EERC Technology… Putting Research into Practice

CO_2 Separation and Capture: Status, Issues, and Opportunities

Presented at the Carbon Capture and Storage Conference

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Outline

- Options to reduce CO_2
- State of technology for CO_2 separation
- Economics

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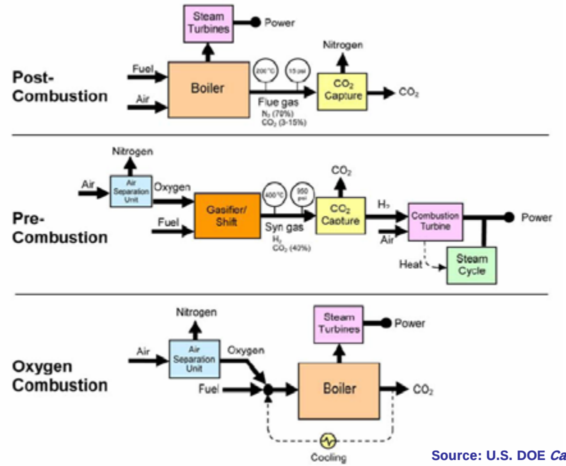
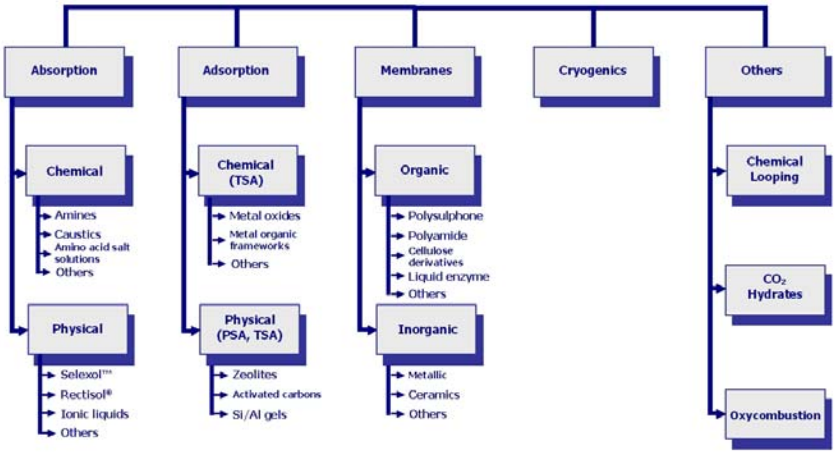
Fuel Conversion Platforms and CO$_2$ Capture



Source: U.S. DOE *Carbon Sequestration Technology Roadmap and Program Plan 2006*

Summary of CO$_2$ Capture Technologies

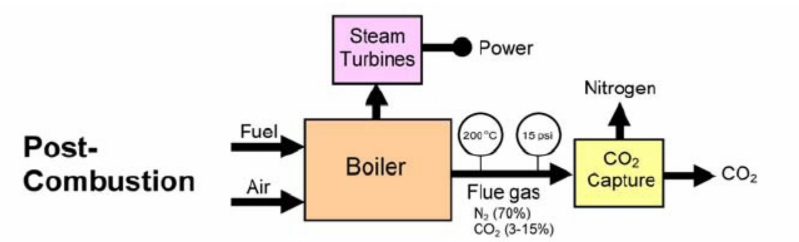


- **Absorption**
  - **Chemical**
    - Amines
    - Caustics
    - Amino acid salt solutions
    - Others
  - **Physical**
    - Selexol™
    - Rectisol®
    - Ionic liquids
    - Others
- **Adsorption**
  - **Chemical (TSA)**
    - Metal oxides
    - Metal organic frameworks
    - Others
  - **Physical (PSA, TSA)**
    - Zeolites
    - Activated carbons
    - Si/Al gels
- **Membranes**
  - **Organic**
    - Polysulphone
    - Polyamide
    - Cellulose derivatives
    - Liquid enzyme
    - Others
  - **Inorganic**
    - Metallic
    - Ceramics
    - Others
- **Cryogenics**
- **Others**
  - **Chemical Looping**
  - **CO_2 Hydrates**
  - **Oxycombustion**

Commercially Available Technologies

- **Chemical absorbents**
  - Monoethanolamine (MEA)
  - Methyldiethanolamine (MDEA)
  - Designer amines
  - Catacarb®
  - Benfield
- **Physical absorbents**
  - Selexol™
  - Rectisol®

Fuel Conversion Platforms and CO_2 Capture



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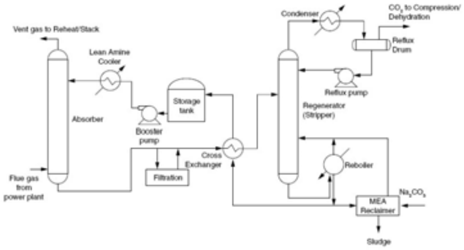
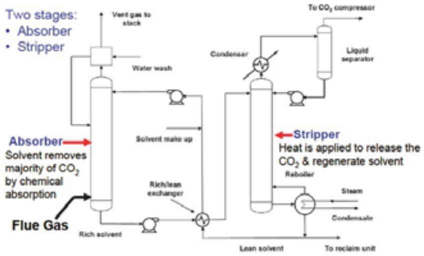
Amine and Ammonia Processes

