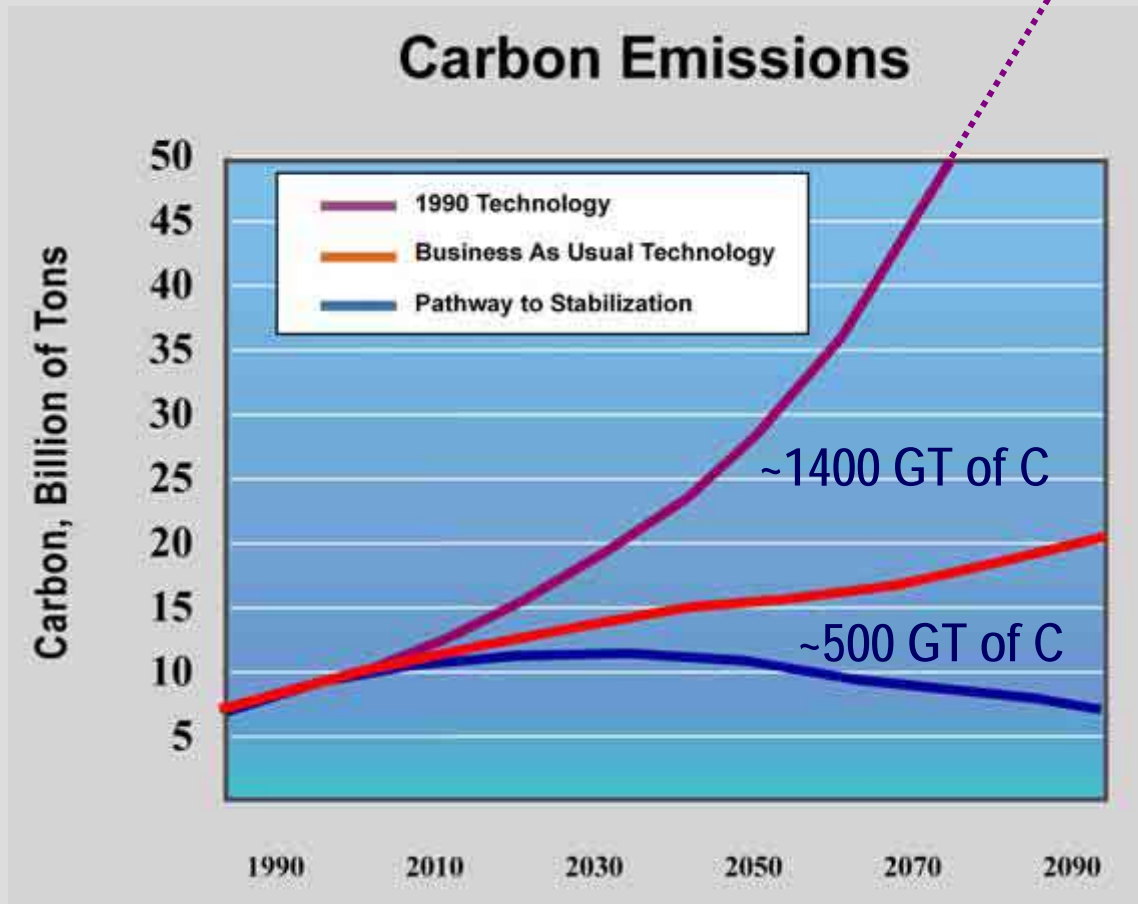
NARUC Summer Meeting  
Austin, Texas  
July 25, 2005

**Battelle**

*The Business of Innovation*



# Commitment to Stabilization Requires Closing TWO “Technology Gaps”





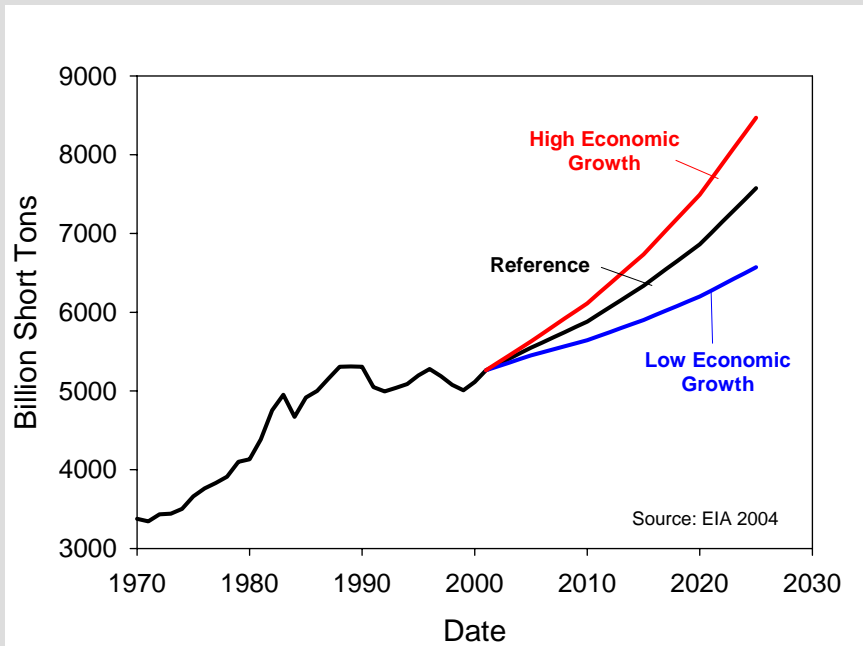
# How Big is a Gigaton?

## *Assuming Today's Technology*

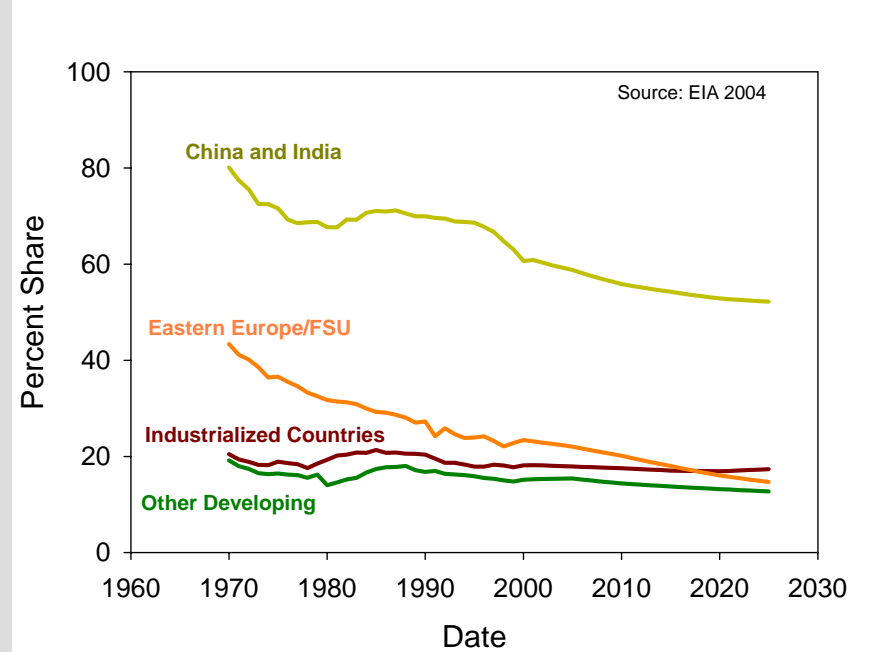
<b>Today's Technology</b>	<b>Actions that Provide 1 Gigaton/year of Mitigation</b>	<b>Major Issues</b>
Coal Plants	Replace 1,000 conventional 500-MW plants with "zero-emission" power plants	Technical, Social, & Economic Viability
Geologic Sequestration	Install 3,500 Sleipners, at 1 Mt of CO <sub>2</sub> per year <sup>1</sup>	Technical, Social, & Economic Viability
Nuclear	Build 500 1 GW plants (in lieu of unsequestered coal)	Economics, Safety, Non-proliferation,
Efficiency	Deploy 1 billion cars at 40 mpg instead of 20 mpg	Distributed opportunity that is hard to capture
Wind	Install 750 x current U.S. wind generation (in lieu of unsequestered coal)	Geographic Limitations, Storage
Solar PV	Install 4,500 x current U.S. solar generation (in lieu of unsequestered coal)	Geographic Limitations, Storage
Biomass fuels from plantations	Convert an area >7.5X the size of Iowa's farmland to biomass	Land-Use Changes
Storage in new forest	Convert an area >30X the size of Iowa's farmland to biomass	Land-Use Changes

