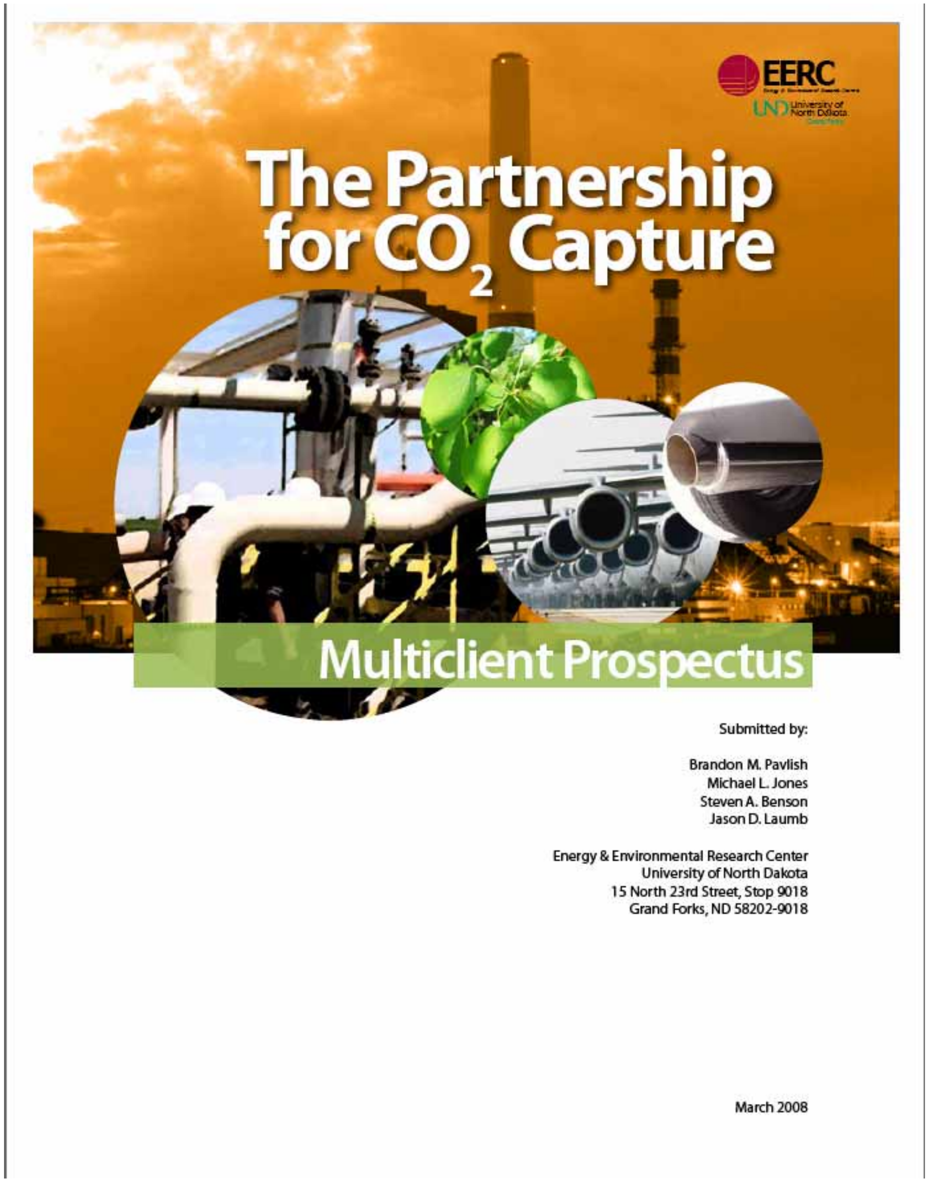
The Partnership for CO_2 Capture

Project Kickoff Meeting

Brandon Pavlish, Mike Jones, Steve Benson, Jason Laumb, John Kay, Josh Stanislowski, and Scott Tolbert

March 26, 2008
Energy & Environmental Research Center

Introductions



The Partnership for CO_2 Capture

Multiclient Prospectus

Submitted by:

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March 2008

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Agenda

Time	Activity	Discussion Leader(s)
8:00 a.m.	Continental Breakfast	All
8:30 a.m.	Welcome and Introductions	Steve Benson
8:35 a.m.	Welcome by the EERC Director	Gerry Groenewold
8:45 a.m.	CO_2 Capture Background	Mike Jones
10:15 a.m.	Break	All
10:45 a.m.	CO_2 Capture Challenges	Brandon Pavlish
11:45 a.m.	The Partnership for CO_2 Capture – Overview	Brandon Pavlish
12:00 Noon	Business Lunch *[Discovery Hall Lobby Area]*	All
1:00 p.m.	Work Plan •Task 1: Design and Construction (postcombustion) •Task 2: Oxycombustion Retrofit •Task 3: Shakedown and Testing •Task 4: Systems Engineering Studies	 Scott Tolbert Jason Laumb John Kay Josh Stanislowski
2:00 p.m.	Deliverables, Schedule, and Management (Task 5)	Brandon Pavlish
2:30 p.m.	Project Sponsor Role	Brandon Pavlish
3:00 p.m.	Wrap-Up and Questions	
3:15 p.m.	Optional Tour of the EERC	Jason Laumb Brandon Pavlish
3:45 p.m.	Adjourn	

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Meeting Goals and Objectives

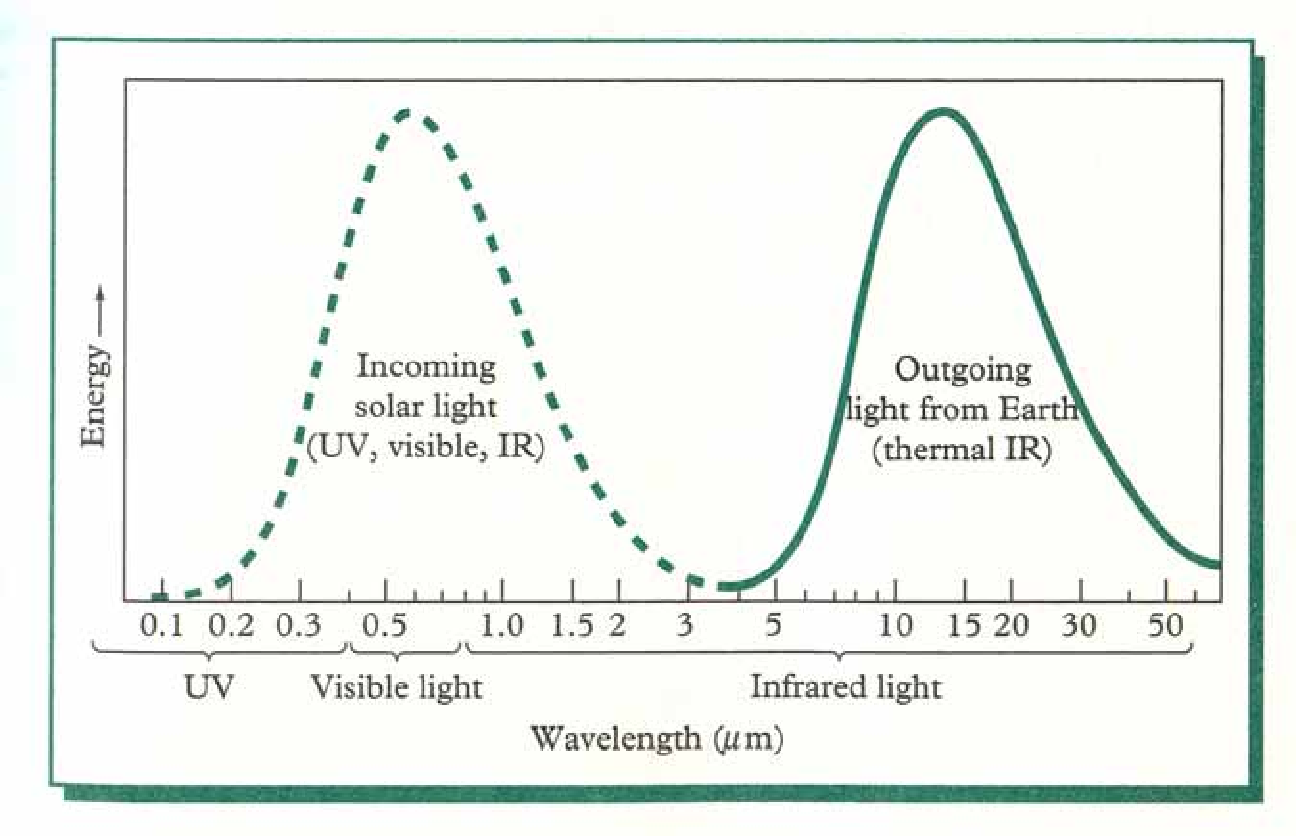
- Provide a synopsis of the current views of the impact of carbon dioxide (CO_2) on the climate
- Identify challenges facing industry
- Demonstrate how this program is addressing these challenges

CO_2 Capture Background

CO_2 and the Environment

Mike Jones

Earth's Energy Balance



Wavelength distribution for light from the sun and by earth surface and troposphere

Source: Environmental Chemistry, Baird and Cann, Freeman and Co., NY, 2005

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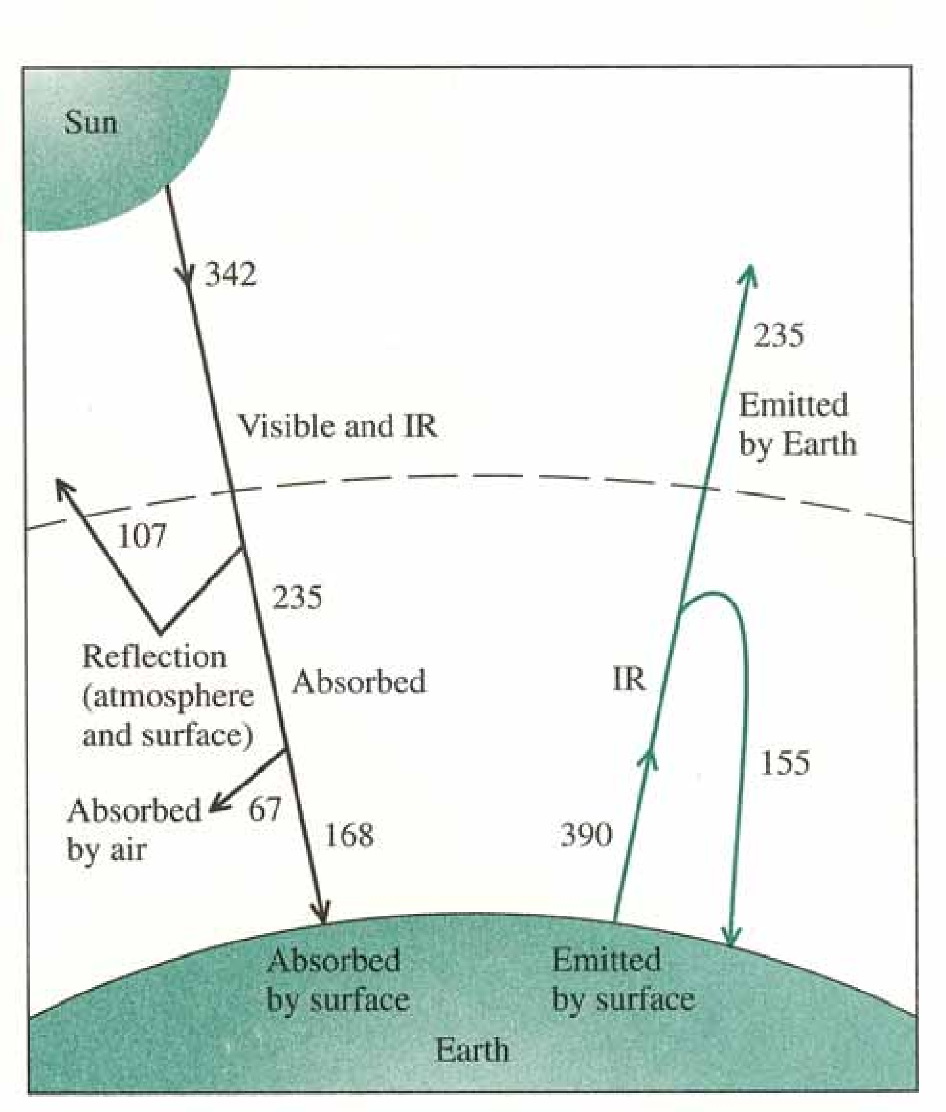
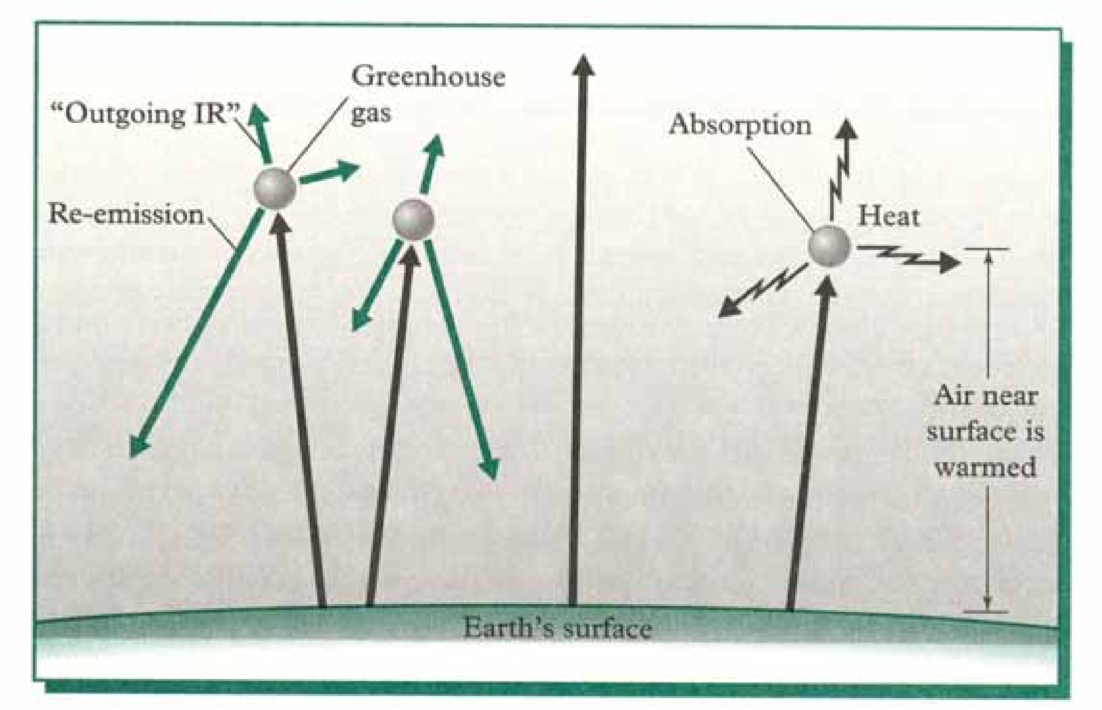
Average Energy Fluxes to and from the Earth (watts/m^2)