Typical Amine Process





Two stages:
- Absorber
- Stripper

Absorber
Solvent removes majority of CO_2 by chemical absorption

Flue Gas

Stripper
Heat is applied to release the CO_2 & regenerate solvent

ALSTOM's Cold Ammonia Process

Pros and Cons of Amine Scrubbing

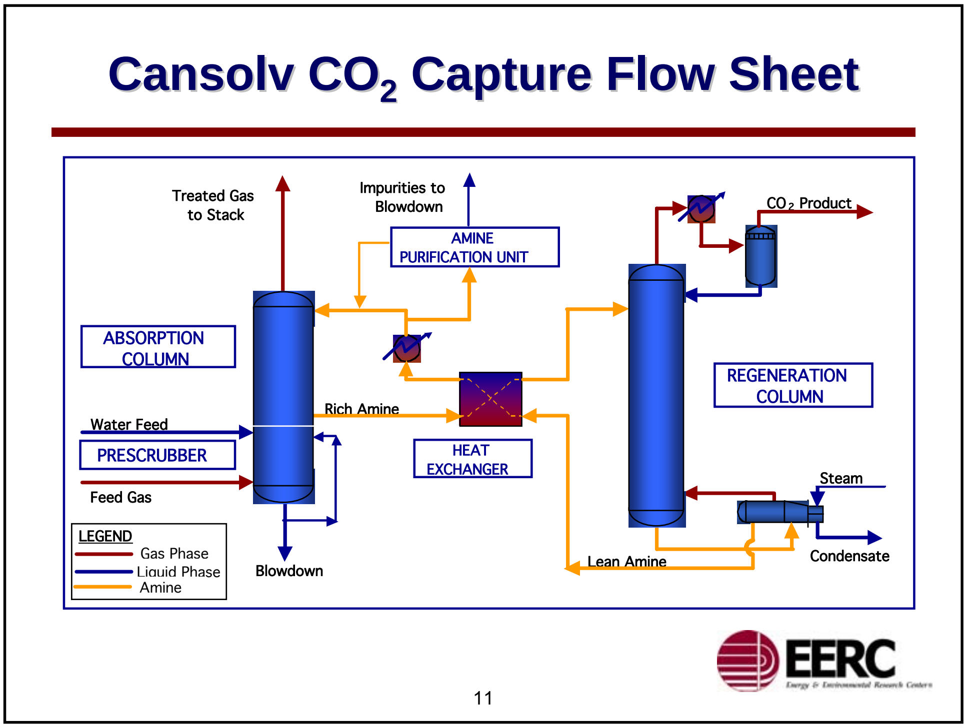
- **Pros**
  - Applicable to low-CO_2 partial pressures.
  - Recovery rates of up to 98% and product purity >99 vol% can be achieved.
- **Cons**
  - Process consumes considerable energy.
  - Solvent degradation and equipment corrosion occur in the presence of O_2.
  - Concentrations of SO_x and NO_x in the gas stream combine with the amine to form nonregenerable, heat-stable salts.

Pros and Cons of Ammonia Processes

- **Pros**
  - Lower heat of regeneration than MEA
  - Higher net CO_2 transfer capacity than MEA
  - Stripping steam not required
  - Offers multipollutant control
- **Cons**
  - Ammonium bicarbonate decomposes at 140°F, so temperatures in the absorber must be lower than that.
  - Ammonia is more volatile than MEA and often produces an ammonia slip into the exit gas.
  - Ammonia is consumed through the irreversible formation of ammonium sulfates and nitrates as well as removal of HCl and HF.

Cansolv Process

- Core platform process is Cansolv SO_2 scrubbing – selective amine scrubbing in an oxidative environment.
- The Cansolv breakthrough in operating costs:
  - Low salt formation
  - Low amine degradation
  - Low heat of regeneration
- R&D focus in 2000–2004 on developing high-performance solvents for NOx, Hg, and CO_2 absorption.
- Commercialization focus in 2005–2007: heat integrating/optimizing processes:
  - CO_2–SO_2
  - SO_2–NO_x–mercury



Cansolv CO_2 Capture Flow Sheet

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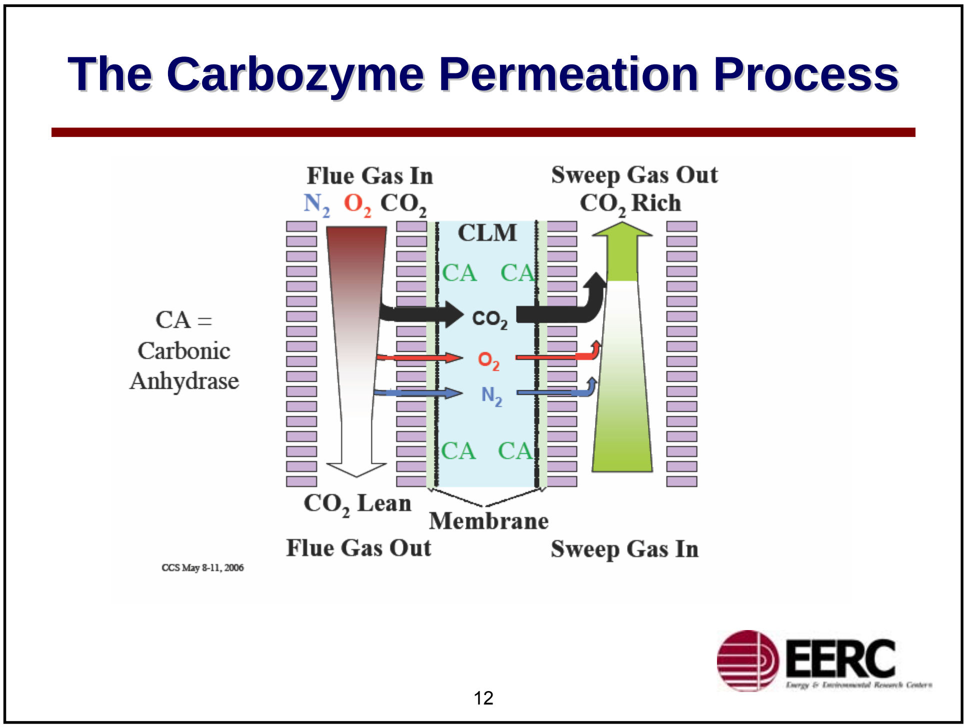