# Coal Consumption will Increase Worldwide and in the U.S.

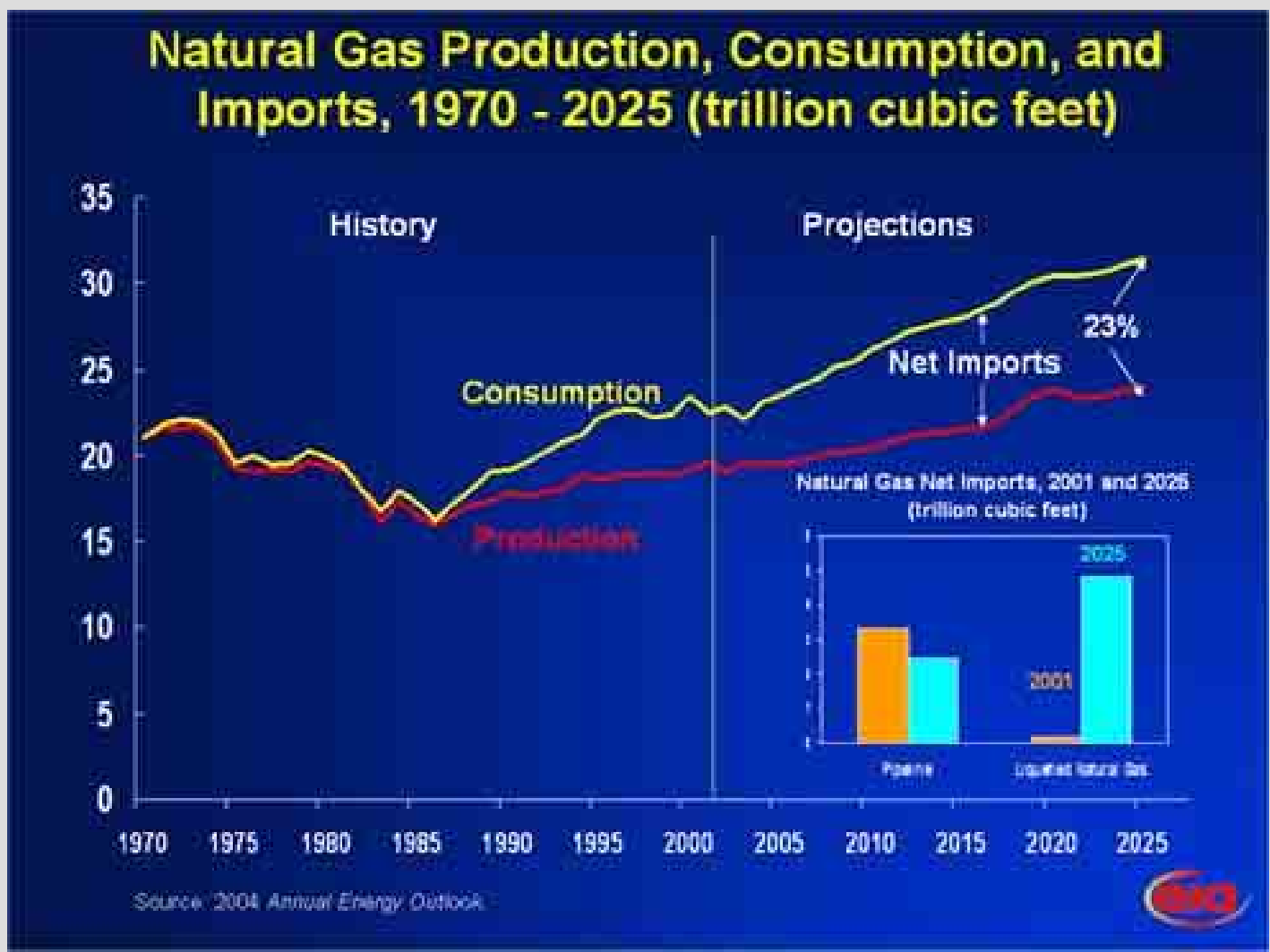
## World Coal Consumption



## Coal Share of Energy Consumption

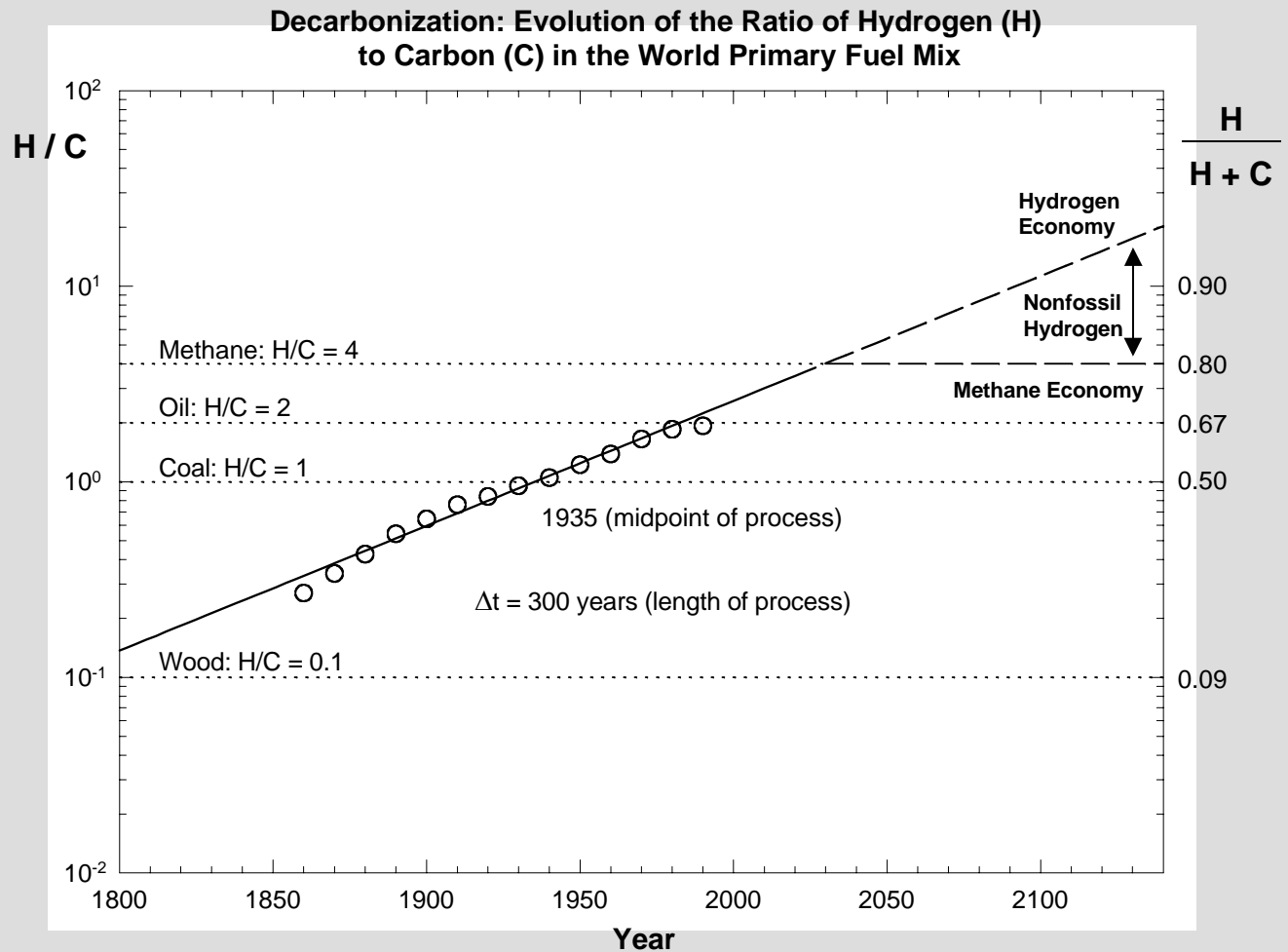


# Natural Gas Imports Projected to Grow

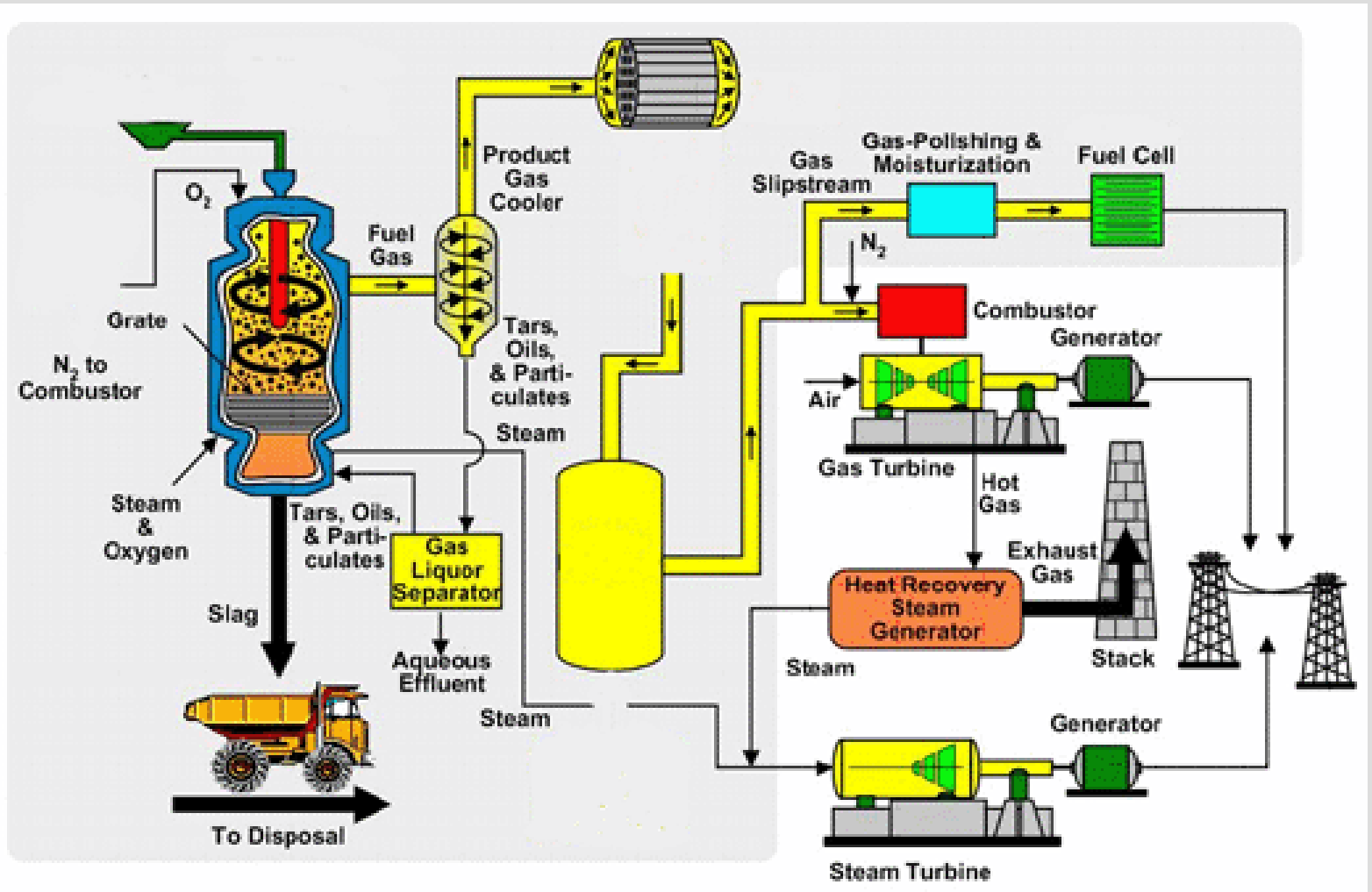


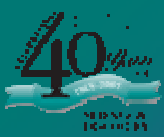


# Decarbonization of the Energy System



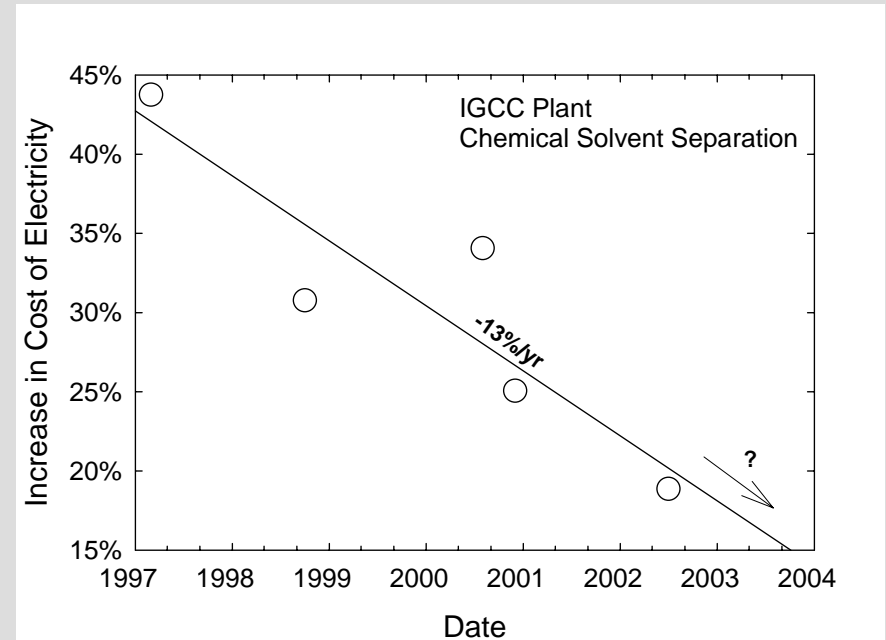
# Hydrogen Production from Coal with Integrated CO<sub>2</sub> Capture





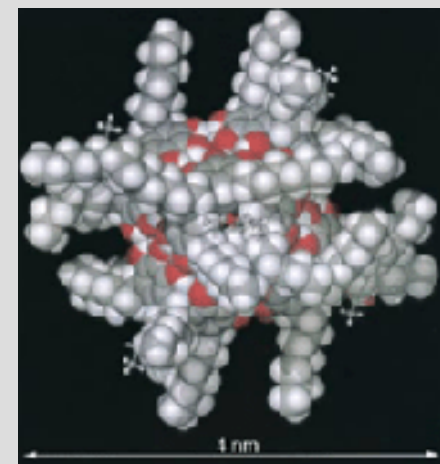
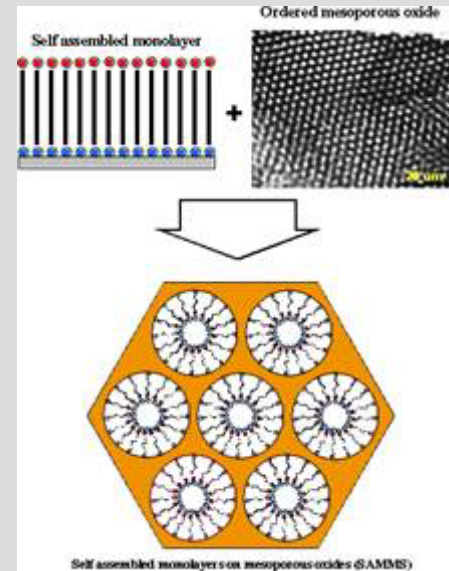