Averaged day and night over all latitudes and longitudes and all seasons

Source: Environmental Chemistry, Baird and Cann, Freeman and Co., NY, 2005

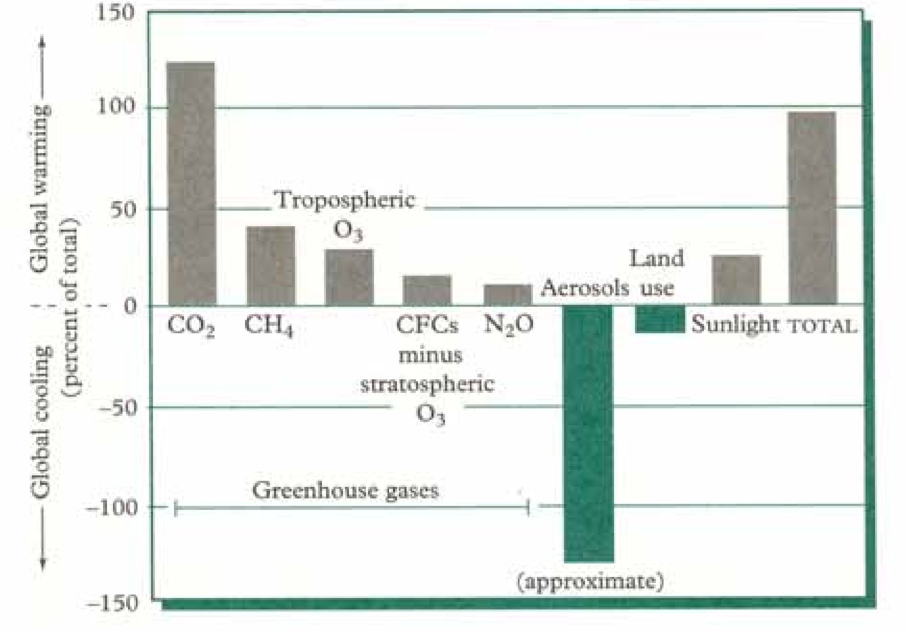
Greenhouse Effect



- Outgoing infrared (IR) absorbed by greenhouse gases is either reemitted or converted to heat.
- Examples – thermal IR region (4 to 50 µm):
  - Carbon dioxide absorbs light in two regions – maximum in the thermal IR region of 15 µm and at 4.26 µm.
  - CFC – Light frequency matches of internal motion of molecule. resulting in vibrations – C–F bonds will absorb outgoing thermal IR light.

Source: Environmental Chemistry, Baird and Cann, Freeman and Co., NY, 2005

Contributions to Global Warming and Cooling



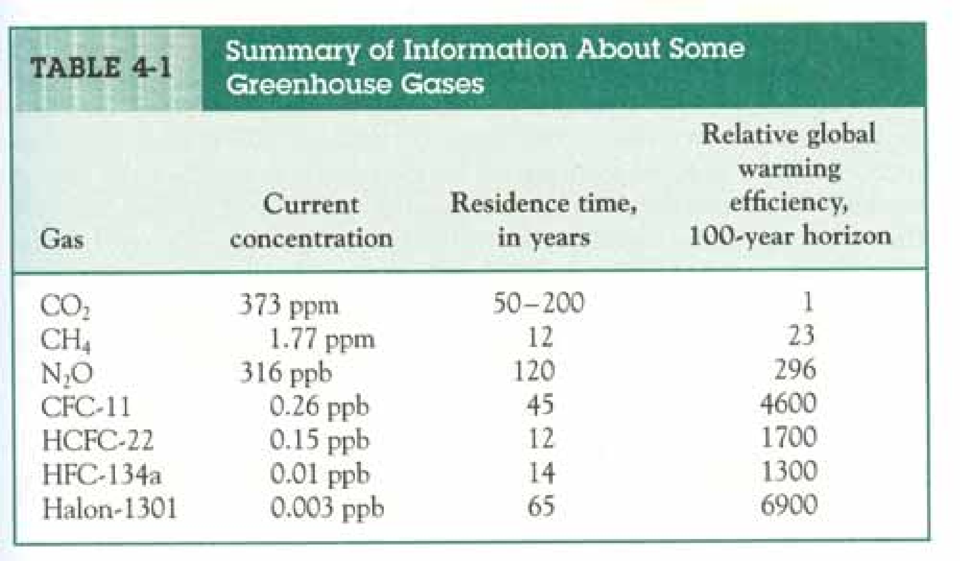


TABLE 4-1 Summary of Information About Some Greenhouse Gases

Gas	Current concentration	Residence time, in years	Relative global warming efficiency, 100-year horizon
CO_2	373 ppm	50–200	1
CH_4	1.77 ppm	12	23
N_2O	316 ppb	120	296
CFC-11	0.26 ppb	45	4600
HCFC-22	0.15 ppb	12	1700
HFC-134a	0.01 ppb	14	1300
Halon-1301	0.003 ppb	65	6900

Source: Environmental Chemistry, Baird and Cann, Freeman and Co., NY, 2005

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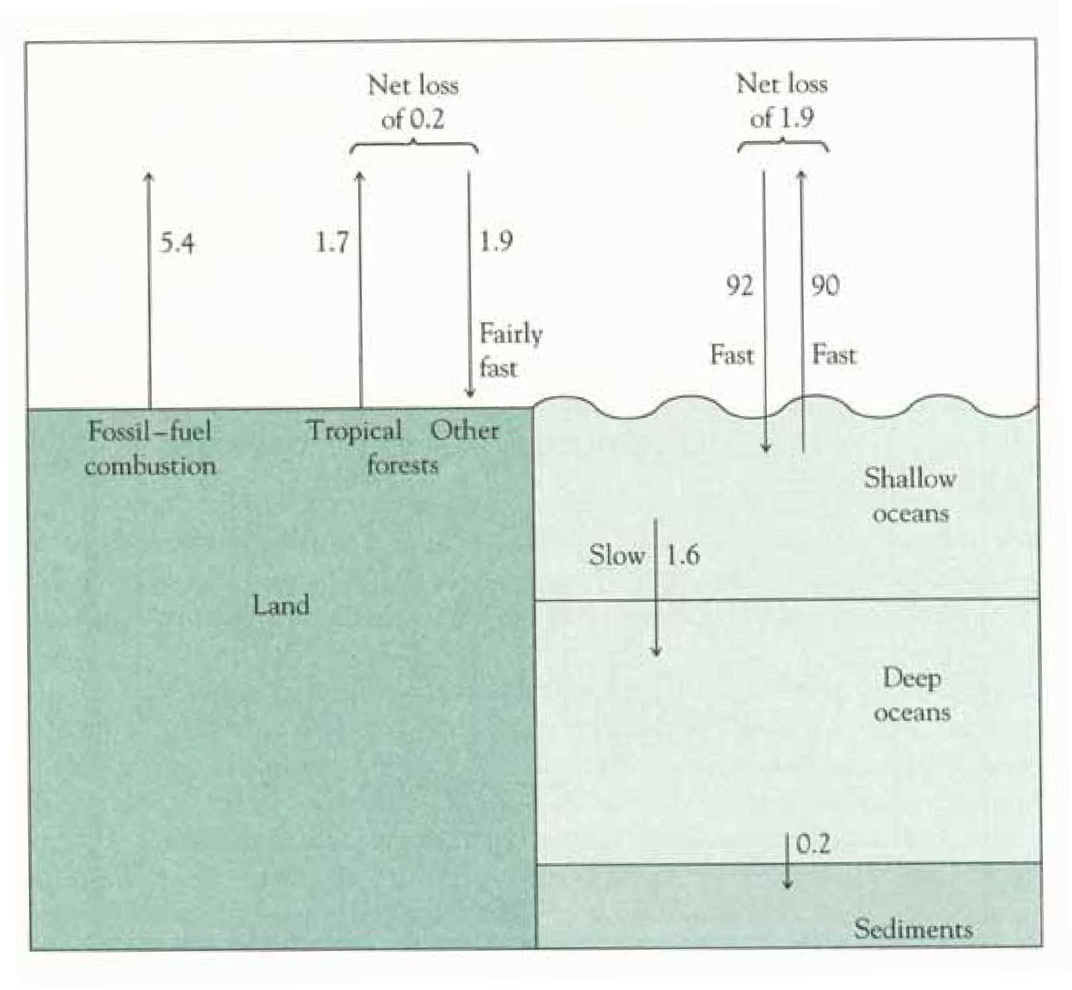
Annual CO_2 Fluxes to and from the Atmosphere (gigatonnes)



Mid-1980s data in gigatonnes of carbon (only)
Note: 3.3 gigatonnes did not find a sink.

Source: Environmental Chemistry, Baird and Cann, Freeman and Co., NY, 2005

Carbon Dioxide

- One atom carbon and two atoms oxygen.
- Natural atmospheric constituent.
- 0.04% of atmosphere.
- Critical to plant life.
- Like water vapor and other greenhouse gases, supports the natural greenhouse effect that keeps the Earth livable.

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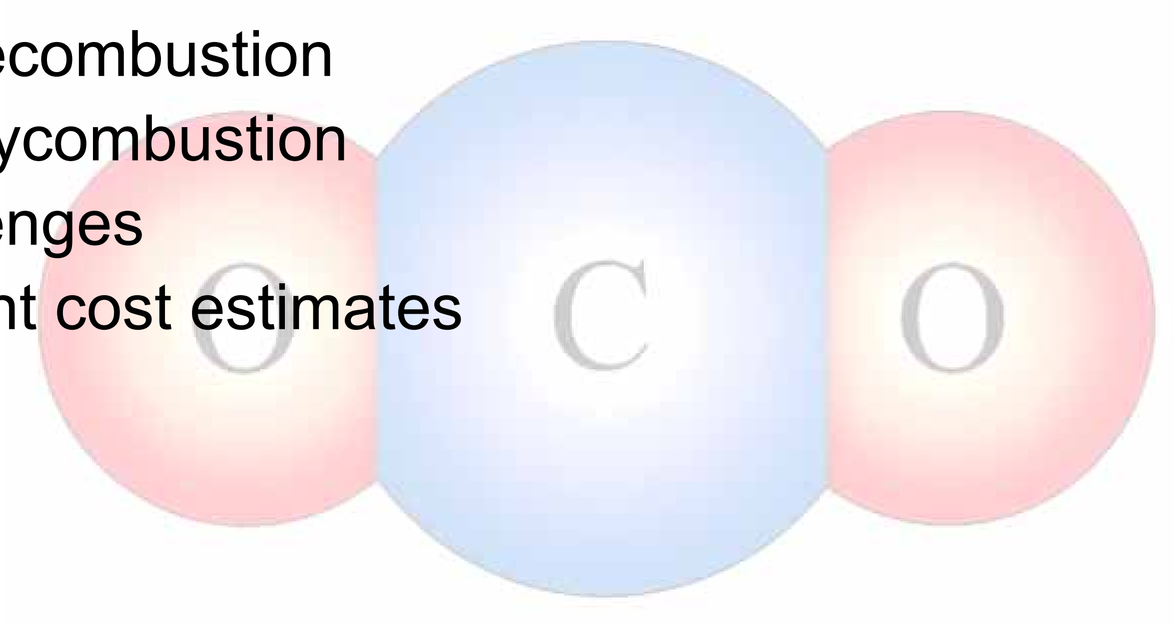
CO_2 Capture Background

- Introduction
- Capture technologies
  - Postcombustion
  - Precombustion
  - Oxycombustion
- Challenges
- Current cost estimates