The Carbozyme Permeation Process

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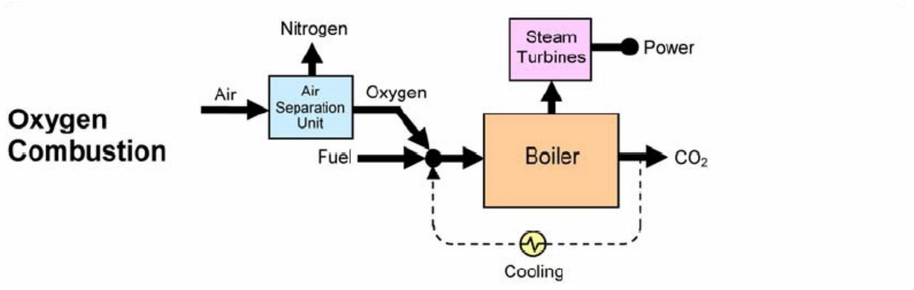
Cryogenics

Cryogenics

CO_2 is separated from a mixed-gas stream by compressing it and removing the heat of compression and condensation. Three methods are as follows:

- – Compress to ~1100 psia; water used for cooling.
- – Compress to 250–350 psia at 10° to 70°F, dehydrate feed stream with activated alumina or silica gel dryer, distill condensate in a stripping column.
- – Cool the mixed-gas stream to condense CO_2.

Fuel Conversion Platforms and CO_2 Capture



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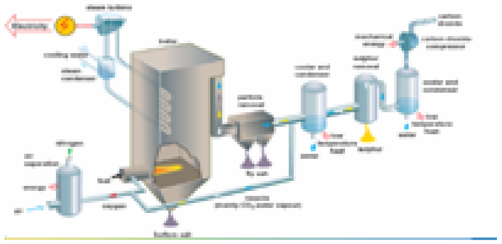
Oxycombustion

- Combustion in O_2/recycled flue gas
- Produce high CO_2 content (>80 vol%) flue gas
- Shown to significantly reduce NO_x
- Potential for zero-emission by sequestering all components in flue gas



Oxygen Separation

- State-of-the-art cryogenic distillation air separation has little room for improvement or cost reduction.
- Current development activities are centered on ion transport membranes.
  - These are complex crystalline structures with oxygen ion vacancies onto which oxygen adsorbs and decomposes into ions. The ions are transported through the membrane by sequential occupation of oxygen ion vacancies with the ion transport balanced by the counterflow of electrons. Oxygen partial pressure provides the driving force, which requires high-pressure air at temperatures above 1292°F. Barring the presence of defects, the membrane is selective to oxygen transport only.

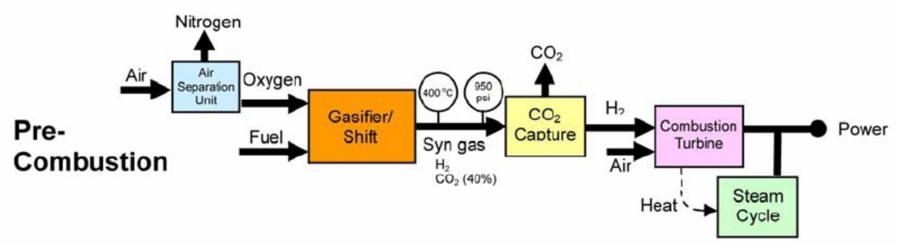
Oxygen Separation (cont.)

- The ion transport membranes can theoretically integrate high-temperature oxygen separation from air with the combustion process, leading to a significant reduction in parasitic power as well as lower cost for O_2 production.
- Development issues include materials of construction, integration with or into the boiler, control of wall temperature (as a consequence of combustion reaction), and carbon formation.
- Developers and systems include Praxair and Alstom Power (oxygen transport membrane [OTM]) and Air Products (ion transport membrane [ITM]).

Oxygen Separation Technologies – Ion Transport

- Advanced zero-emission power (AZEP) process (Alstom Power, Norsk Hydro), which is utilized with conventional gas turbines. Air from the compressor is supplied to a new MCM reactor. The reactor combines O_2 separation, combustion, and heat transfer. Preliminary evaluations show a 2% loss in plant efficiency for separation vs. a 10% loss with flue gas CO_2 separation.
- Integration into a fired boiler (Praxair) in which an OTM is incorporated directly into the boiler. It can be utilized with gaseous or liquid fuel.
- Utilization with circulating fluid-bed (CFB) or circulating moving-bed (CMB) boiler (Alstom Power). In this case, the OTM stands alone but is thermally integrated with the boiler. It requires a high-temperature air source and is heated by in-bed heat exchange of CFB or CMB.