# Costs for Carbon Capture

Reference	Date	$\Delta$ COE
IEA Greenhouse Gas R&D Programme	1997	44%
SFA Pacific	1998	31%
MIT	2000	34%
Parsons Energy Inc.	2000	25%
IEA Greenhouse Gas R&D Programme	2002	18%
PSA		279%
TSA		306%
Cryogenic		47%
Gas Separation Membrane		143%
Gas Absorption Membrane		58%



# New Capture Technologies

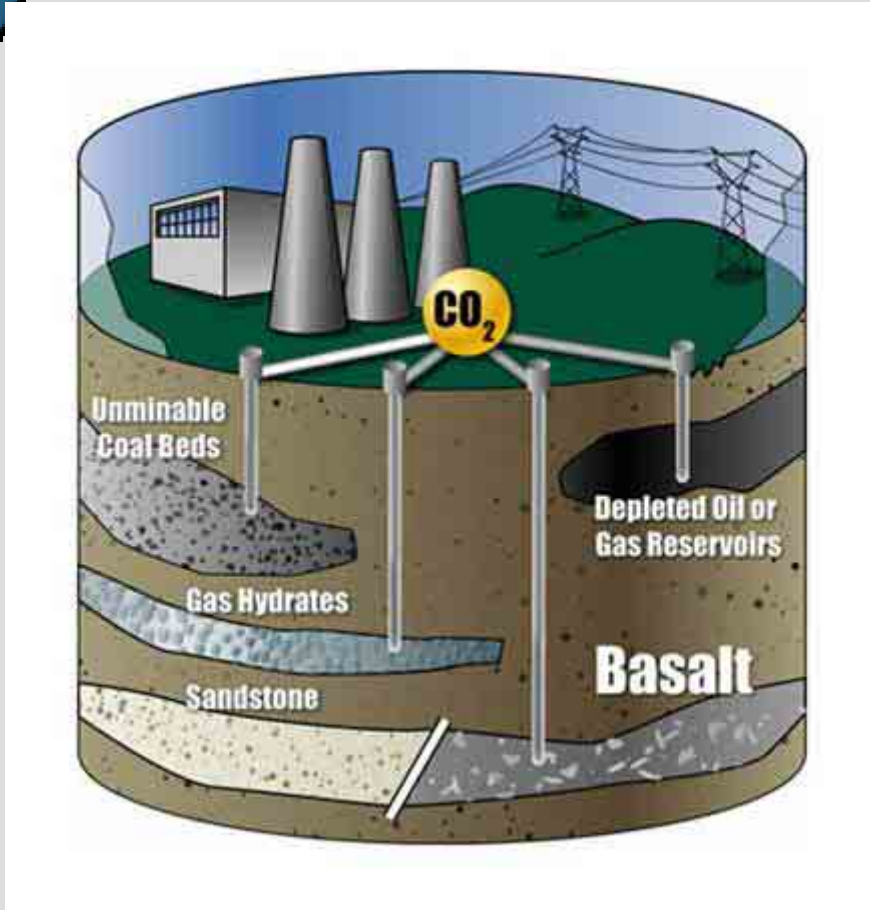
- ▶ Membranes
  - Catalytic
  - Ion transport
  - Facilitated transport
  - Polymeric
  - Ceramic
  - Nanocomposites
- ▶ Clathrates
- ▶ Carbon nanotubes/carbon-carbon composites
  - Electrical swing adsorption
- ▶ Ordered mesoporous oxides/aerogels