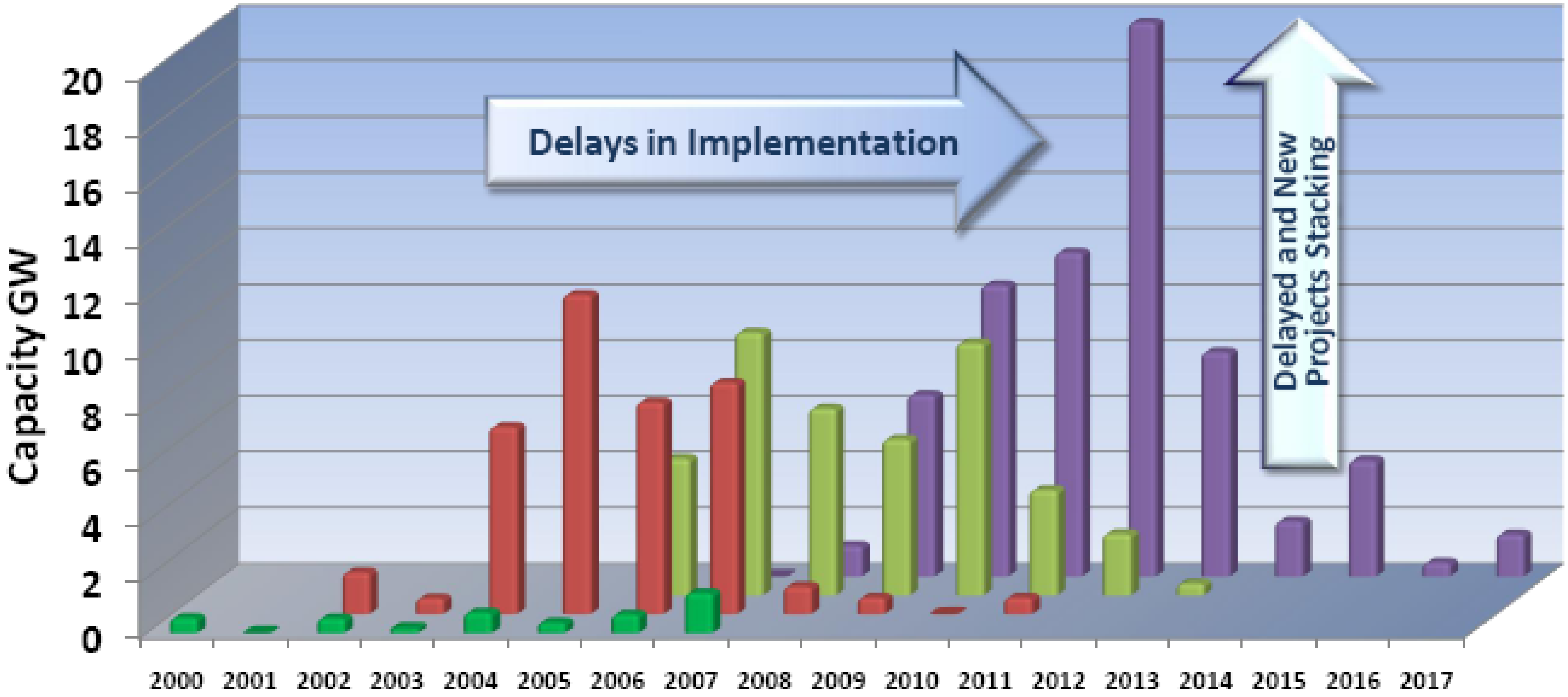


Introduction

Need for Research and Development

Past Capacity Announcements vs. Actual

Figure 1



Historically, actual capacity has been seen to be significantly less than proposed capacity. For example, the 2002 report listed 36,161 MW of proposed capacity by the year 2007 when actually only 4,478 MW (12%) were constructed.

Source: 2007 data Global Energy Decisions – Velocity Suite (12/31/2007)
2002 – 2005 data – Previous NETL Tracking New Coal-Fired Power Plants Reports

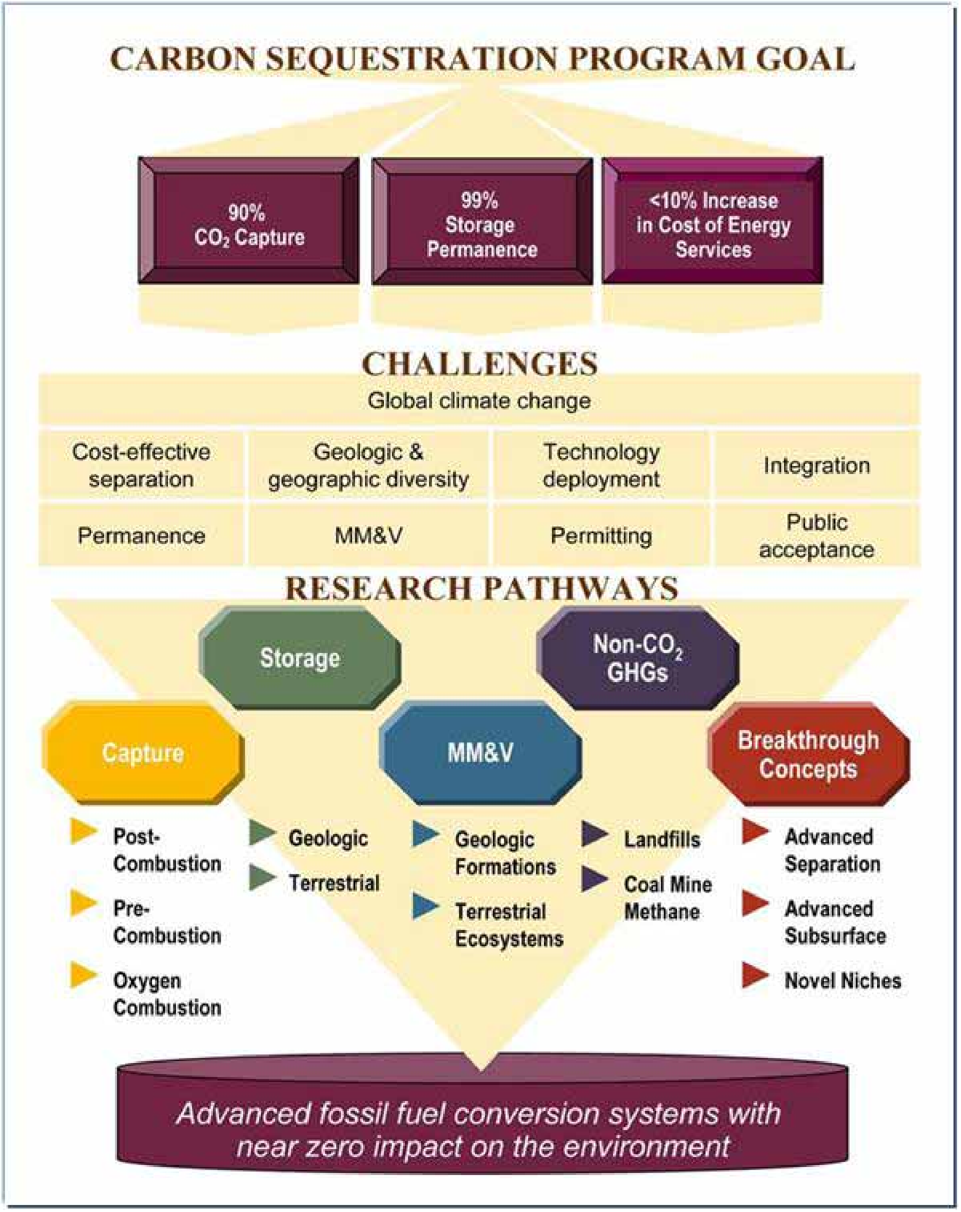
2/18/2008

DOE NETL Program Goals

Carbon Sequestration Program Goal and Research Pathways:

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) technology goal: “To develop, by 2012, fossil fuel conversion systems that offer 90% CO_2 capture with 99% storage permanence at less than a 10% increase in the cost of energy services.”

Source: DOE NETL, “Carbon Sequestration Technology Roadmap and Program Plan 2007,” www.netl.doe.gov (Accessed March 2008)



CARBON SEQUESTRATION PROGRAM GOAL

90% CO_2 Capture

99% Storage Permanence

<10% Increase in Cost of Energy Services

CHALLENGES

Global climate change

Cost-effective separation	Geologic & geographic diversity	Technology deployment	Integration
Permanence	MM&V	Permitting	Public acceptance

RESEARCH PATHWAYS

Capture
- Post-Combustion
- Pre-Combustion
- Oxygen Combustion

Storage
- Geologic
- Terrestrial

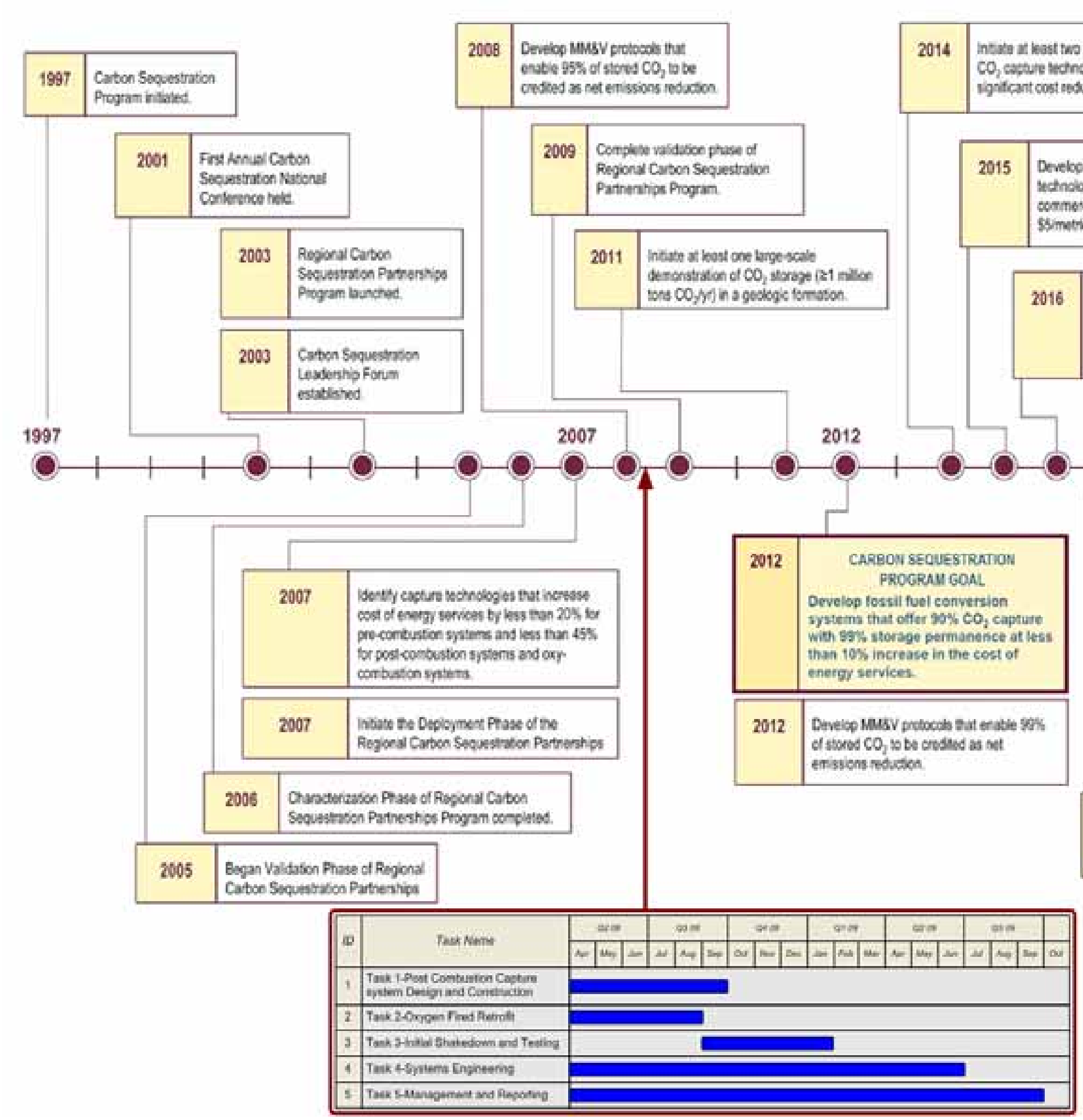
MM&V
- Geologic Formations
- Terrestrial Ecosystems

Non-CO_2 GHGs
- Landfills
- Coal Mine Methane

Breakthrough Concepts
- Advanced Separation
- Advanced Subsurface
- Novel Niches

Advanced fossil fuel conversion systems with near zero impact on the environment

Time Line of Research Activities



1997 Carbon Sequestration Program initiated.

2001 First Annual Carbon Sequestration National Conference held.

2003 Regional Carbon Sequestration Partnerships Program launched.

2003 Carbon Sequestration Leadership Forum established.

2005 Began Validation Phase of Regional Carbon Sequestration Partnerships

2006 Characterization Phase of Regional Carbon Sequestration Partnerships Program completed.

2007 Identify capture technologies that increase cost of energy services by less than 20% for pre-combustion systems and less than 45% for post-combustion systems and oxy-combustion systems.

2007 Initiate the Deployment Phase of the Regional Carbon Sequestration Partnerships

2008 Develop MM&V protocols that enable 95% of stored CO_2 to be credited as net emissions reduction.

2009 Complete validation phase of Regional Carbon Sequestration Partnerships Program.

2011 Initiate at least one large-scale demonstration of CO_2 storage (≥1 million tons CO_2/yr) in a geologic formation.

2012 CARBON SEQUESTRATION PROGRAM GOAL
Develop fossil fuel conversion systems that offer 90% CO_2 capture with 99% storage permanence at less than 10% increase in the cost of energy services.

2012 Develop MM&V protocols that enable 99% of stored CO_2 to be credited as net emissions reduction.

2014 Initiate at least two slipstream tests of novel CO_2 capture technologies that offer significant cost reductions.

2015 Develop terrestrial sequestration technologies to the point of commercialization at a cost not exceeding $5/metric ton of carbon sequestered.