Fuel Conversion Platforms and CO_2 Capture



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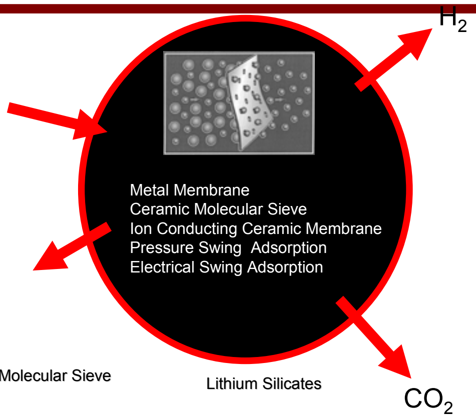
Gas Separation/Purification – Shift/Separation

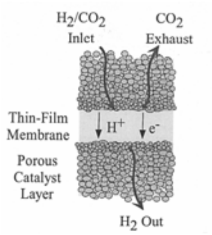
High Temperature
(up to 700°C?)

- Metal membrane
- Ceramic sieves
- Ion conductor ceramic membrane
- High temperature – lithium silicates

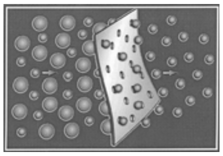


Metal Membrane
Ceramic Molecular Sieve
Ion Conducting Ceramic Membrane
Pressure Swing Adsorption
Electrical Swing Adsorption

Ionic Conducting Ceramic Membrane



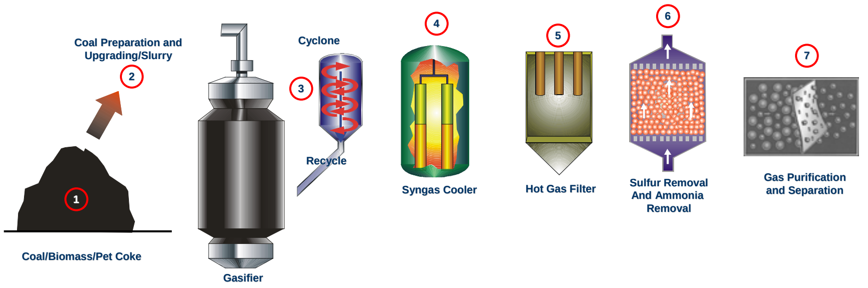
Ceramic Molecular Sieve



Lithium Silicates

$$Li_4SiO_4 + CO_2 = Li_2SiO_3 + Li_2CO_3$$

Fate and Impacts of Impurities on Gasification and Gas Cleanup



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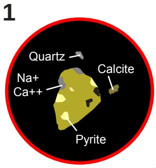

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Fuel Prep and Upgrading

- Slurry Prep
- Drying
- Mineral Removal
- Blending

3

Gasification

- Fuel Reactivity
- Partitioning (Vapor, Liquid, Solid)
- Slag Flow
- Bed/Ash Reaction
- Deposition

4

Gas Processing/ Cooling

- Condensation
- Transport
- Deposition Growth and Removal

5

Hot Gas Cleanup

- Particulate
- Hg
- Na
- Trace elements
- Halogens

6

Sulfur Removal

- H_2S --Metal Oxide
- Impact of Na, K
- Trace elements
- Hg
- Halogens

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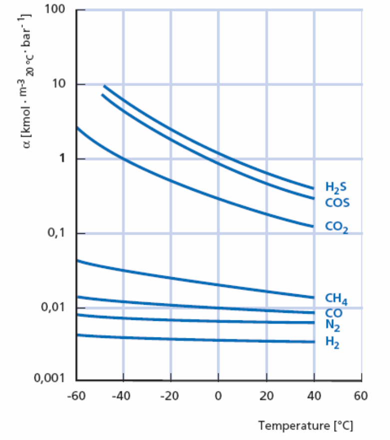
Gas Purification and Separation

- Shift Reactions
- Separation and Purification including CO2 removal

Rectisol

- Rectisol uses refrigerated methanol at −94°F as the solvent for physical absorption of CO_2 and H_2S.
- Removes all impurities and trace contaminants in one single absorption process.
- Ultrapure product gas: e.g., total sulfur <0.1 ppmv, CO_2 <2 ppmv.

Absorption Coefficients in Methanol



Physical Absorption

- Used primarily to remove CO_2 from gasification fuel or synthesis gas.
  - Selexol (glycol)
  - Rectisol (methanol)

Other Technologies

- Dry, regenerable, solid sorbents are under development for postcombustion CO_2 capture.
  - Currently at bench scale.
  - Essentially pure CO_2 because of selective adsorption.
  - Dry system eliminates need to heat and cool large quantities of water.

Pros and Cons of Physical Absorbents

- **Pros**
  - Low utility consumption.
  - Rectisol uses inexpensive, easily available methanol.
  - Selexol has a higher capacity to absorb gases than amines.
  - Selexol can remove H_2S and organic sulfur compounds.
  - Both provide simultaneous dehydration of the gas stream.
- **Cons**
  - Rectisol refrigeration costs can be high.
  - Hydrocarbons are coabsorbed in Selexol, resulting in reduced product revenue and often requiring recycle compression.
  - Refrigeration is often required for the lean Selexol solution.
  - More economical at high pressures.