# CO<sub>2</sub> Phase Behavior

# Geologic Sequestration Options

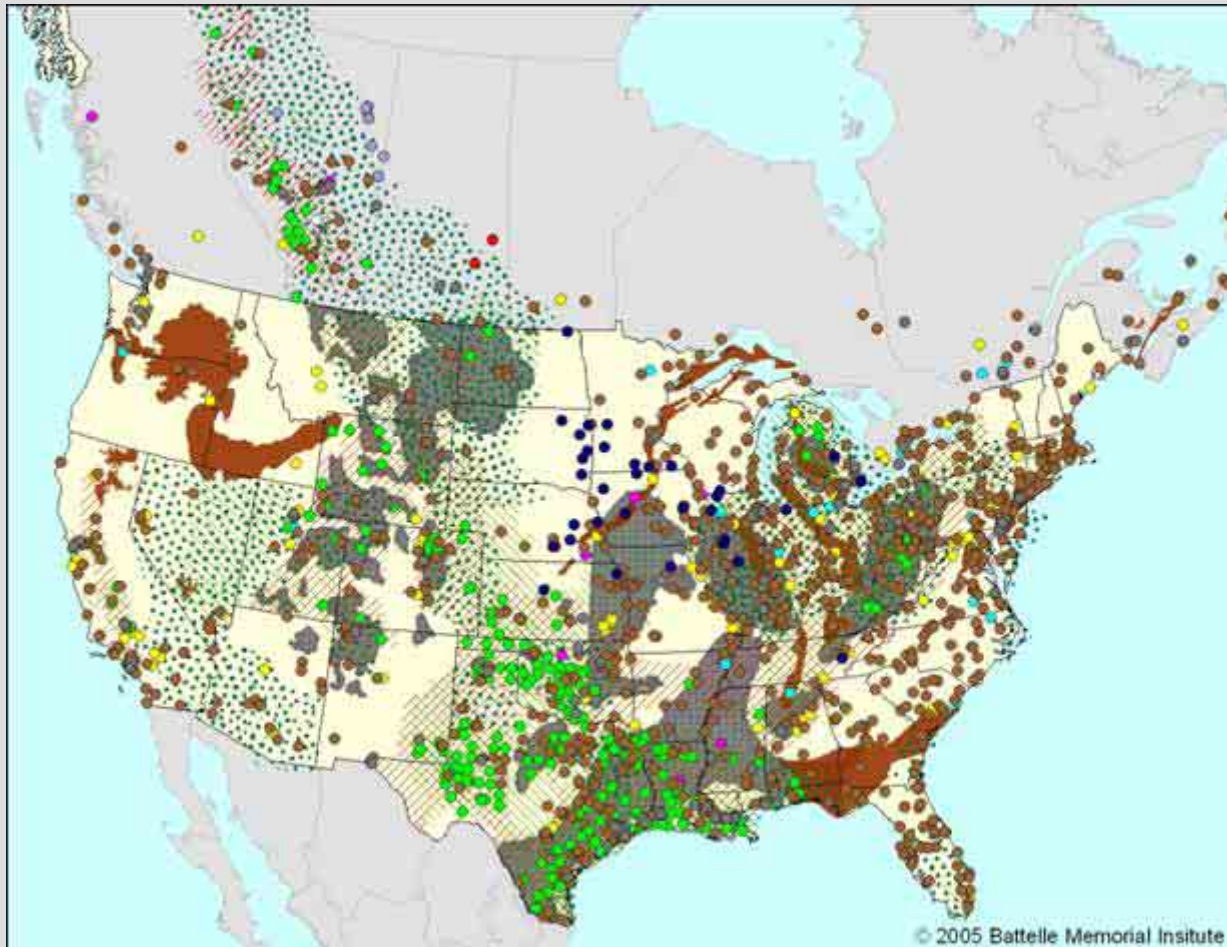


## CO<sub>2</sub> Trapping Mechanisms

- ▶ Physical trapping
- ▶ Hydrodynamic trapping
- ▶ Solubility trapping
- ▶ Mineral trapping

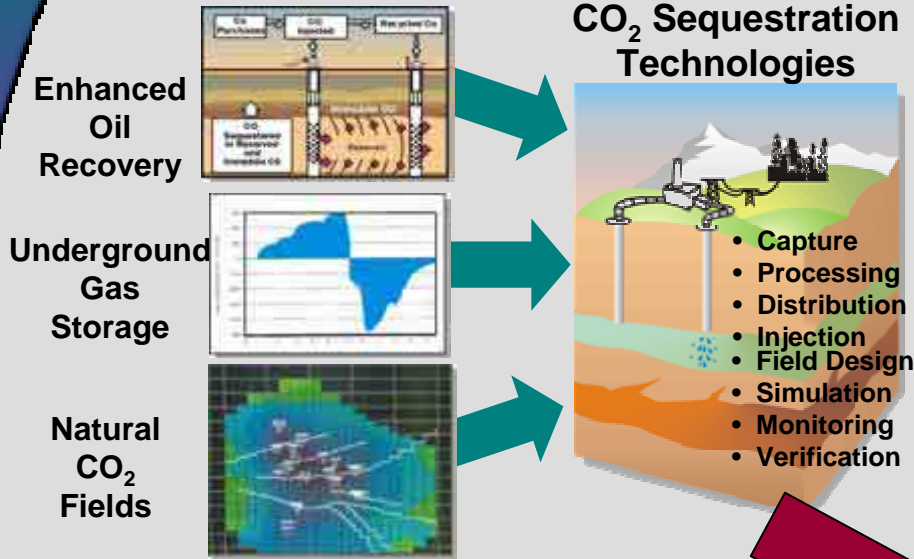
Different geologies have differing primary and secondary trapping mechanisms

# GIS Database of CO<sub>2</sub> Sources and Potential Geologic Storage Reservoirs



# Early “Value-Added” Markets

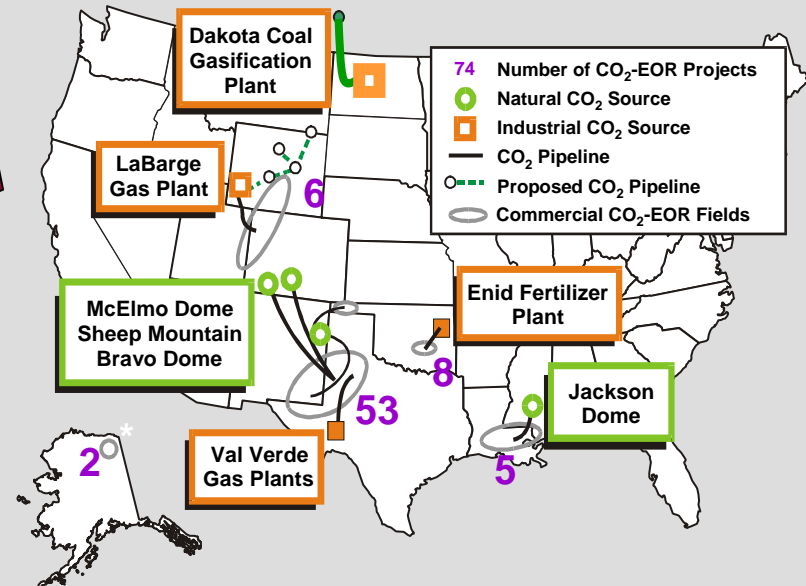
## Industrial Technology Base



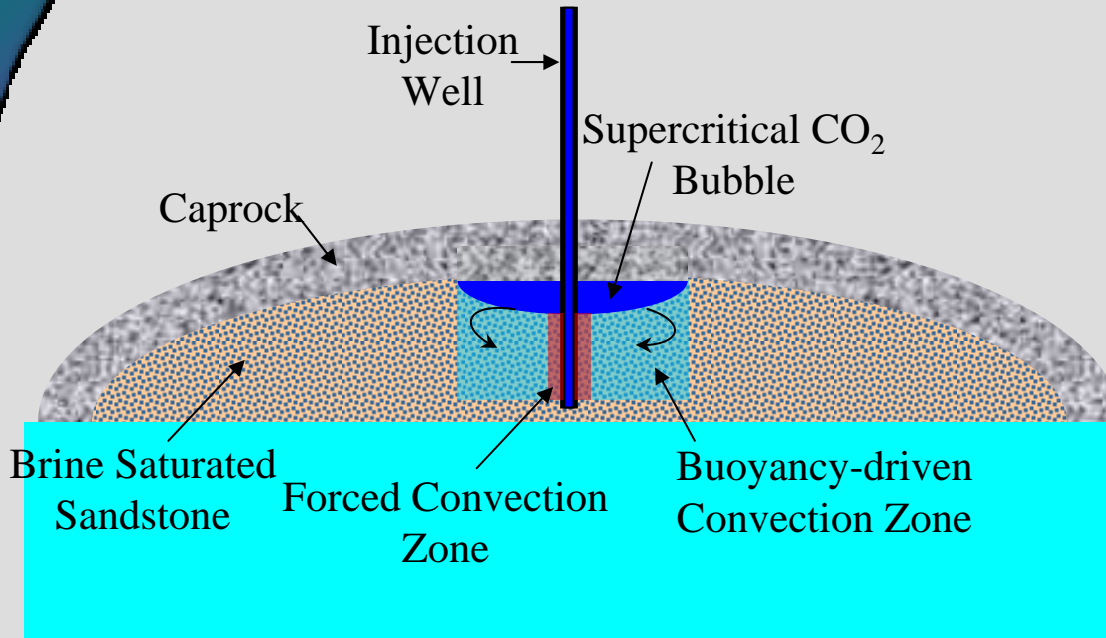
▶ EOR Market served mostly by natural sources now

- 30 Mt/yr total, 7Mt/yr man-made
- Average delivered price \$10-12/t
- Current Cost from existing power plants \$40-60/t