2016 Begin at least one demonstration in which CO_2 is sequestered in a saline formation and brine water from the saline formation is recovered for beneficial use.

2018 Initiate large-scale field testing of promising novel CO_2 capture technologies.

2020 Initiate a field demonstration of at least one technology for enhancing the rate of CO_2 mineralization in-situ.

2022 Initiate at least one large-scale demonstration to evaluate the carbon sequestration benefits achieved by integrating biomass gasification and coal gasification.

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PCOR Partnership

The Plains CO_2 Reduction (PCOR) Partnership, one of seven regional partnerships funded by DOE NETL's Regional Carbon Sequestration Partnership (RCSP) Program, is managed by the Energy & Environmental Research Center (EERC) at the University of North Dakota in Grand Forks, North Dakota.

EERC ES31650.CDR

EERC Facilities in Grand Forks, North Dakota

Regional Carbon Sequestration Partnerships

EERC ES29046.AI

The RCSP Program represents more than 350 organizations in 41 states, three Indian nations, and four Canadian provinces.

What Is our Region Doing?

PCOR Partnership Region

Nine states and four provinces

Over 1.4 million square miles

The PCOR Partnership is assessing the technical and economic feasibility of capturing and storing (sequestering) CO_2 emissions from stationary sources in the central interior of North America.

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The PCOR Partnership currently has over 80 partners representing public agencies, utilities, oil and gas companies, engineering firms, associations and nonprofit organizations, and universities.

PCOR Partnership Members

EERC
University of North Dakota
Advanced Geotechnology
Air Products
Alberta Energy
EUB
AGS
ALLETE
Ameren

American Lignite Energy
Apache
Basin Electric Power Cooperative
Bechtel
Blue Source
BNI Coal
British Columbia Ministry of Energy and Mines
Carbozyme Inc.
CEED Center for Energy and Economic Development
Dakota Gasification Company
CCX Chicago Climate Exchange
Ducks Unlimited Canada

Ducks Unlimited
Eagle Operating Inc.
Enbridge
Encore Acquisition Company
Environment Canada
Excelsior Energy
Fischer Oil and Gas, Inc.
Great River Energy
Missouri Department of Natural Resources

HESS
DNR
Kiewit
Manitoba Hydro
MEG Energy Corp
Melzer Consulting
Minnesota Pollution Control Agency
minnesota power

Minnkota Power Cooperative, Inc.
Missouri River
Montana-Dakota
Environmental Quality
Murex Petroleum Corporation
National Commission on Energy Policy
Natural Resources Canada
Nexant
North American Coal

North Dakota Department of Commerce
North Dakota Department of Health
North Dakota Geological Survey
Industrial Commission of North Dakota Lignite Research, Development and Marketing Program
Industrial Commission of North Dakota Oil and Gas Research Council
Natural Resources Trust
North Dakota Petroleum Council
NDSU
Otter Tail Power Company

ptrc Petroleum Technology Research Centre
Prairie Public Television
Pratt & Whitney
Ramgen
RPS Energy
Saskatchewan Industry and Resources
SaskPower
Schlumberger
Shell Canada Limited
Spectra Energy

Strategic West Energy Ltd.
Suncor Energy
NETL
Tesoro
USGS
University of Alberta
University of Regina
Western Governors' Association
Westmoreland Coal Company
Xcel Energy

PCOR Partnership Phase I Goals

- Gauged public understanding
- Developed database for:
  - Sources
  - Sinks
  - Separation and transportation options
  - Regulatory and permitting requirements
  - Environmental benefits and risks
- Identified sequestration opportunities
- Conducted public outreach campaign
- Developed action plan for Phase II (field validation tests)

PCOR Partnership Phase II Goals

- Increase public understanding of CO_2 sequestration
- Perform field validation tests that develop:
  - Monitoring, mitigation, and verification (MMV) protocols
  - Regional sequestration strategies
  - Best separation–source matches
  - Regulatory and permitting strategies
  - Environmental benefits and risks
  - Information needed to monetize C credits
- Continued regional characterization
- Regional partnership program integration

Phase II: Field Validation Tests

CO_2-Rich Gas in a Pinnacle Reef Structure

Wind Energy for CO_2 Compression

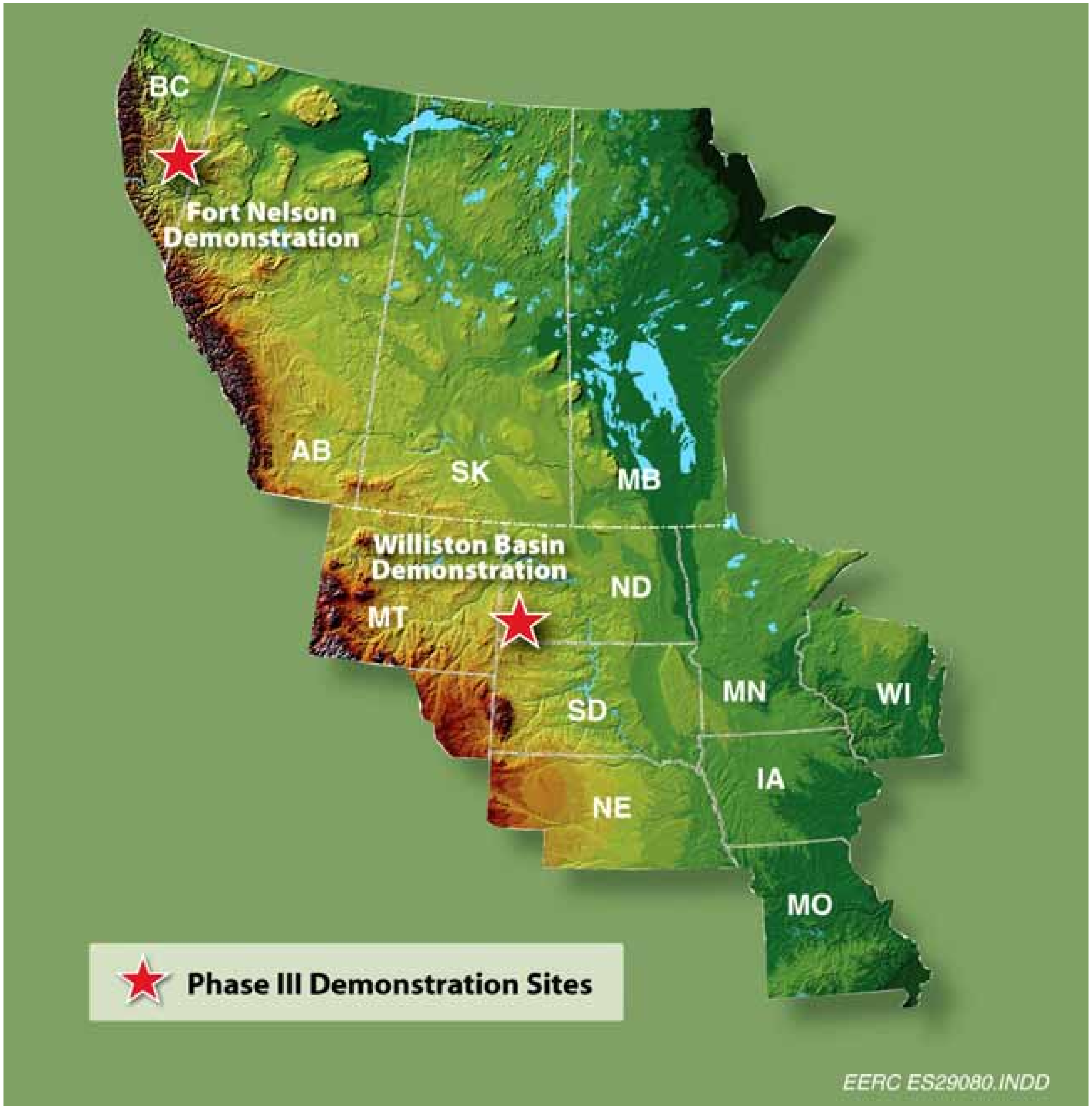
CO_2 Management Plan

CO_2 in an Unminable Lignite Seam

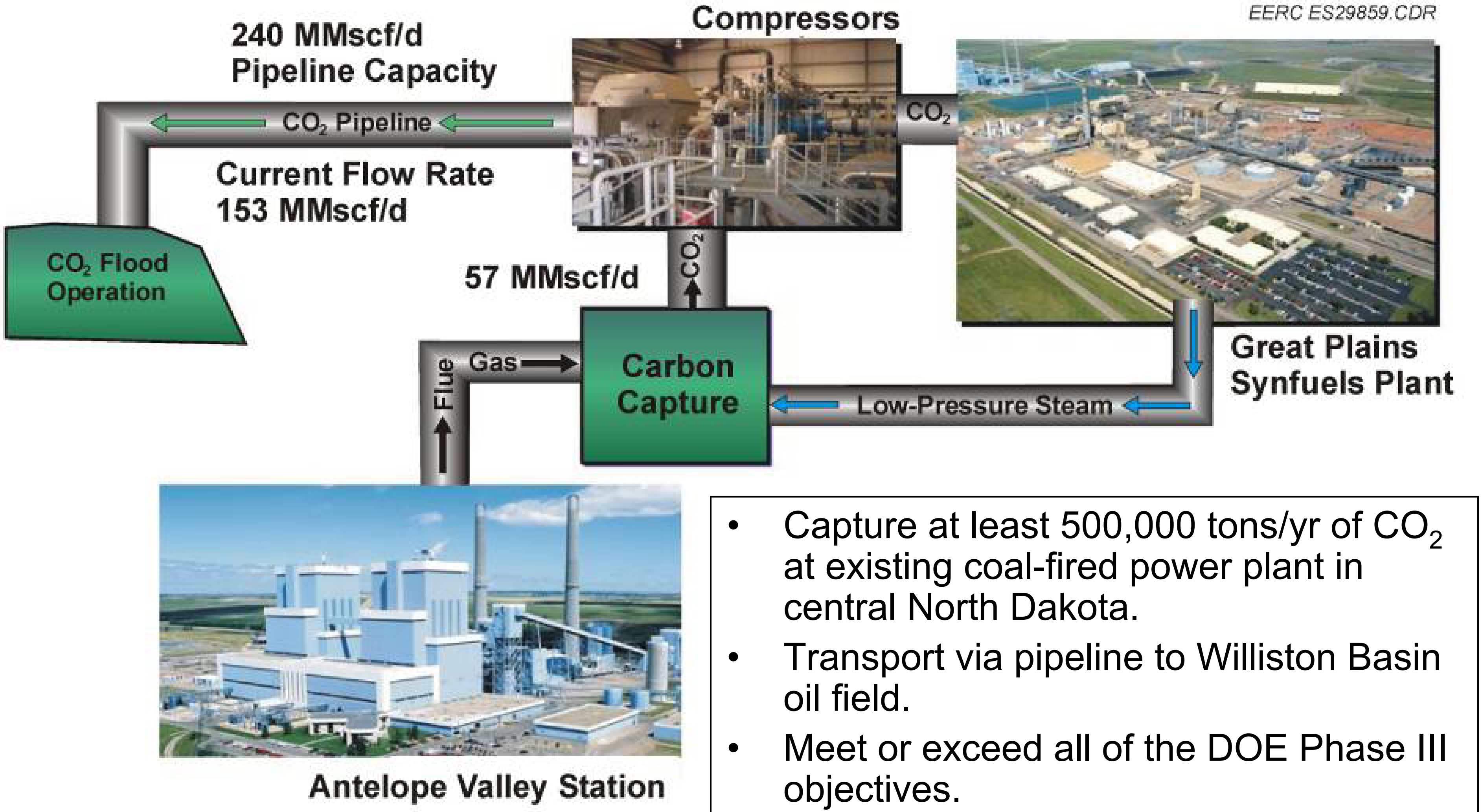
Out of the Air – Into the Soil

CO_2 in a Deep Oil Reservoir

Phase III: Demonstration Tests



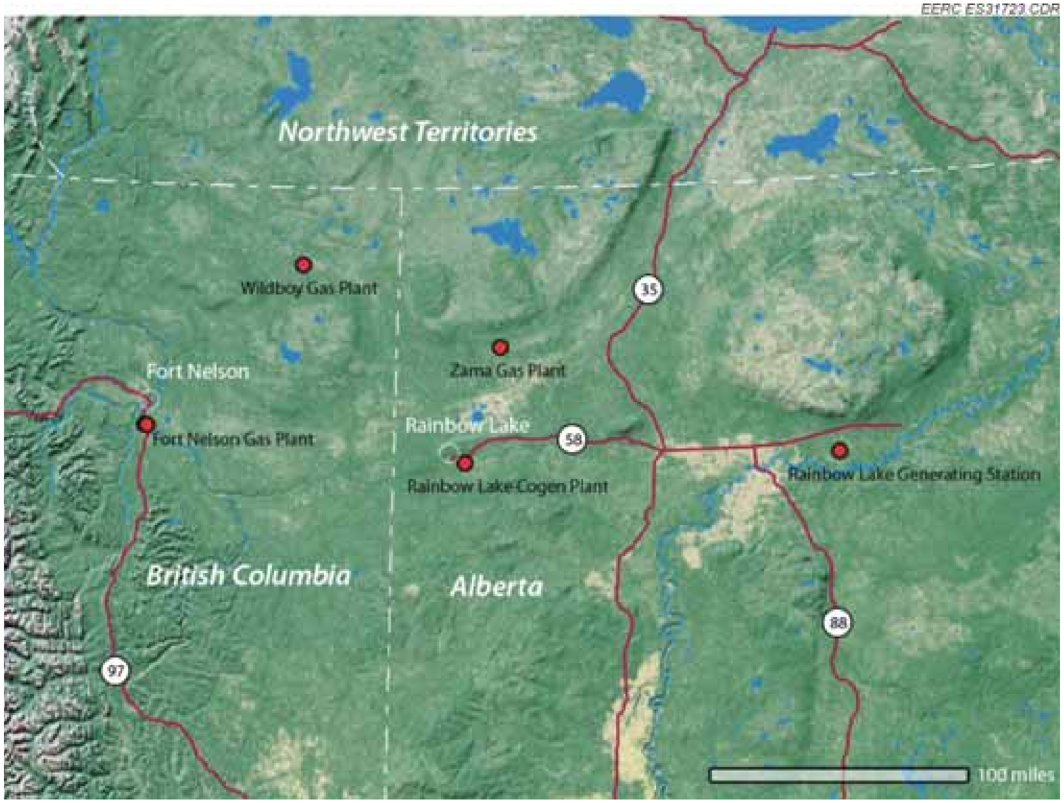
Phase III Williston Basin Project Overview



- Capture at least 500,000 tons/yr of CO_2 at existing coal-fired power plant in central North Dakota.
- Transport via pipeline to Williston Basin oil field.
- Meet or exceed all of the DOE Phase III objectives.
- Conduct activities to document the efficacy of carbon capture and storage.
- Ultimately monetize credits.