Capture Technology Commercial Demonstrations

- **North America**
  - *ABB Lummus scrubber with MEA* – Shady Point Power Plant, OK, and Warrior Run Power Plant, Cumberland, MD
  - *Fluor Econamine FG*^{SM} – Cogeneration Facility, Bellingham, MA
  - *Rectisol®* – Great Plains Synfuels Plant, Beulah, ND
  - *Solvent Absorption (unspecified)* – Trona, CA
  - *Precombustion Capture*, BP Carson Refinery, CA
- **South America**
  - *MEA-based scrubber* – Prosint Methanol Production Plant, Rio de Janeiro, Brazil
- **Africa**
  - *Unspecified capture technology* – In Salah Project, Algeria
- **Europe**
  - *Solid sorbents* – Hammerfest, Norway
  - *Unspecified* – RWE IGCC Power Plant, Germany
  - *Unspecified* – Tjeldbergodden and offshore, Norway
  - *Precombustion* – Peterhead Power Station, Aberdeen, Scotland, and Miller field offshore UK, North Sea

Capture Technology Commercial Demonstrations (cont.)

- **Asia**
  - *Fluor Econamine FG*^{SM} – Sumitomo Chemicals Plant, Chiba, Japan; The Indo Gulf Fertilizer Company, Jagdishpur, Uttar Pradesh, India; Luzhou Natural Gas Chemicals, Luzhou City, China
  - *Novel Amine Solvent Absorption* – Petronas Fertilizer Company, Malaysia, Malaysia
- **Australia**
  - *ZeroGen Precombustion Capture* – Stanwell IGCC, Queensland, Australia

CO_2 Capture R&D Projects

Many CO_2 capture R&D projects are under way:

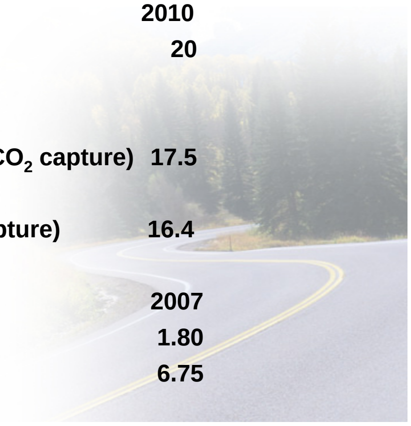
- North America – 22
- Europe – 15
- Asia – 1
- Australia – 1

Technologies being investigated cover the gamut:

- Regenerable sorbents
- Vortex tubes
- Membranes
- Oxyfuel combustion
- Postcombustion using potassium carbonate
- Photosynthesis of microalgae

Economics

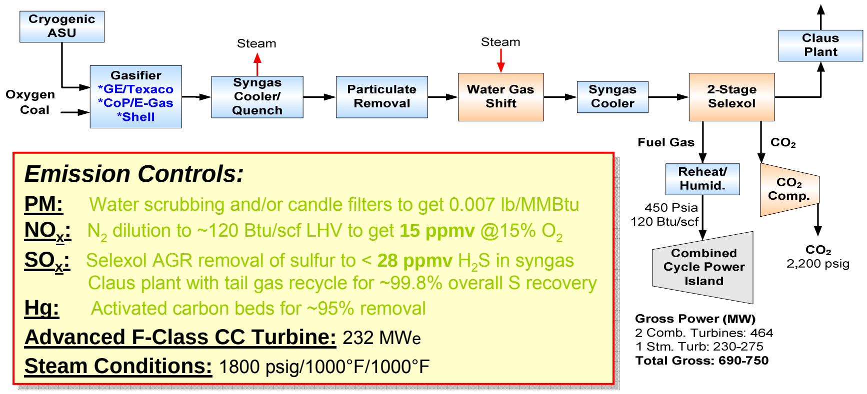
Economic Assumptions



Start-Up	2010
Plant Life (years)	20
Capital Charge Factor, %	
High Risk	
(All IGCC, PC/NGCC with CO_2 capture)	17.5
Low Risk	
(PC/NGCC without CO_2 capture)	16.4
Dollars (constant)	2007
Coal ($/MM Btu)	1.80
Natural Gas ($/MM Btu)	6.75
Capacity Factor	
IGCC	80
PC/NGCC	85

www.netl.doe.gov/energy-analyses/baseline_studies.html

Current Technology
IGCC Power Plant with CO_2 Scrubbing



Emission Controls:

PM: Water scrubbing and/or candle filters to get 0.007 lb/MMBtu

NO_x: N_2 dilution to ~120 Btu/scf LHV to get **15 ppmv** @15% O_2

SO_x: Selexol AGR removal of sulfur to < **28 ppmv** H_2S in syngas
Claus plant with tail gas recycle for ~99.8% overall S recovery