## CO<sub>2</sub> Sources for EOR in The USA



# Conceptual Model for CO<sub>2</sub> Injection



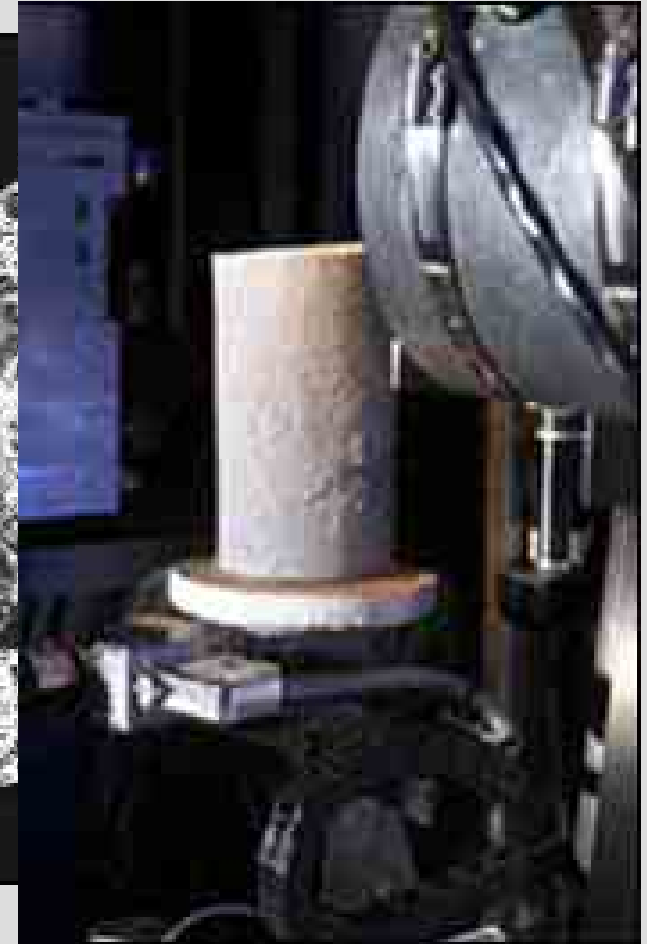
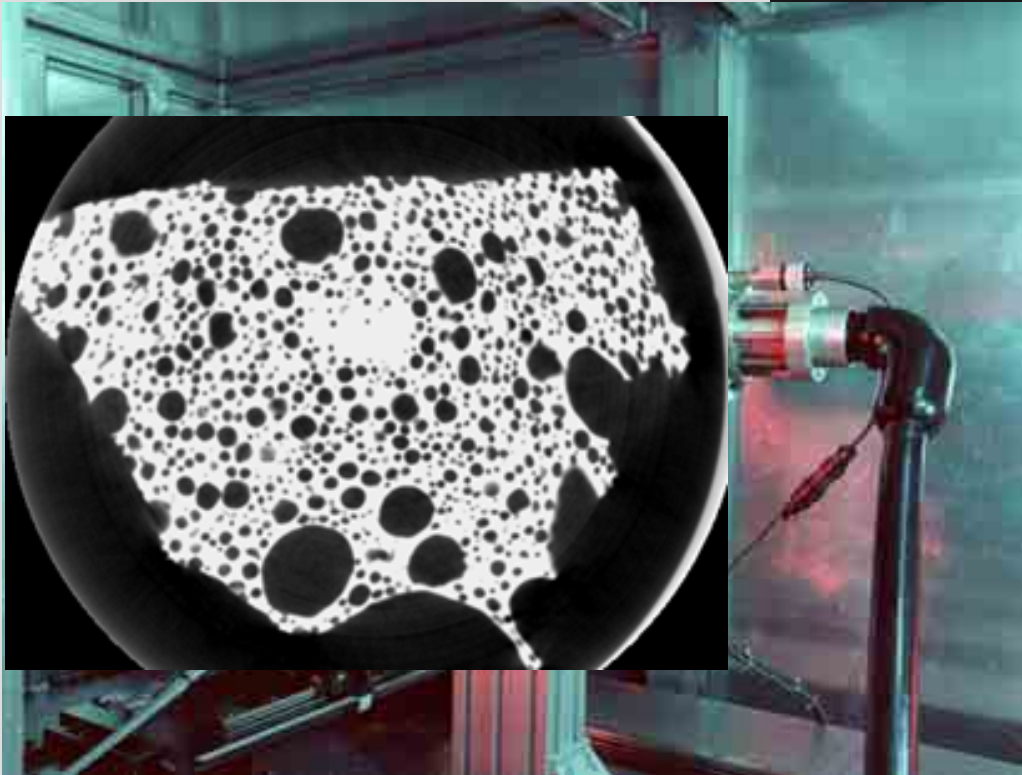
- ▶ Lower density of scCO<sub>2</sub> as compared with brine causes the injected CO<sub>2</sub> to float as a bubble restrained by a low permeability caprock
- ▶ Area of review around well is determined by injection rate and reservoir properties
- ▶ Mineral trapping is not a significant process

# Layered Basalt Flows



- ▶ Assume only 10 flows (3%) suitable for injection, thickness of only 10 m, 15% porosity, 1400 psi average pressure
- ▶  $\approx 100$  GtCO<sub>2</sub> storage capacity

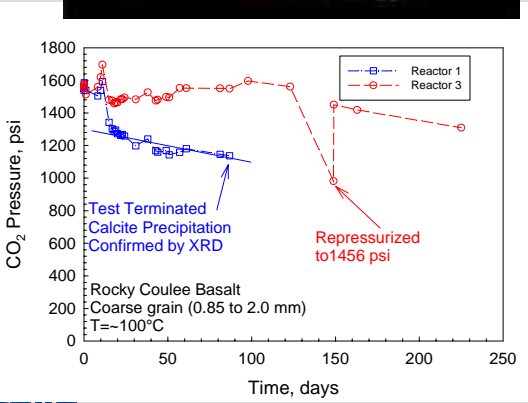
# X-ray Microtomographic Imaging of Vesicles in Basalt Flow Top



# Supercritical CO<sub>2</sub> Pressure Cell Experiments with Columbia River Basalt



Long-term experiments showing transition from calcite to ankerite, Ca(Fe, Mg, Mn)(CO<sub>3</sub>)<sub>2</sub>