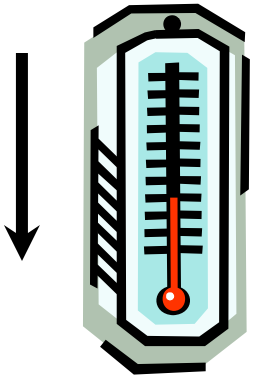
Phase III Canadian Project Overview

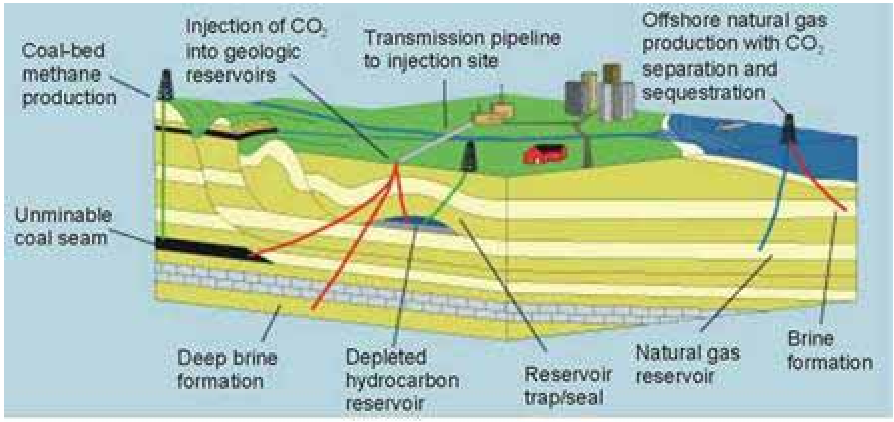
- The PCOR Partnership Phase III Canadian (Fort Nelson) Demonstration Test will develop detailed and previously unavailable insight regarding a wide variety of issues associated with the geological sequestration of CO_2. The primary research and development targets are:
  - Cost-effective MMV approaches for large-scale CO_2 sequestration in brine formations will be suggested for deployment and evaluation.
  - Modeling simulation approaches to predict and estimate CO_2 injectivity, plume areal extent, mobility, and fate within the target formation will be recommended for field testing.
  - Approaches to predict the effects of CO_2 on the integrity of overlying sealing formations will be suggested for verification and validation with field- and laboratory-based data.

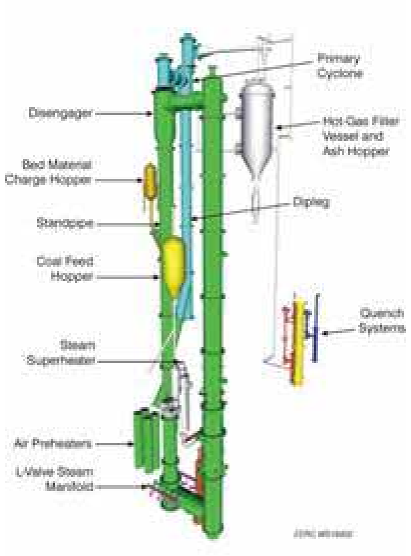


Options to Reduce and Manage Anthropogenic Greenhouse Gas (GHG) Emissions, Including CO_2

- Renewable energy technologies
- Advanced high-efficiency energy systems
- Improve efficiency on existing systems
- Reduce consumption of energy
- Capture and Sequester GHG emissions







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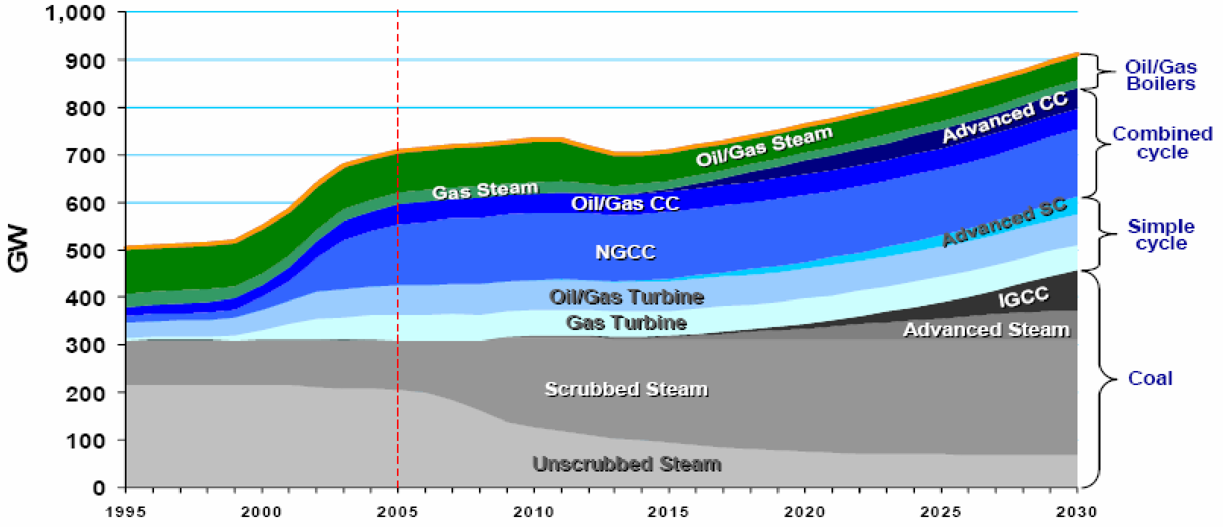
What Is the U.S. CO_2 Capture Market?

- **Total 9,877 units installed in the U.S.**
  - 337 GW of coal-fired units
  - 422 GW of gas-fired units
  - 64 GW of oil-fired units
- **423 existing coal-fired power plants**
  - Comprise of 1,089 boiler units
  - Generate 323 GW (Phase 1&2)
  - Emit 1,917.2 million metric tons of CO_2



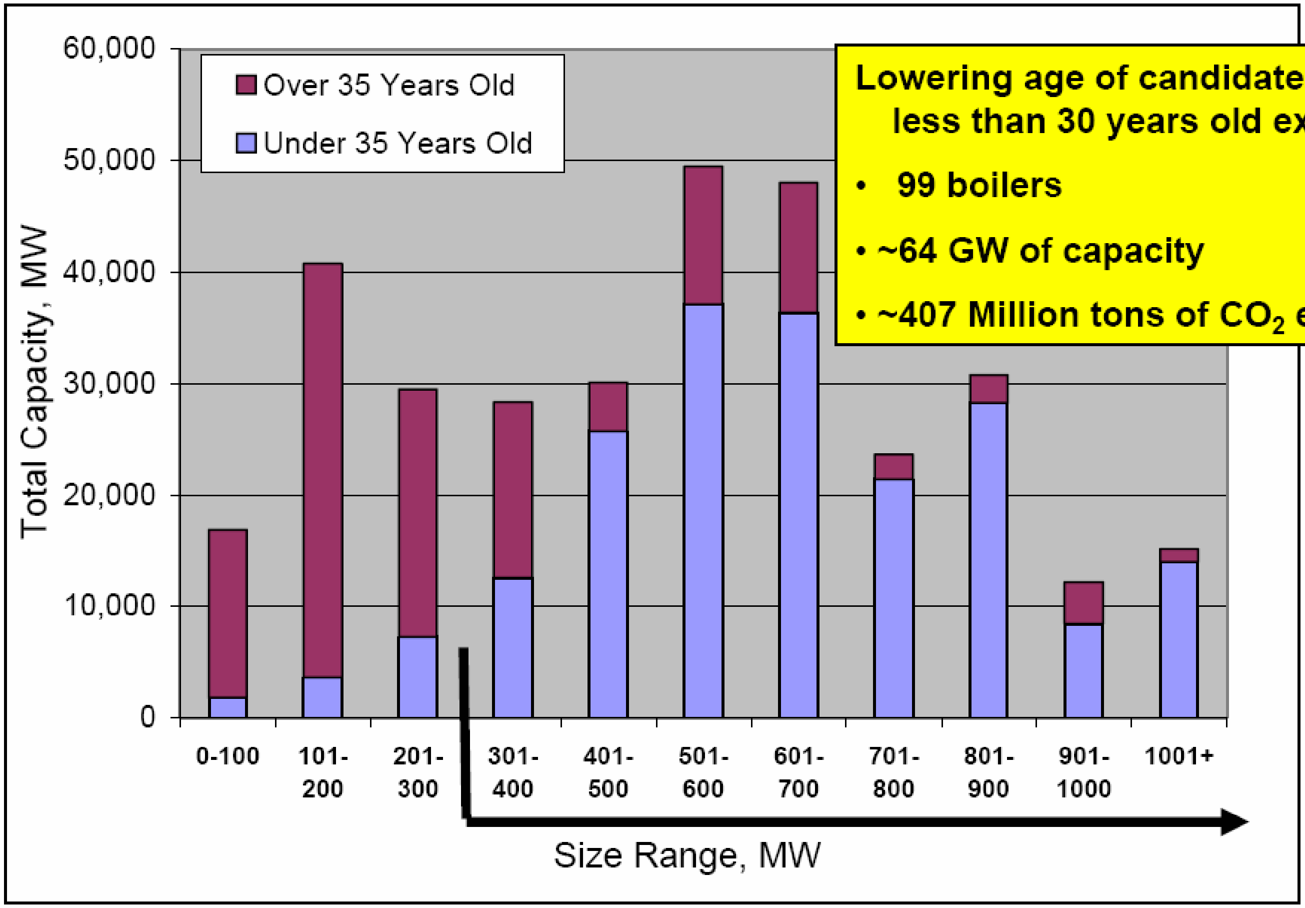
Who is the customer so that there is a focus for Capture R&D?

Fossil Power Generation Technology Types

José D. Figueroa et. al./ 5th Annual Conference on Carbon Capture and Sequestration / May 8-11, 2006

Source: EIA, UDI, EPA

U.S. Power Market Sector Most Likely to Adopt CO_2 Capture and Separation



Lowering age of candidate boilers to less than 30 years old excludes:

- **99 boilers**
- **~64 GW of capacity**
- **~407 Million tons of CO_2 emissions**

José D. Figueroa et. al./ 5th Annual Conference on Carbon Capture and Sequestration / May 8-11, 2006