Hg: Activated carbon beds for ~95% removal

Advanced F-Class CC Turbine: 232 MWe

Steam Conditions: 1800 psig/1000°F/1000°F

Gross Power (MW)
2 Comb. Turbines: 464
1 Stm. Turb: 230-275
Total Gross: 690-750

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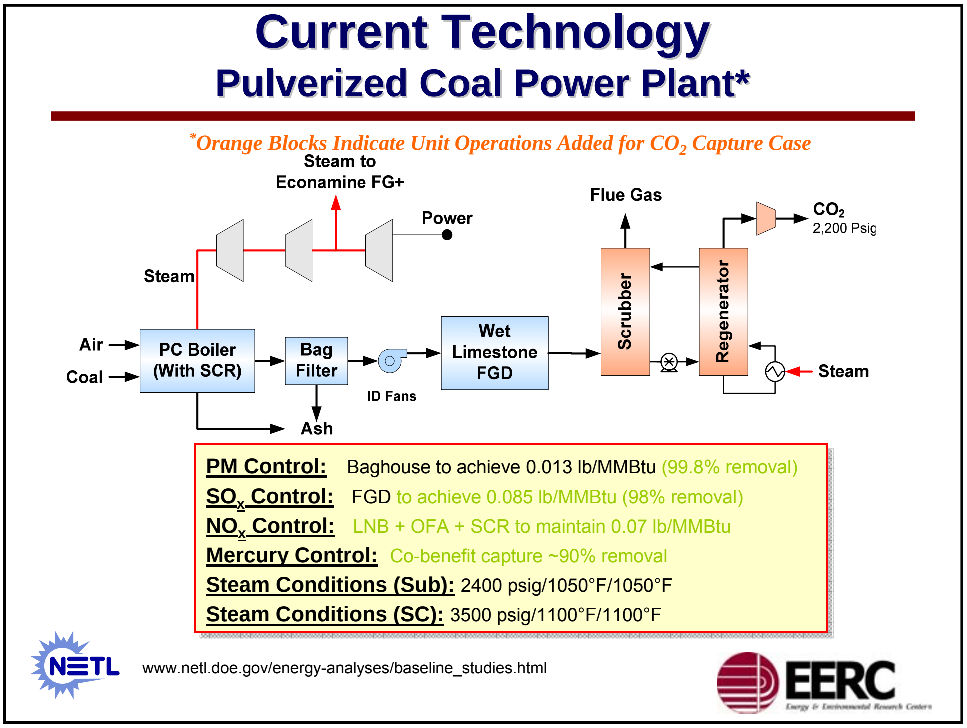

Current Technology

Pulverized Coal Power Plant*

Orange Blocks Indicate Unit Operations Added for CO_2 Capture Case

PM Control: Baghouse to achieve 0.013 lb/MMBtu (99.8% removal)
SO_x Control: FGD to achieve 0.085 lb/MMBtu (98% removal)
NO_x Control: LNB + OFA + SCR to maintain 0.07 lb/MMBtu
Mercury Control: Co-benefit capture ~90% removal
Steam Conditions (Sub): 2400 psig/1050°F/1050°F
Steam Conditions (SC): 3500 psig/1100°F/1100°F

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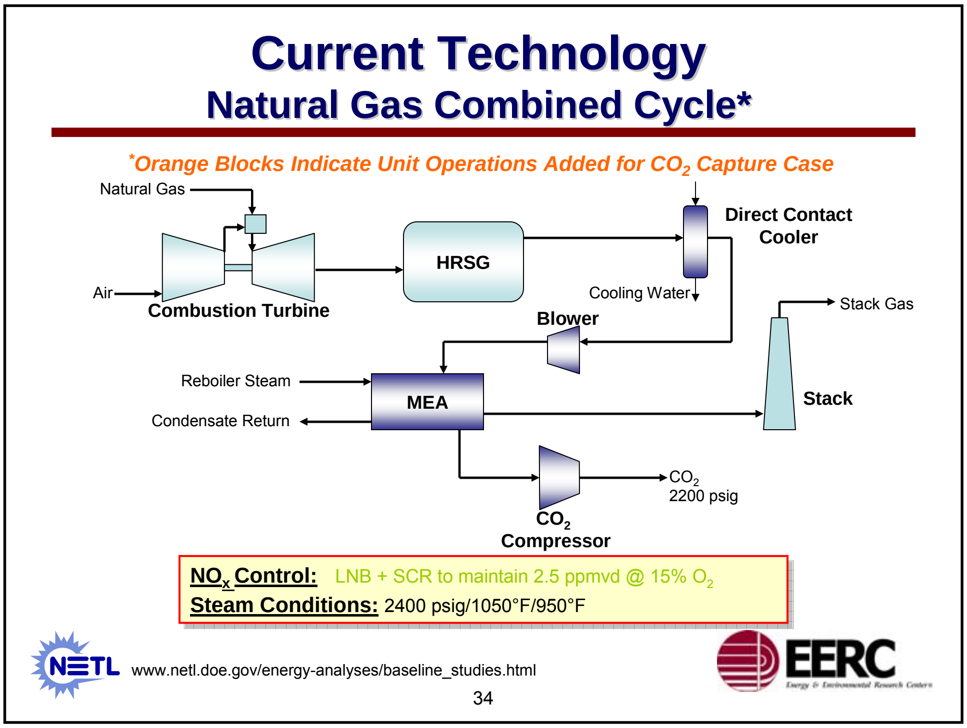

Current Technology

Natural Gas Combined Cycle*

Orange Blocks Indicate Unit Operations Added for CO_2 Capture Case

NO_x Control: LNB + SCR to maintain 2.5 ppmvd @ 15% O_2
Steam Conditions: 2400 psig/1050°F/950°F