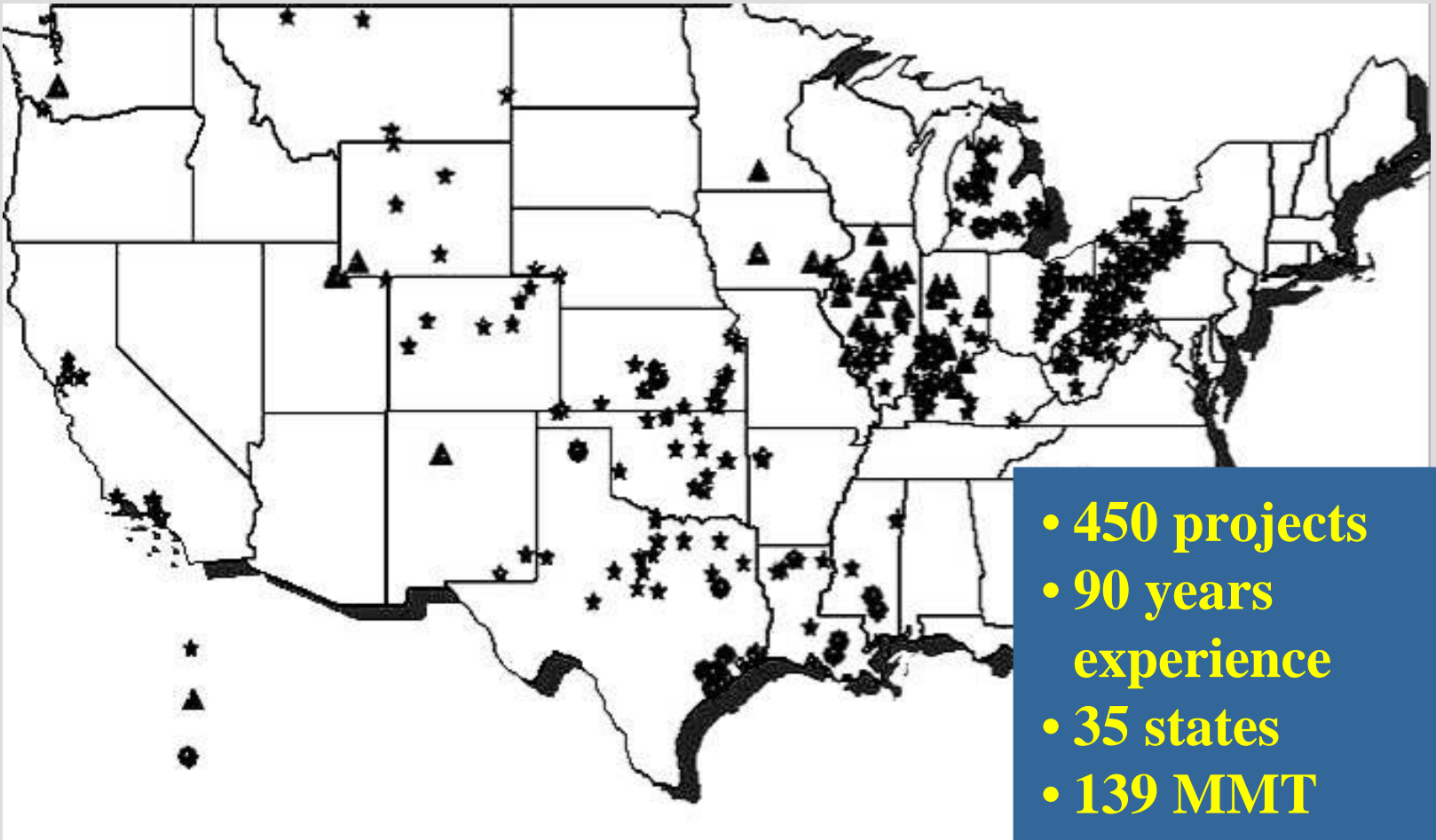




# Industry Experience Relevant to Geologic Sequestration

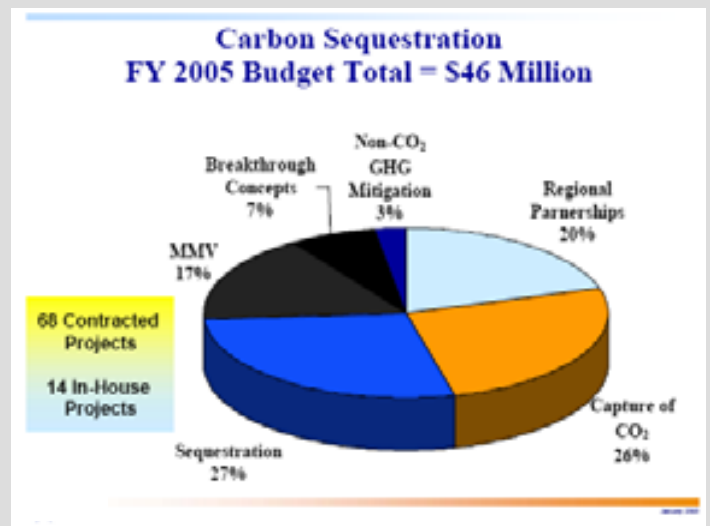
- ▶ Natural gas storage
- ▶ Deep injection of liquid and hazardous wastes
- ▶ Enhanced oil recovery
- ▶ Coal-bed methane

# Natural Gas Storage Is Widely Practiced




- 450 projects
- 90 years experience
- 35 states
- 139 MMT stored annually

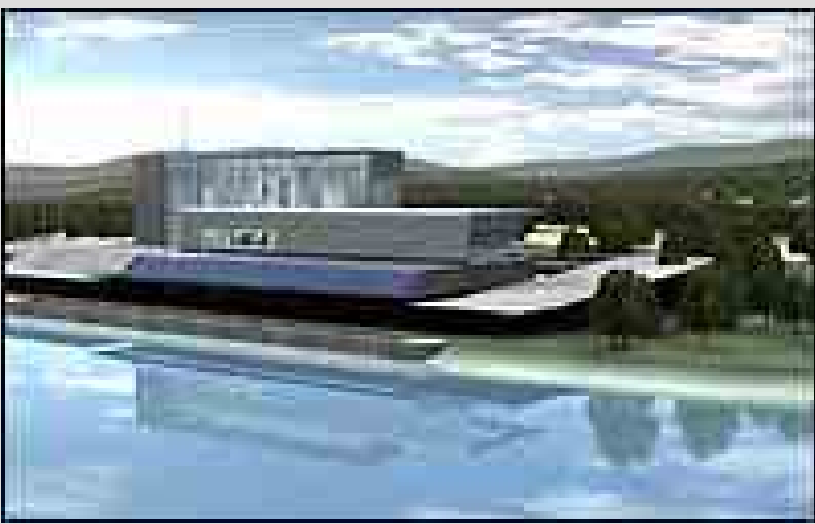
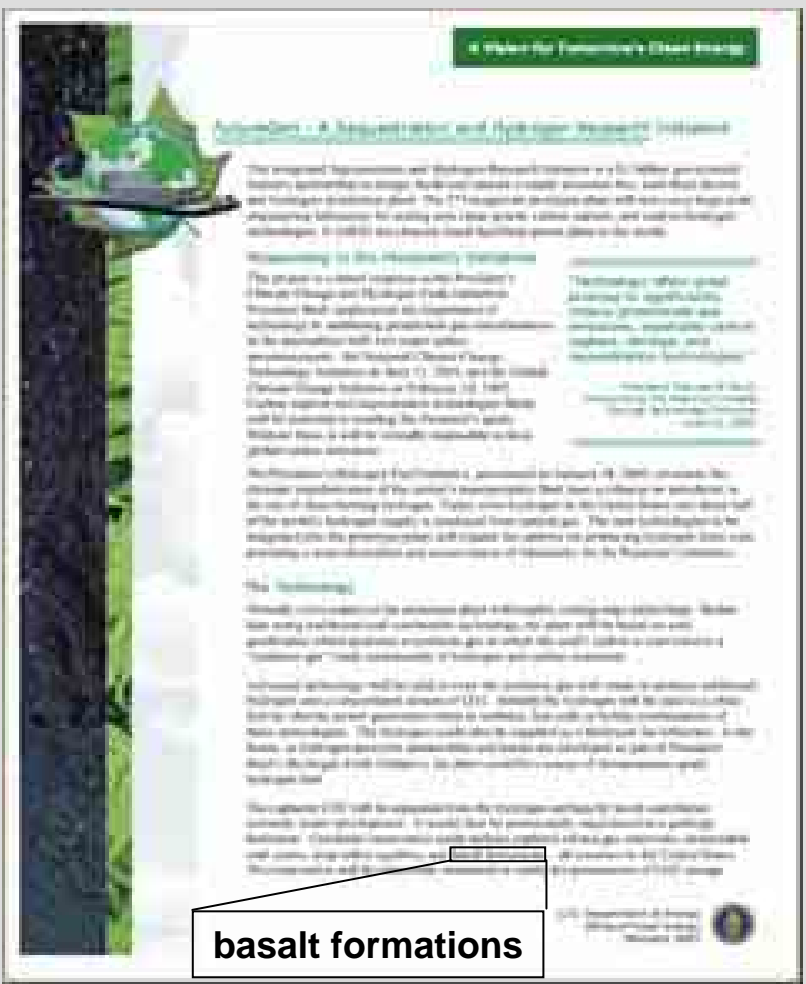
# U.S. DOE Portfolio of CCS Projects



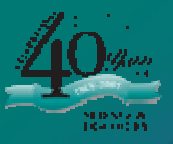
# Regional Carbon Partnerships Phase II

	Lead Organization/ Webpage	Highlights
	California Energy Commission <a href="http://www.westcarb.org/">http://www.westcarb.org/</a>	<ul style="list-style-type: none"> <li>• Identified candidate enhanced coal bed methane and enhanced oil recovery projects</li> <li>• Detailed assessment of forestation as mitigation by storage, fire management, and biofuel opportunities</li> </ul>
	New Mexico Institute of Mining and Technology <a href="http://www.southwestcarbonpartnership.org/">http://www.southwestcarbonpartnership.org/</a>	<ul style="list-style-type: none"> <li>• Resource-rich region with two CO<sub>2</sub> pipelines</li> <li>• Identified seven candidate sites for field testing</li> <li>• Conducted web-based "town hall" meetings</li> </ul>
	Montana State University <a href="http://www.bigskyco2.org/">http://www.bigskyco2.org/</a>	<ul style="list-style-type: none"> <li>• Large storage potential in basalt formations</li> <li>• Focus on agriculture and forestry project protocols to increase salability of credits</li> <li>• Close interaction with state governments</li> </ul>
	University of North Dakota, Energy & Environmental Research Center <a href="http://www.undecm.org/pcor/">http://www.undecm.org/pcor/</a>	<ul style="list-style-type: none"> <li>• Region rich in value-added geologic sequestration options</li> <li>• Wetlands a unique regional opportunity</li> <li>• Half-hour sequestration documentary aired on Prairie Public Television</li> </ul>
	University of Illinois, Illinois State Geological Survey <a href="http://www.sequestration.org/">http://www.sequestration.org/</a>	<ul style="list-style-type: none"> <li>• Efforts centered on a CO<sub>2</sub> pipeline "fairway" and a focused region</li> <li>• Transportation plans highly developed</li> <li>• Link to agriculture interests through ethanol</li> </ul>
	Battelle Memorial Institute <a href="http://198.87.0.58/default.aspx">http://198.87.0.58/default.aspx</a>	<ul style="list-style-type: none"> <li>• Strong analysis and cost-supply curves for CO<sub>2</sub> sequestration</li> <li>• Region accounts for &gt;20% of GHG emissions in the U.S.</li> <li>• Interactive website as outreach tool</li> </ul>
	Southern States Energy Board <a href="http://www.secarbon.org/">http://www.secarbon.org/</a>	<ul style="list-style-type: none"> <li>• Electricity supply industry and governor-level participation</li> <li>• Carbon offset program, a web-based portal for advertising sequestration opportunities</li> </ul>