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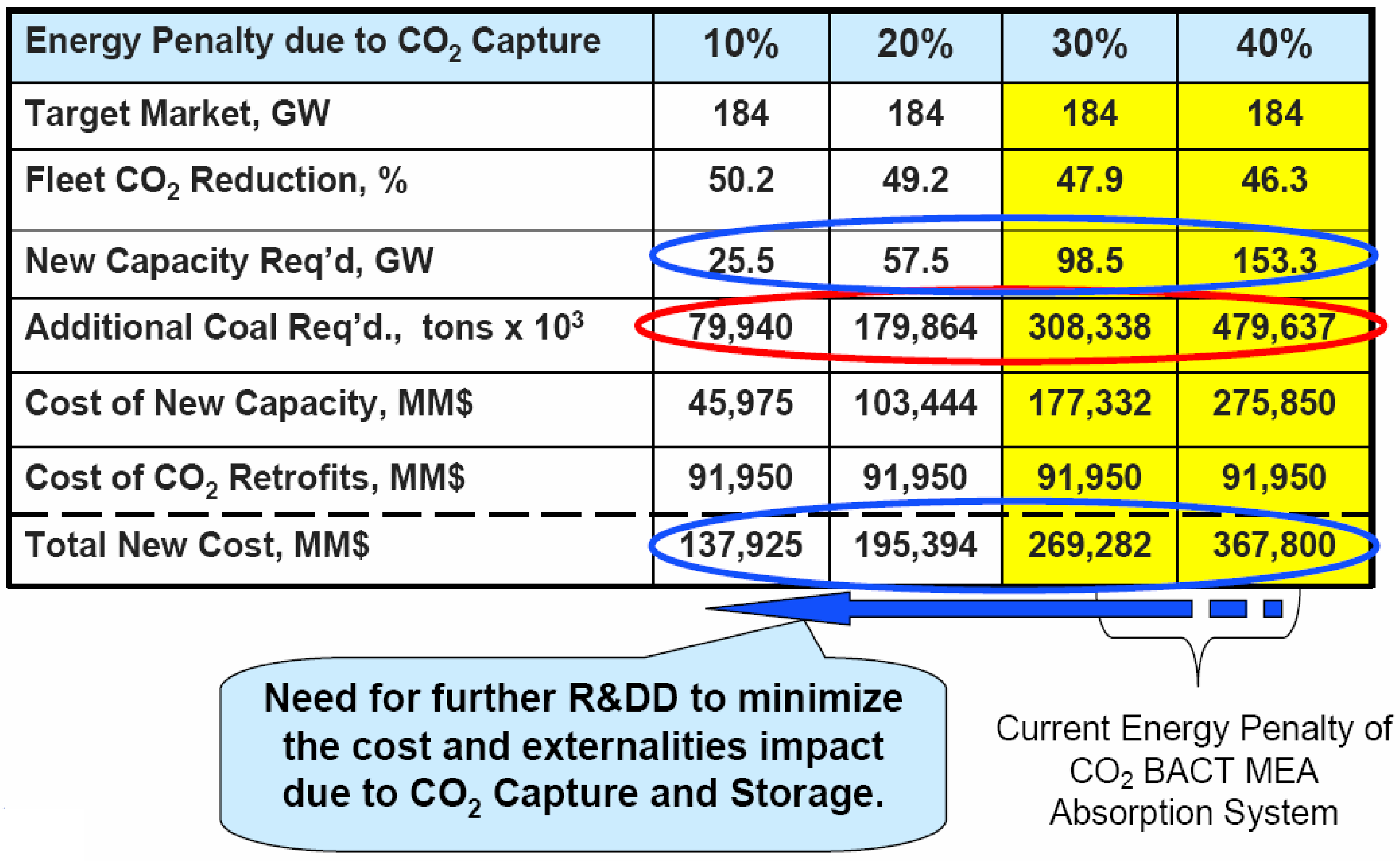
The Need to Focus on CO_2 Capture R&D in the United States



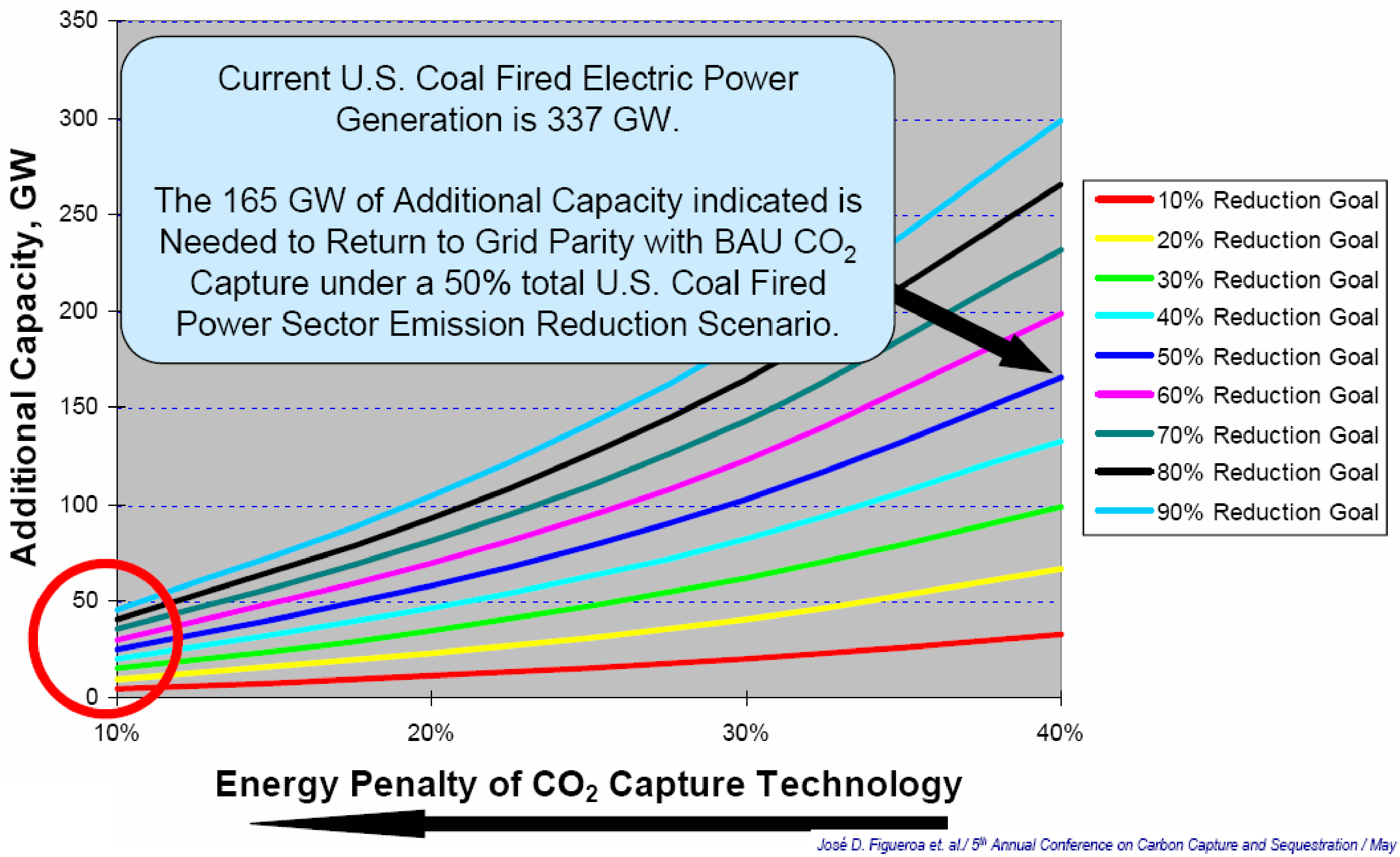
Energy Penalty due to CO_2 Capture	10%	20%	30%	40%
Target Market, GW	184	184	184	184
Fleet CO_2 Reduction, %	50.2	49.2	47.9	46.3
New Capacity Req'd, GW	25.5	57.5	98.5	153.3
Additional Coal Req'd., tons x 10^3	79,940	179,864	308,338	479,637
Cost of New Capacity, MM$	45,975	103,444	177,332	275,850
Cost of CO_2 Retrofits, MM$	91,950	91,950	91,950	91,950
Total New Cost, MM$	137,925	195,394	269,282	367,800

Need for further R&DD to minimize the cost and externalities impact due to CO_2 Capture and Storage.

Current Energy Penalty of CO_2 BACT MEA Absorption System

José D. Figueroa et. al./ 5th Annual Conference on Carbon Capture and Sequestration / May 8-11, 2006

Additional Capacity Required to Meet Increased Targets for U.S. CO_2 Emission Reduction



Current U.S. Coal Fired Electric Power Generation is 337 GW.

The 165 GW of Additional Capacity indicated is Needed to Return to Grid Parity with BAU CO_2 Capture under a 50% total U.S. Coal Fired Power Sector Emission Reduction Scenario.

José D. Figueroa et. al./ 5th Annual Conference on Carbon Capture and Sequestration / May 8-11, 2006

CO_2 Point Source Contributions

Sources	Total Tonnes
Power Generation[1]	2,239,700,000
Coal[1]	1,868,400,000
Natural Gas[1]	299,100,000
Oil[1]	72,200,000
Industries	324,789,000
Refinery[2]	184,918,000
Iron and Steel[3]	54,411,000
Cement[3]	42,898,000
Ammonia[3]	17,652,000
Aluminum[3]	4,223,000
Lime[3]	12,304,000
Ethanol[3]	8,383,000
Total	2,564,489,000

[1] Environmental Protection Agency Greenhouse Gas Inventory Sector Analysis (3).

[2] Estimate from U.S. DOE, 2002 BPD totals (5).

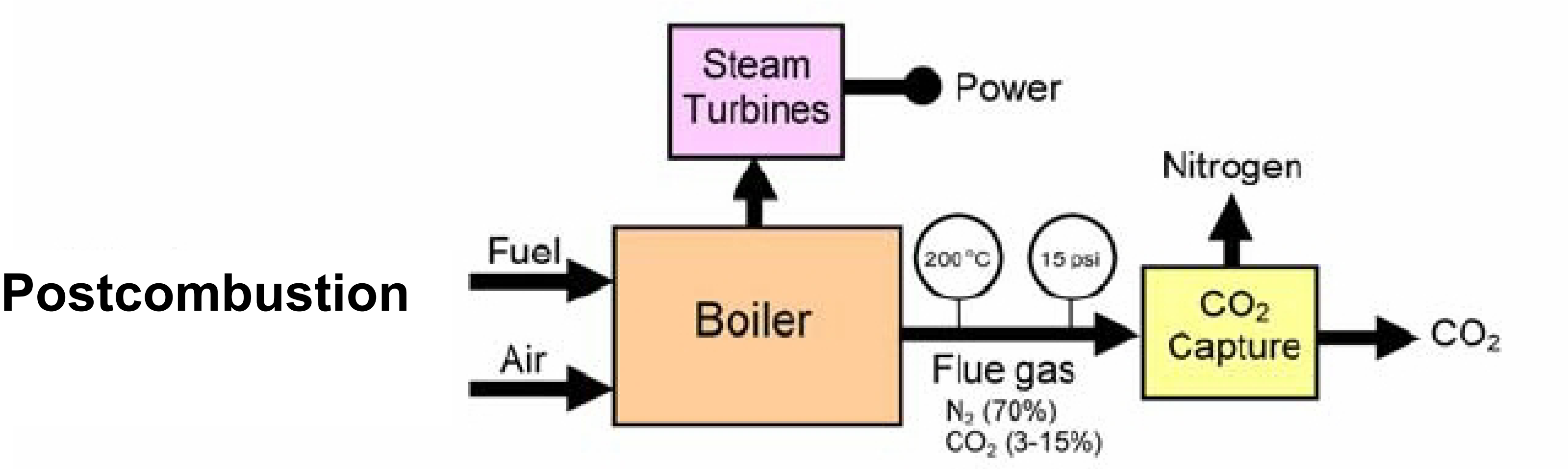
[3] EPA (2004) Greenhouse Gas Inventory Industrial Process Analysis (6).

Capture Technologies

Outline

1. Postcombustion and precombustion
    - Capture technology options
    - Challenges
2. Oxyfuel combustion
    - Oxygen separation
    - Fireside performance issues – heat transfer, ash deposition, corrosion
3. Other technologies
4. Research, development, and commercial projects