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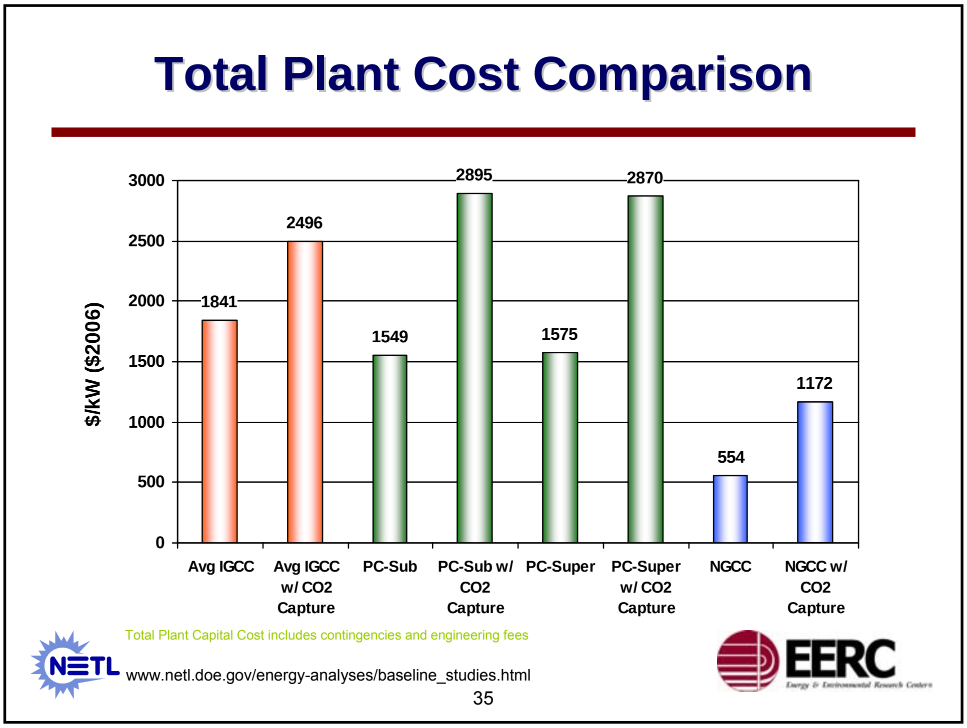
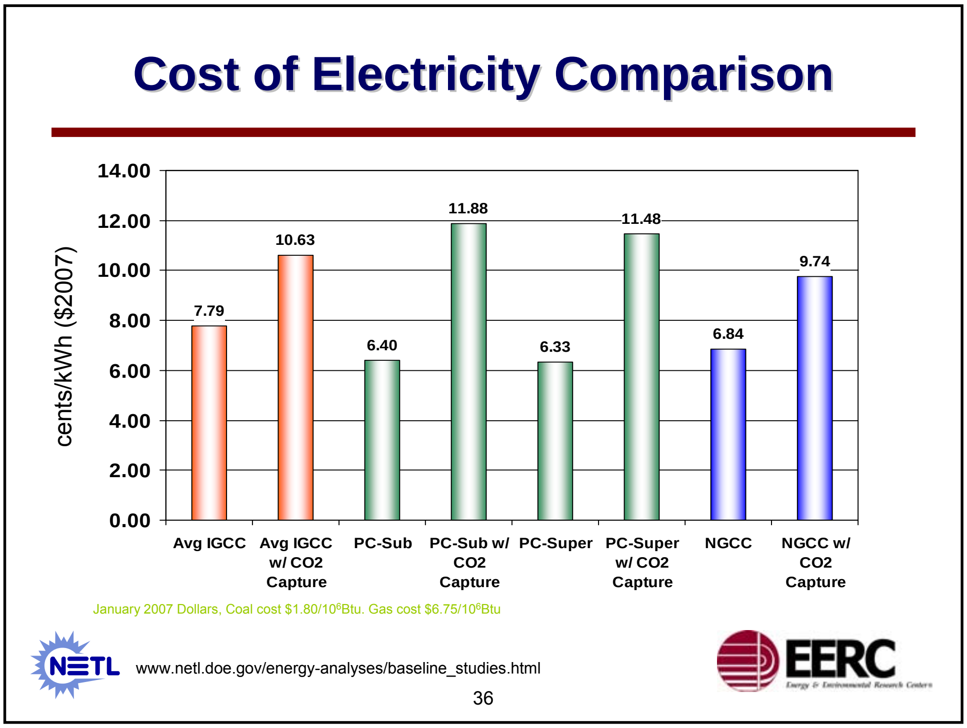


Total Plant Cost Comparison

Total Plant Capital Cost includes contingencies and engineering fees

www.netl.doe.gov/energy-analyses/baseline_studies.html



Cost of Electricity Comparison

January 2007 Dollars, Coal cost $1.80/10^6Btu. Gas cost $6.75/10^6Btu

www.netl.doe.gov/energy-analyses/baseline_studies.html

Results Highlights: COE

- 20-year levelized COE: pc lowest cost generator
  - pc: 64 mills/kWh (average)
  - NGCC: 68 mills/kWh
  - IGCC: 78 mills/kWh (average)

- With CCS: IGCC lowest coal-based option
  - NGCC: 96 mills/kWh
  - IGCC: 105 mills/kWh (average)
  - pc: 116 mills/kWh (average)

- Break-even LCOE* when natural gas price is:
  - No Capture IGCC: \$7.99/MMBtu PC: \$6.15/MMBtu
  - With Capture IGCC: \$7.73/MMBtu PC: \$8.87/MMBtu