# FutureGen: A \$1B Presidential Initiative

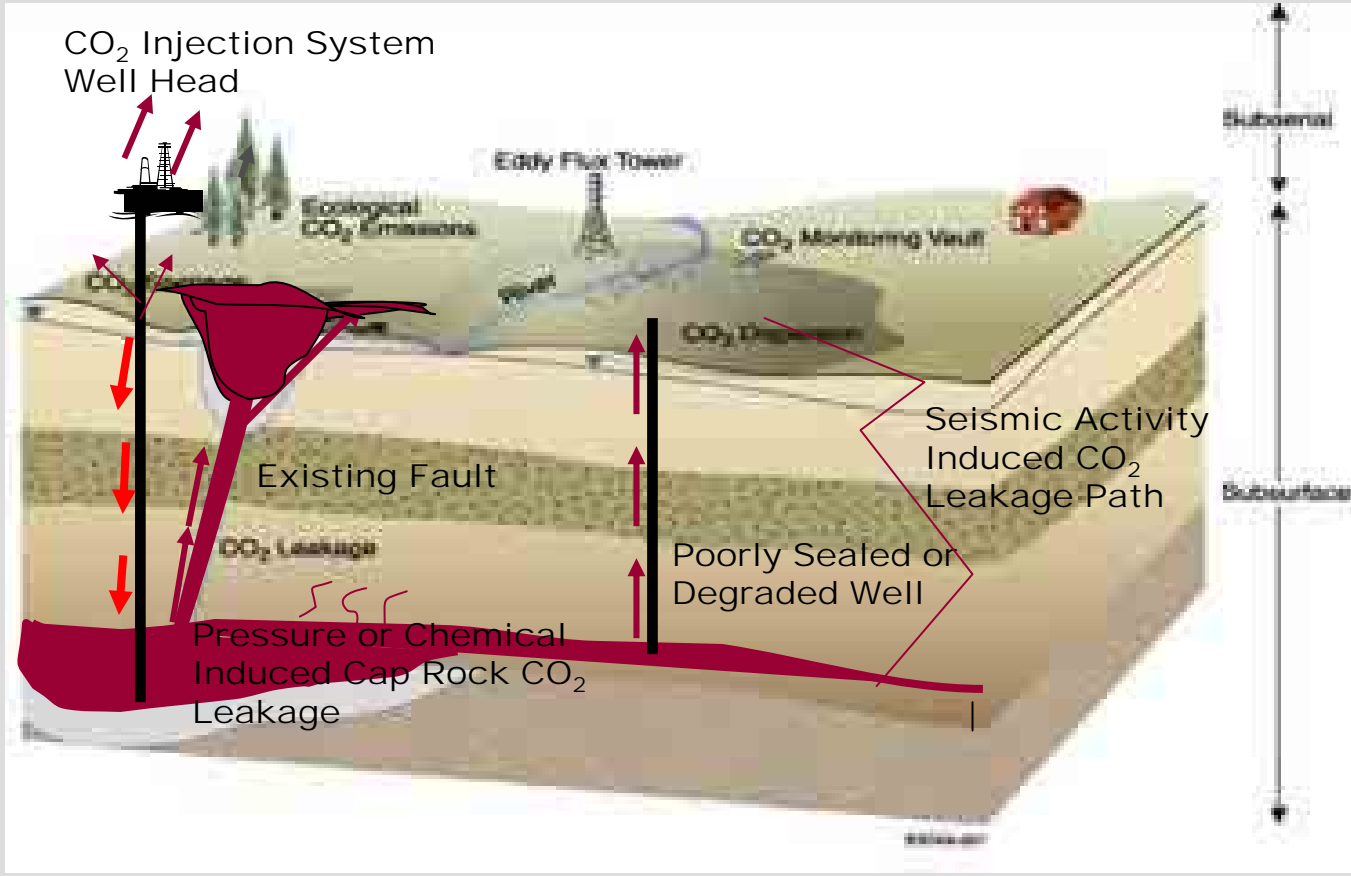


- ▶ Nominal 275 MWe Plant
  - ≈1 MMT CO<sub>2</sub> generated per year
  - >50% net efficiency
- ▶ Coal Gasification
  - H<sub>2</sub> production
    - Onsite electrical generation
      - Gas turbine
      - Fuel cells
      - Hybrids
    - Petrochemical feedstock
    - Transportation grade fuel
  - **CO<sub>2</sub> Capture (90% target)**



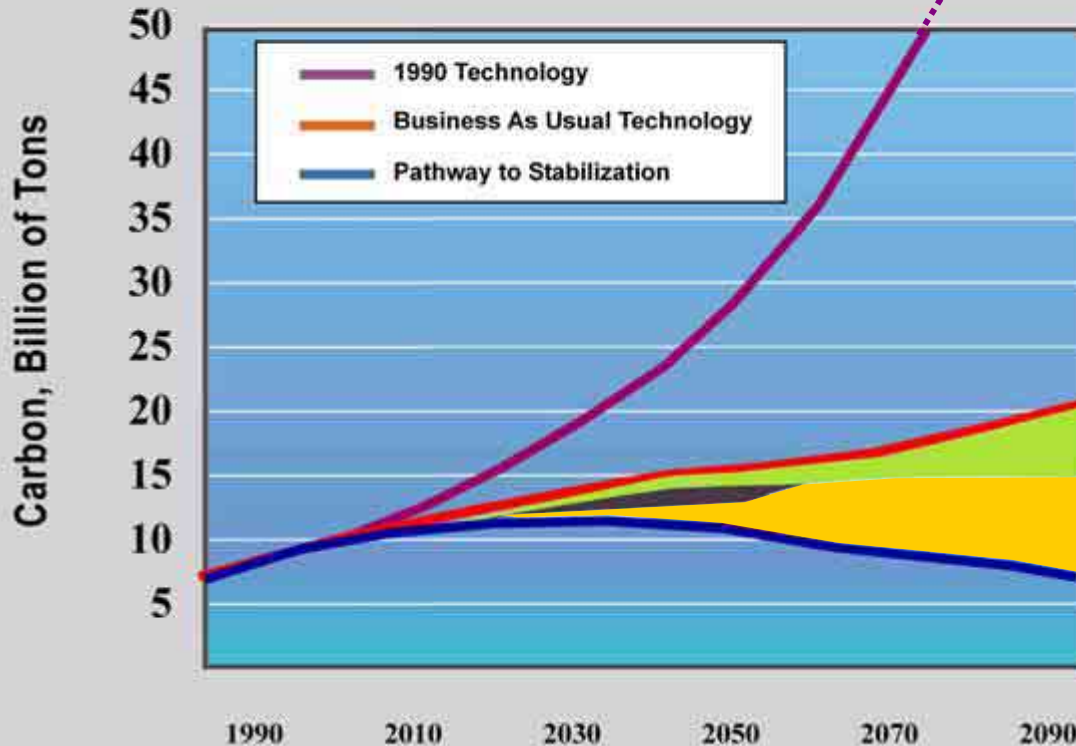
# Backup Slides

# CO<sub>2</sub> Leakage Pathways



# Role of Carbon Sequestration in Atmospheric CO<sub>2</sub> Stabilization

## Carbon Emissions

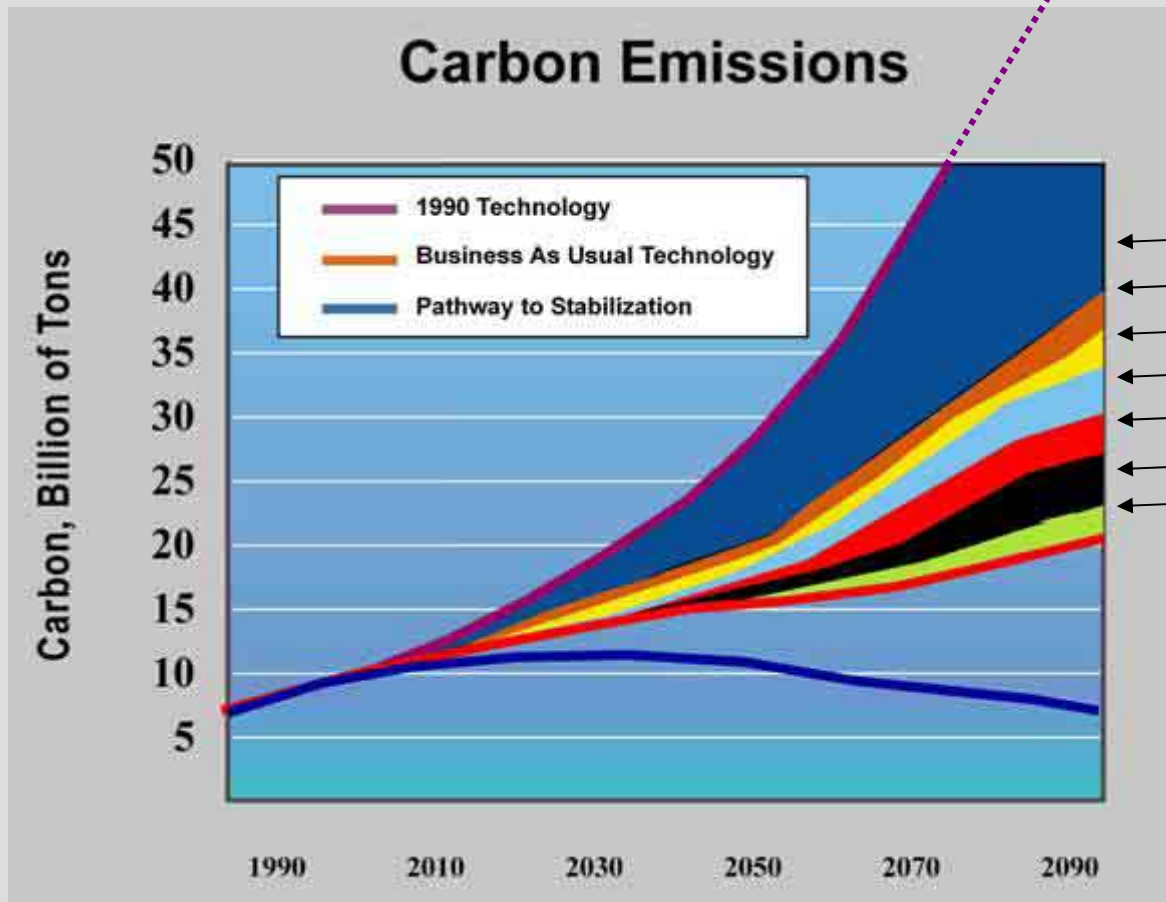


**"Stabilization"  
Technology Gap**

- Advanced Biomass
- Soil Sequestration
- H<sub>2</sub> + Fossil Power w/Sequestration