Postcombustion


Postcombustion

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

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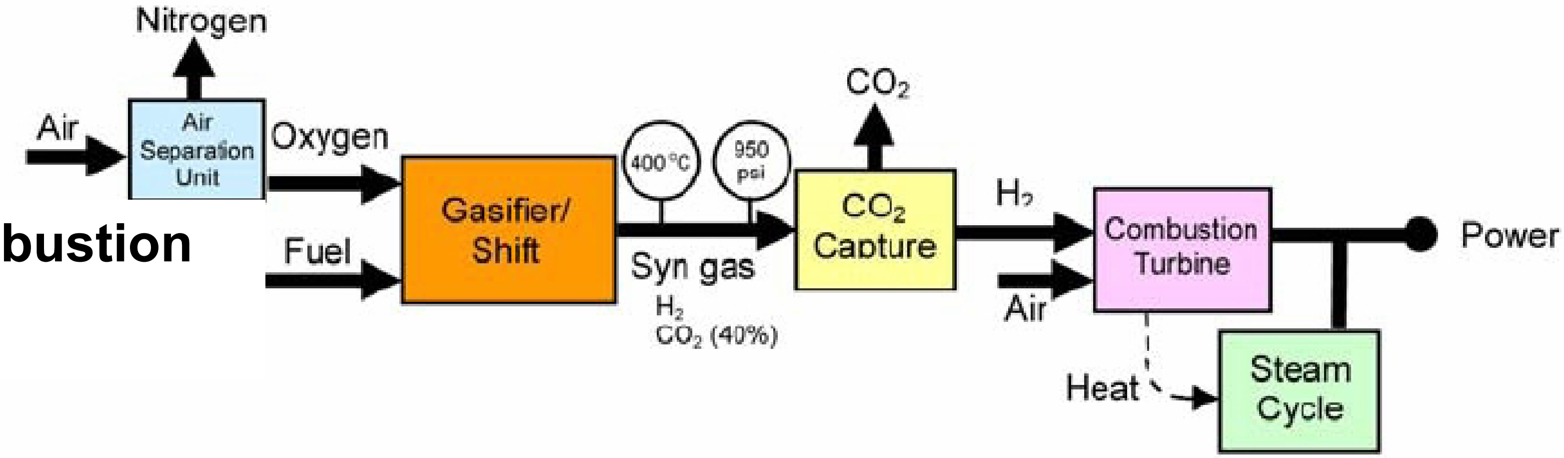
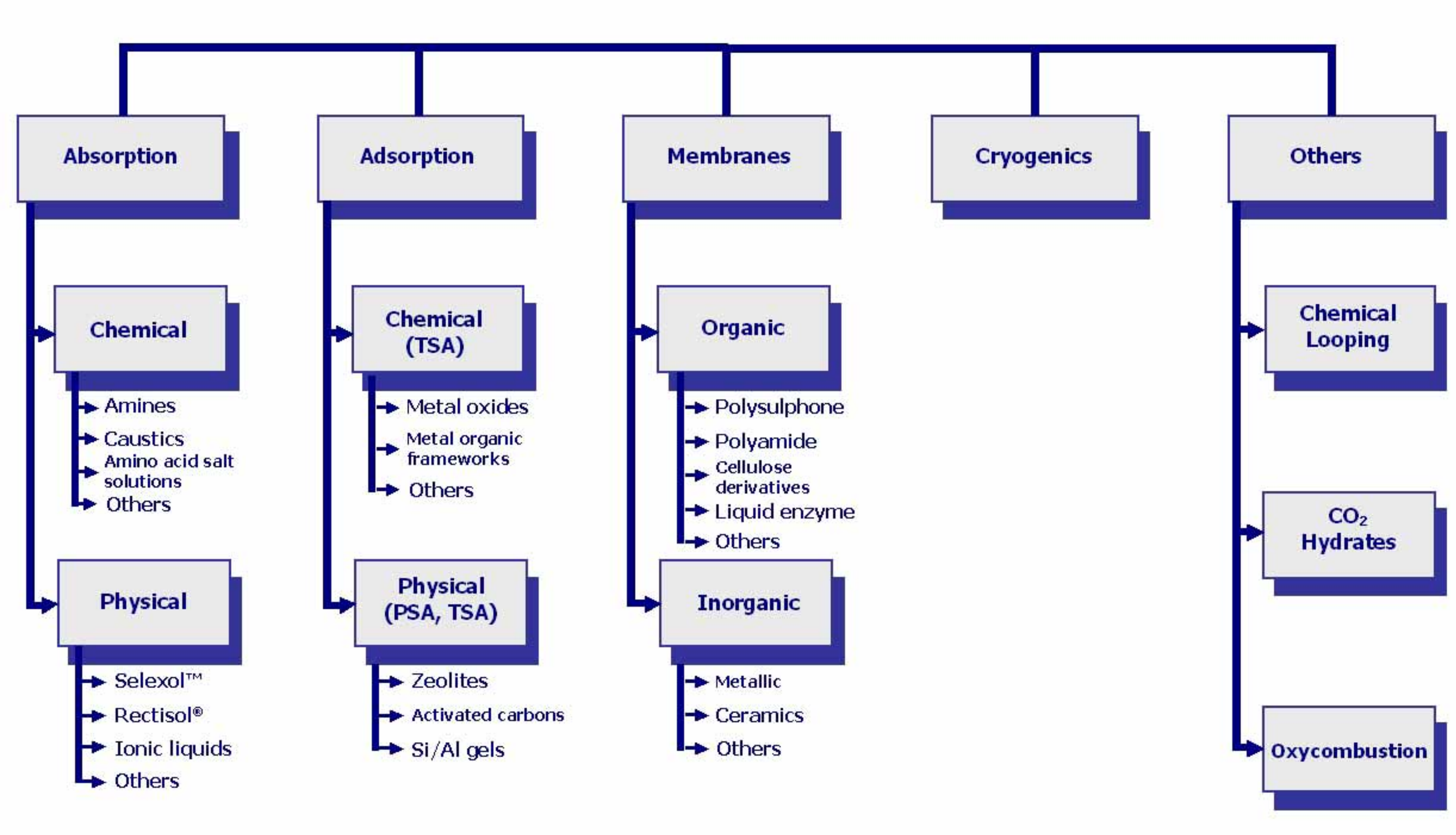
Precombustion

Precombustion



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**

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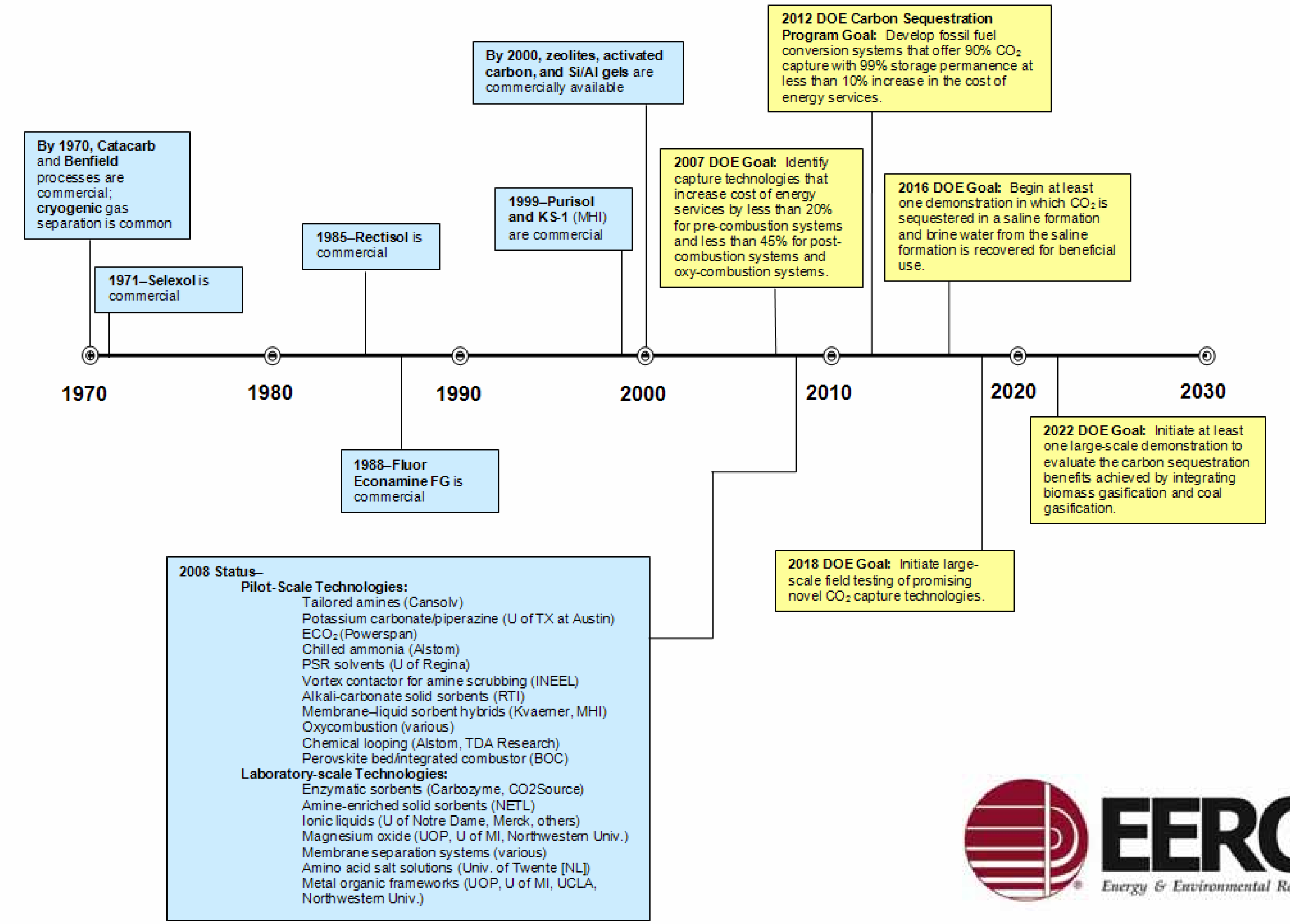
Commercially Available Technologies

- **Chemical absorbents**
  - MEA (monoethanolamine)
  - MDEA (methyldiethanolamine)
  - Designer amines
  - Hot potassium carbonate (Catacarb®, Benfield)
- **Physical absorbents**
  - Dimethyl ether of polyethylene glycol (Selexol™)
  - Methanol (Rectisol®)

CO_2 Capture Technology Time Line



By 1970, Catacarb and **Benfield** processes are commercial; **cryogenic** gas separation is common

1971–Selexol is commercial

1985–Rectisol is commercial

1988–Fluor Econamine FG is commercial

1999–Purisol and KS-1 (MHI) are commercial

By 2000, zeolites, activated carbon, and Si/Al gels are commercially available

2007 DOE Goal: Identify capture technologies that increase cost of energy services by less than 20% for pre-combustion systems and less than 45% for post-combustion systems and oxy-combustion systems.

2008 Status–

- **Pilot-Scale Technologies:**
  - Tailored amines (Cansolv)
  - Potassium carbonate/piperazine (U of TX at Austin)
  - ECO_2 (Powerspan)
  - Chilled ammonia (Alstom)
  - PSR solvents (U of Regina)
  - Vortex contactor for amine scrubbing (INEEL)
  - Alkali-carbonate solid sorbents (RTI)
  - Membrane–liquid sorbent hybrids (Kvaerner, MHI)
  - Oxycombustion (various)
  - Chemical looping (Alstom, TDA Research)
  - Perovskite bed/integrated combustor (BOC)
- **Laboratory-scale Technologies:**
  - Enzymatic sorbents (Carbozyme, CO2Source)
  - Amine-enriched solid sorbents (NETL)
  - Ionic liquids (U of Notre Dame, Merck, others)
  - Magnesium oxide (UOP, U of MI, Northwestern Univ.)
  - Membrane separation systems (various)
  - Amino acid salt solutions (Univ. of Twente [NL])
  - Metal organic frameworks (UOP, U of MI, UCLA, Northwestern Univ.)

2012 DOE Carbon Sequestration Program Goal: Develop fossil fuel conversion systems that offer 90% CO_2 capture with 99% storage permanence at less than 10% increase in the cost of energy services.

2016 DOE Goal: Begin at least one demonstration in which CO_2 is sequestered in a saline formation and brine water from the saline formation is recovered for beneficial use.

2018 DOE Goal: Initiate large-scale field testing of promising novel CO_2 capture technologies.

2022 DOE Goal: Initiate at least one large-scale demonstration to evaluate the carbon sequestration benefits achieved by integrating biomass gasification and coal gasification.

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Absorption

Chemical

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Absorption – Amines

State-of-the-Art Postcombustion Capture

- Fluor Daniel Econamine FG^{SM}
  - 30% MEA solution incorporating additives to control corrosion and (oxidative and thermal) degradation
  - >20 commercial plants ranging in size from 5 to 400 tons CO_2/day
- ABB-Lummus
  - 15%–20% MEA solution
  - Four commercial plants ranging in size from 150 to 850 tons CO_2/day
- Mitsubishi Heavy Industries
  - KS-1 – sterically hindered amines
  - Two commercial plants: ~210 and 330 ton CO_2/day
- Cansolv
  - Mixture of amines
  - Commercial plant case study at NSC (Japan)
- Praxair
  - Mixture of amines – no commercial plant

Absorption Processes

- Commonly used in commercial systems to remove CO_2 from mixed-gas streams over a wide range of pressures and CO_2 concentrations.
- Two types of solvents used for CO_2 removal:
  - Physical solvents dissolve CO_2 following Henry's law but do not react with it. Physical solvents are more suitable for mixed-gas streams that are under high pressure. The elevated pressure increases CO_2 solubility. Physical solvent recovered by flashing off CO_2 at lower pressures.
  - Chemically reactive solvents first dissolve CO_2 and then react with it. Pressure does not affect the performance of chemically reactive solvents. Chemically reactive solvents require heat to separate CO_2 from solvent.
  - Hybrid solvents combine the best characteristics of both chemical and physical solvents and are usually composed of a number of complementary solvents – under development.

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Chemical Absorption

- Amine scrubbing
  - Alkanolamines are a group of amines used for CO_2 removal that includes MEA, diethanolamine (DEA), diglycolamine (DGA), disopropanolamine (DIPA), and triethanolamine (TEA).
  - MEA is considered state-of-the-art.
    - Advantages – high capacity for CO_2 and high rate of absorption.
    - Limitations include high heat of absorption and corrosion issues.
    - Improving MEA solvent performance is conducted by blending amines or promoting with potassium carbonate.