* At baseline coal cost of \$1.80/MMBtu

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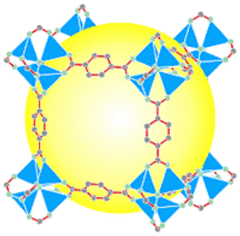
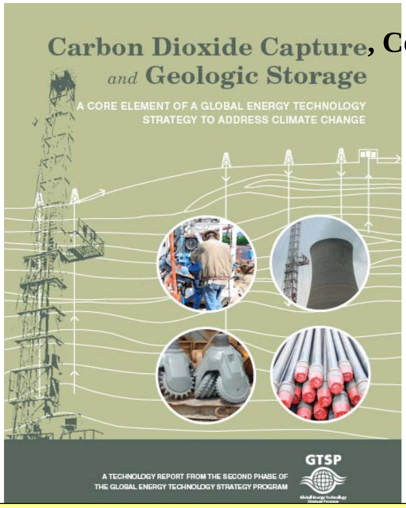
Breakthrough Concepts



- Ionic liquid absorbents
- Metal organic frameworks
- Separation membranes
- Subsurface technologies
  - Mineral carbonation
  - Mineral dissolution kinetics
- Microbial conversion of CO_2 to value-added chemicals

CC(C)S: Compression Is the Third “C”


Carbon Dioxide Capture, Compression
and Geologic Storage
A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE
A TECHNOLOGY REPORT FROM THE SECOND PHASE OF THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM
GTSP

“A Funny Thing Happened on the Way to the Printer”

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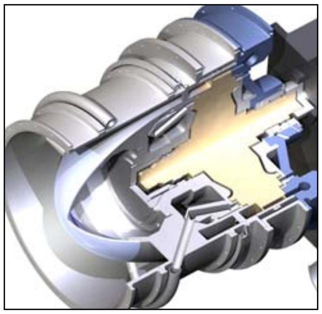
Benefits

MAN Turbo CO_2 Compressor

- **10-stage 6000 hp**
  - **$8.0 million ⇨$1350/hp**
  - **Pr 200:1 ⇨1.70 per stage**
- **8-stage 20,000 hp**
  - **$20.0 million ⇨$1000/hp**
  - **Pr 143:1 ⇨1.86 per stage**

Ramgen CO_2 Compressor



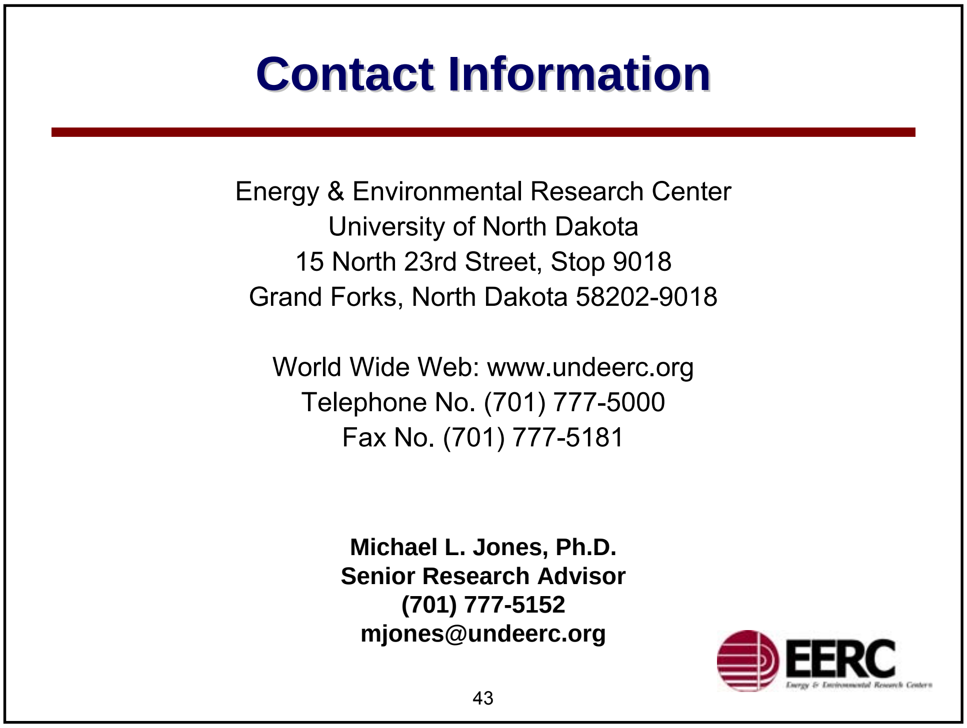
- **Pr 10:1 per stage**
- **1/20th the physical size**
- **1/3 the capital cost - $350/hp**
- **Same input power requirements**
- **Recover of 70%–80% of the input Btu**

Summary

- Several options exist to capture CO_2 from coal-fired power plants, but few of these options exist on a commercial level.
- IGCC or polygeneration facilities based on gasification have demonstrated options for CO_2 capture – cost is an issue.
- The most proven of the commercially available options is amine scrubbing. Although these options exist today, none of them can provide an inexpensive means to capture CO_2 in terms of energy or economics.

Summary (cont.)

- Key issue will be cleaning the flue gases prior to CO_2 separation step.
- The technologies currently available all require a large amount of energy, which, in most cases, will more than double the auxiliary power requirements of the plant. High costs also accompany the large energy requirements.
- Research is ongoing to develop ways to provide an economical CO_2 capture technology, with several promising technologies in the research and development phases.



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