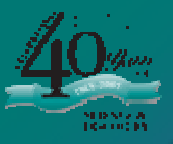
# Business-As-Usual Gap

*Extraordinary Improvement is Built into BAU*

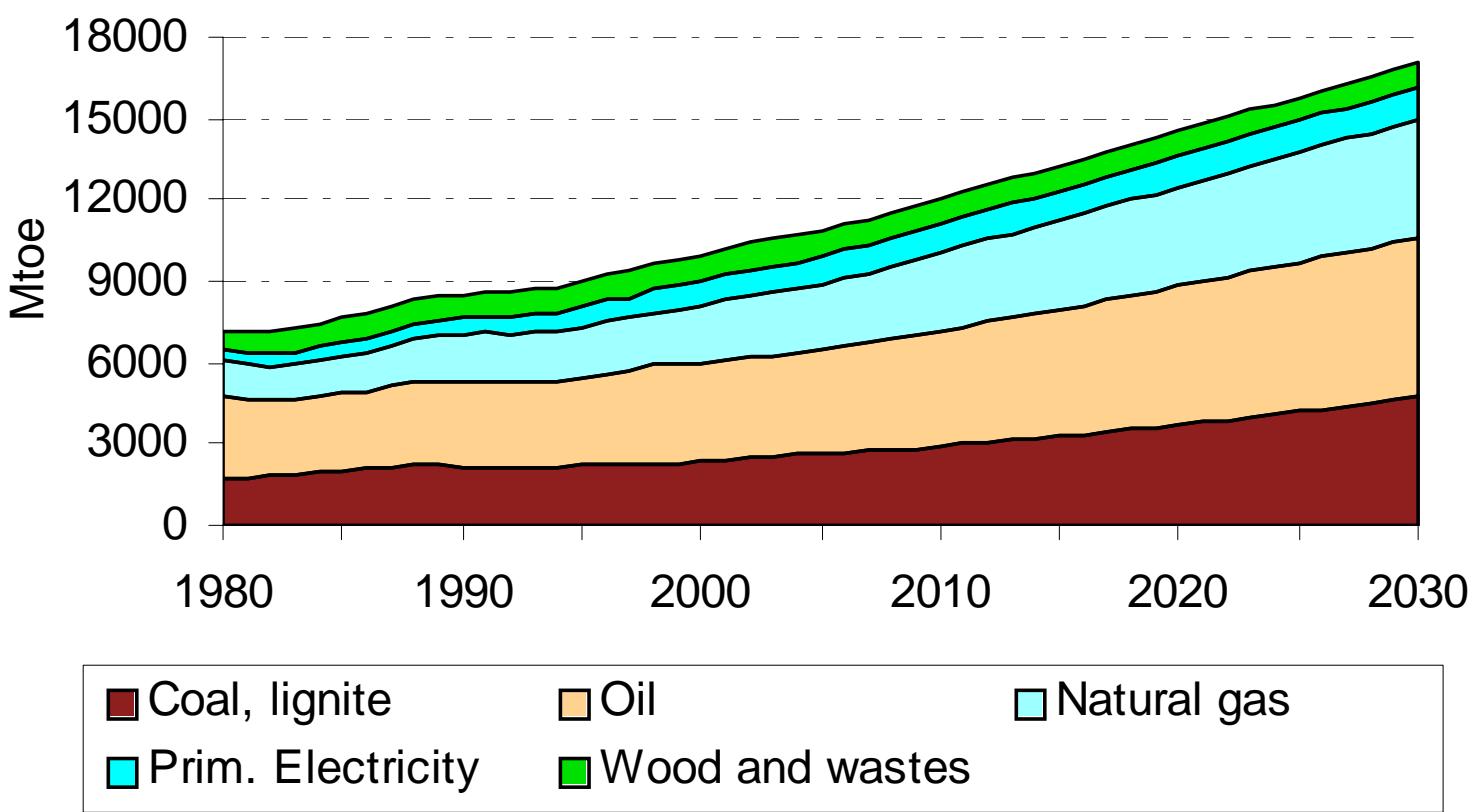


**"Business-As-Usual"  
Technology Gap**

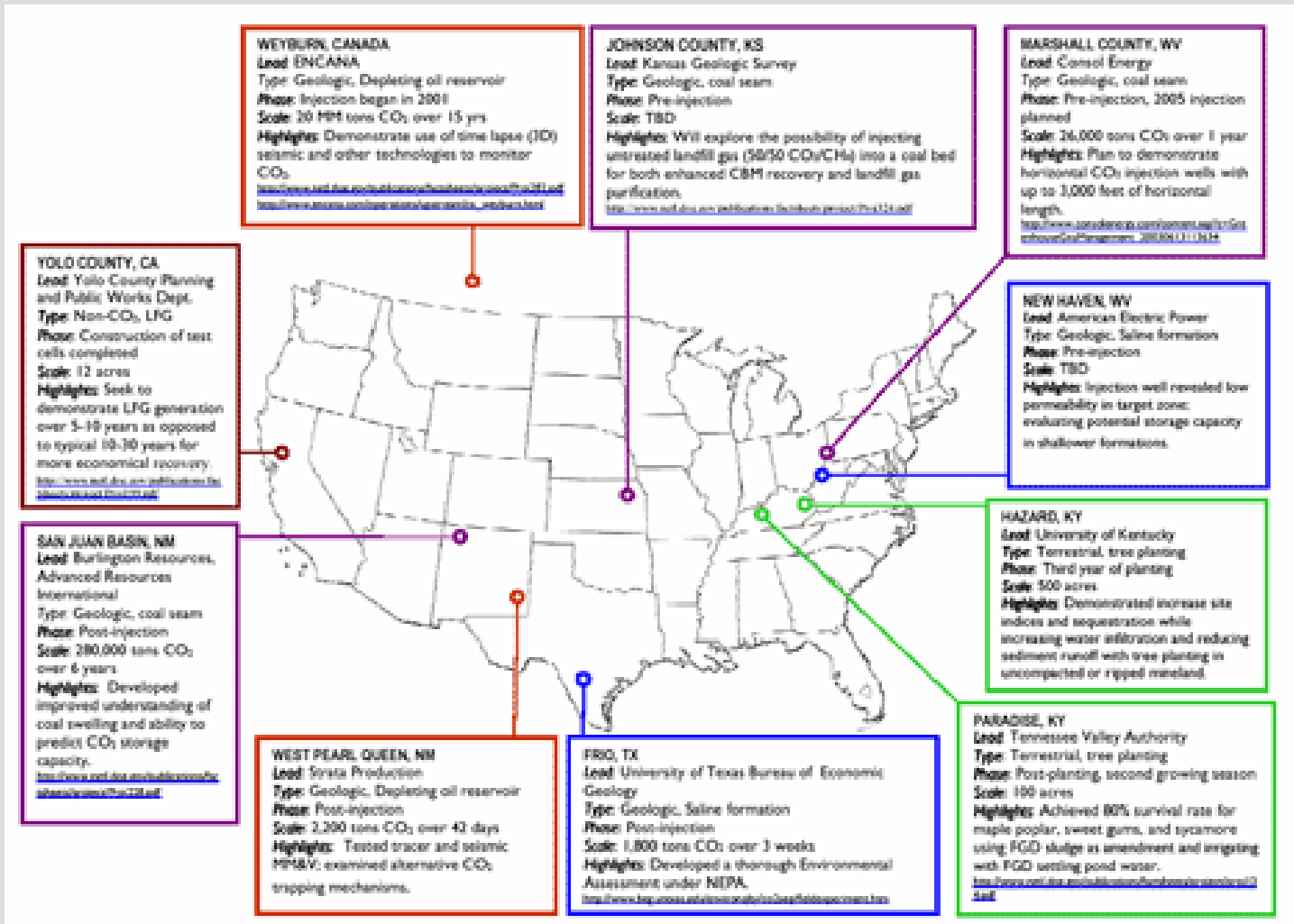




# World Energy Outlook



# Portfolio of Sequestration Field Projects





# State of Science?

	Web of Science		Information Bridge		Google	
	<u>2003</u>	<u>2005</u>	<u>2003</u>	<u>2005</u>	<u>2003</u>	<u>2005</u>
<b>Fuel Cell</b>	4311	7152	1239	1459	468000	4,060,000
<b>CO2 Capture</b>	171	301	80	133	1100	21500
<b>CO2 Capture + syngas</b>	81	145	47	72	137	772
<b>Carbon Sequestration</b>	389	1087	297	462	110,000	372,000
<b>Cold Fusion</b>	798	851	37	39	504,000	2,370,000