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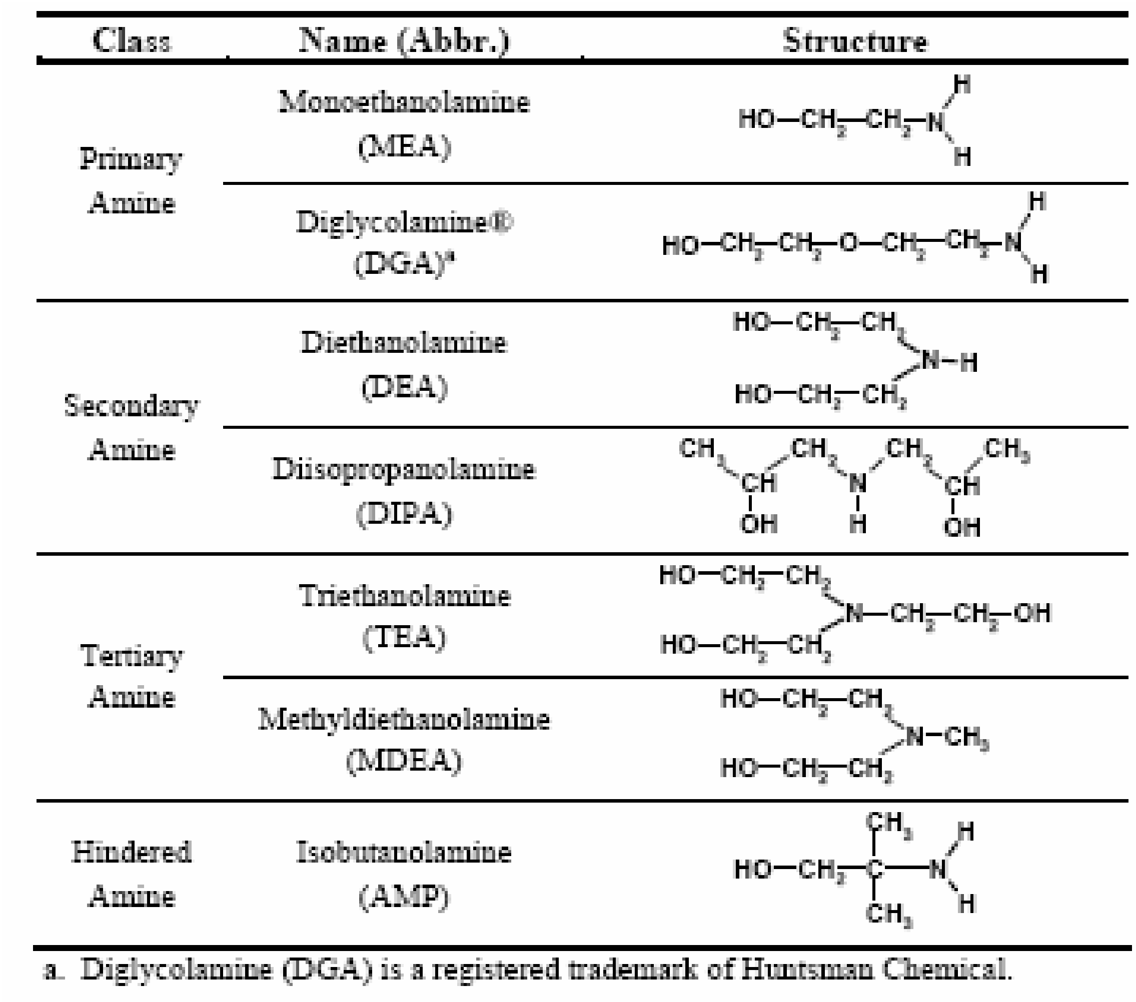
Common Amines Used in Gas Treating



Class	Name (Abbr.)	Structure
Primary Amine	Monoethanolamine (MEA)	$HO-CH_2-CH_2-\underset{H}{\overset{H}{N}}$
	Diglycolamine® (DGA)[a]	$HO-CH_2-CH_2-O-CH_2-CH_2-\underset{H}{\overset{H}{N}}$
Secondary Amine	Diethanolamine (DEA)	$\begin{matrix}HO-CH_2-CH_2\\HO-CH_2-CH_2\end{matrix}>N-H$
	Diisopropanolamine (DIPA)	$CH_3-\underset{OH}{CH}-CH_2-\underset{H}{N}-CH_2-\underset{OH}{CH}-CH_3$
Tertiary Amine	Triethanolamine (TEA)	$\begin{matrix}HO-CH_2-CH_2\\HO-CH_2-CH_2\end{matrix}>N-CH_2-CH_2-OH$
	Methyldiethanolamine (MDEA)	$\begin{matrix}HO-CH_2-CH_2\\HO-CH_2-CH_2\end{matrix}>N-CH_3$
Hindered Amine	Isobutanolamine (AMP)	$HO-CH_2-\underset{CH_3}{\overset{CH_3}{C}}-\underset{H}{\overset{H}{N}}$

a. Diglycolamine (DGA) is a registered trademark of Huntsman Chemical.

Commercial Facilities Use MEA-Based Solvents

- Food industry and oil industry (enhanced oil recovery [EOR])
  - Capture CO_2 from coal-, fuel oil-, and natural gas-derived flue gas streams.
  - Capacities in the range of 100 to 1100 tons/day, (500-MW power plant produces 5500 tons/day).
  - Commercial providers of MEA technology include Fluor Daniel and ABB Lummus Global.

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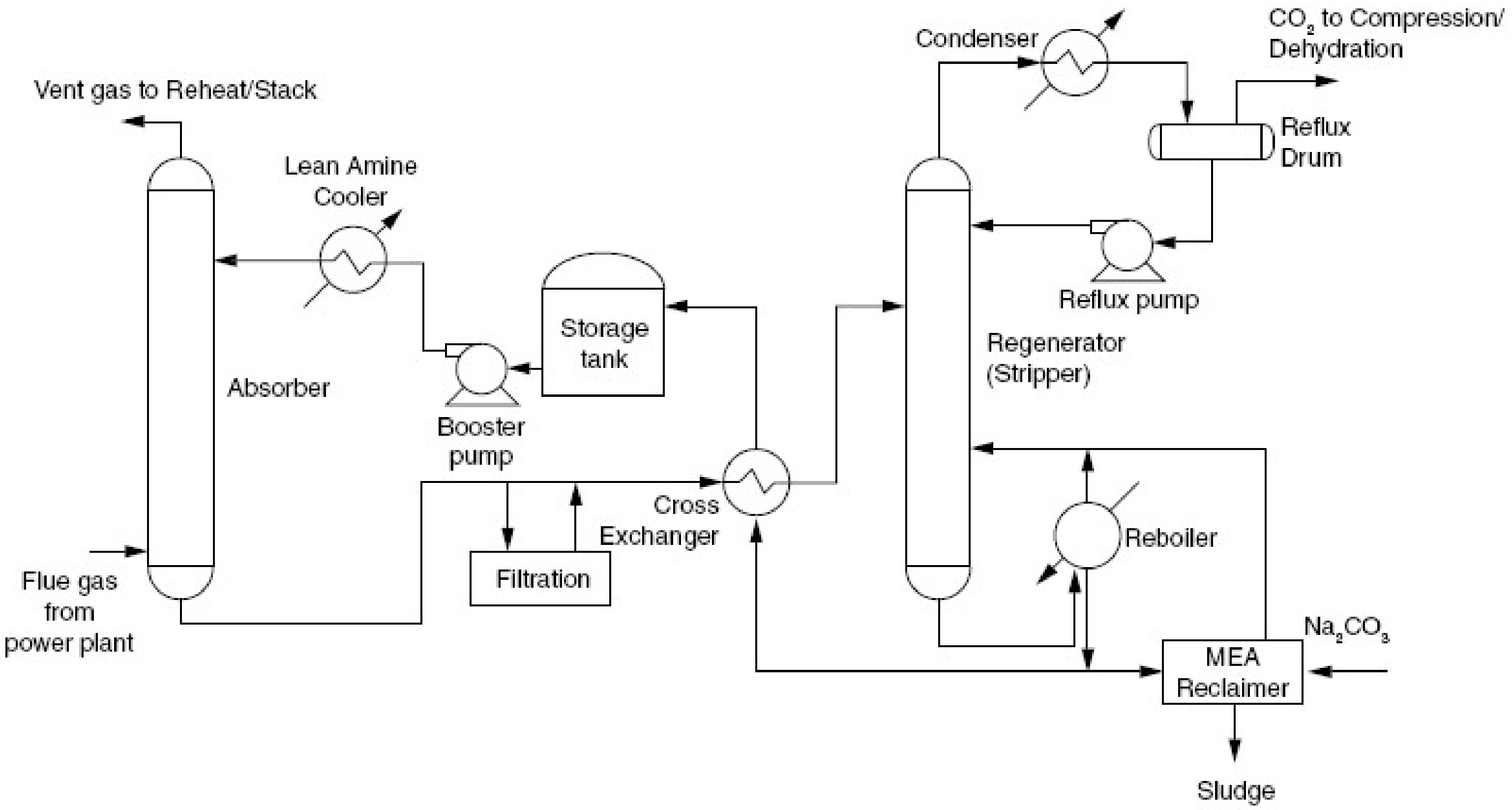
Schematic of an MEA Absorption System for Capturing CO_2 from Flue Gas



How the MEA System Works

- Flue gas is cooled to about 110°F.
- The flue gas is partially compressed to 17.5 psia by a centrifugal blower to overcome the gas path pressure drop.
- Flue gas enters the absorber base and flows upward countercurrent to the lean MEA solution.
- CO_2 is removed from the flue gas in the packed-bed absorber column through direct contact with MEA.
- The CO_2-depleted flue gas is exhausted to the atmosphere.
- The CO_2-rich solution is heated to liberate the CO_2.
- The CO_2 vapor is condensed, cooled, and sent to a multistaged compressor where the CO_2 is compressed to a pressure of over 1200 psia.
- The CO_2-laden stream is dehydrated using glycol or molecular sieve processes.

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Other Chemical Absorption Methods

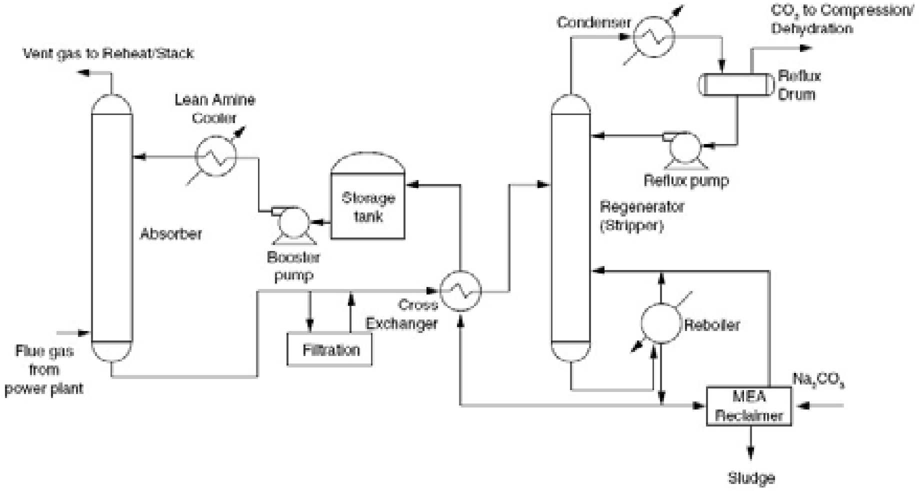
- KS-family of sterically hindered amines (Mitsubishi Heavy Industries [MHI]).
- Potassium carbonate/piperazine complex (University of Texas at Austin).
- Ammonia Processes (Powerspan, NETL, Alstom [Chilled Ammonia]).
- PSR solvents (University of Regina, Saskatchewan), which are proprietary designer solvents formulated for optimized separation of CO_2 from any gas stream.
- Advanced amine scrubbing (Cansolv Technologies, Inc.), in which a proprietary amine is utilized.
- Amine-enriched sorbents (NETL)
- Amino acid salt solutions (Norwegian University of Science and Technology)

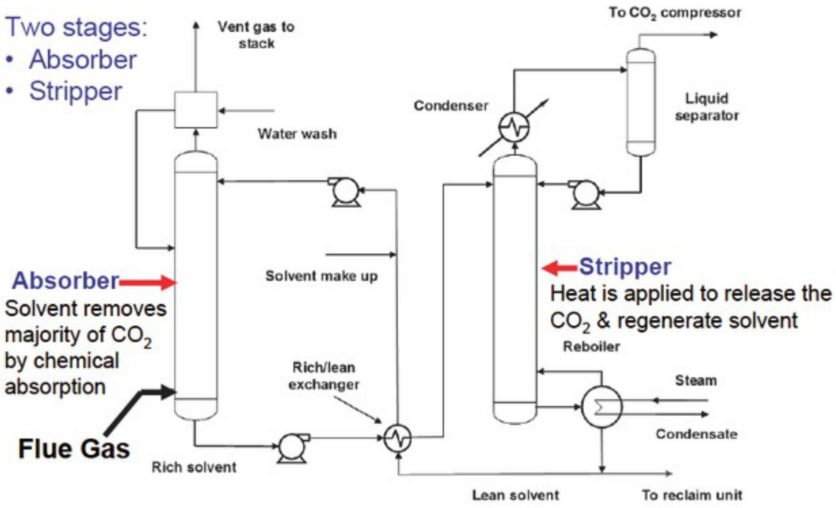
Mitsubishi Heavy Industries

- KS-family of sterically hindered amines
- Advantages claimed
  - Enhance reactivity toward CO_2.
  - 1 mol of hindered amine is required to react with 1 mol CO_2 (compared with 2 mol MEA).
  - 90% less solvent degradation, 20% lower regeneration energy, 15% less power, 40% lower solvent recirculation rates due to higher net absorption capacity, lower regeneration temperature, less corrosion in the presence of dissolved oxygen, and lower chemical additive cost.

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

Powerspan ECO$_2$ Technology

- Selected by Basin Electric for 125-MW demonstration.
- Uses ammonia scrubbing – joint research with DOE NETL.
- Higher CO_2 loading (kg CO_2 absorbed per kg sorbent) compared to MEA.
- Requires less energy to release CO_2 and regenerate sorbent.
- Minimal sorbent degradation by other flue gas constituents.
- Lower-cost reagent.
- Lower corrosion issues.
- No degradation, requiring less makeup.

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Ammonia Process Chemistry (absorption)

- $2\ NH_3 + CO_2 \longrightarrow NH_2COONH_4$
- $NH_2COONH_4 + CO_2 + 2\ H_2O \longrightarrow 2\ NH_4HCO_3$
- $NH_2COONH_4 + H_2O \longrightarrow NH_4HCO_3 + NH_3$
- $NH_3 + H_2O + CO_2 \longrightarrow NH_4HCO_3$
- $2\ NH_3 + H_2O + CO_2 \longrightarrow (NH_4)_2CO_3$
- $(NH_4)_2CO_3 + CO_2 + H_2O \longrightarrow 2\ NH_4HCO_3$

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Ammonia Process Chemistry (regeneration)

- $2\ NH_4HCO_3(aq) \longrightarrow (NH_4)_2CO_3(aq) + CO_2(g) + H_2O$
- $NH_4HCO_3(aq) \longrightarrow NH_3(aq) + CO_2(g) + H_2O$
- $(NH_4)_2CO_3(aq) \longrightarrow 2\ NH_3(aq) + CO_2(g) + H_2O$

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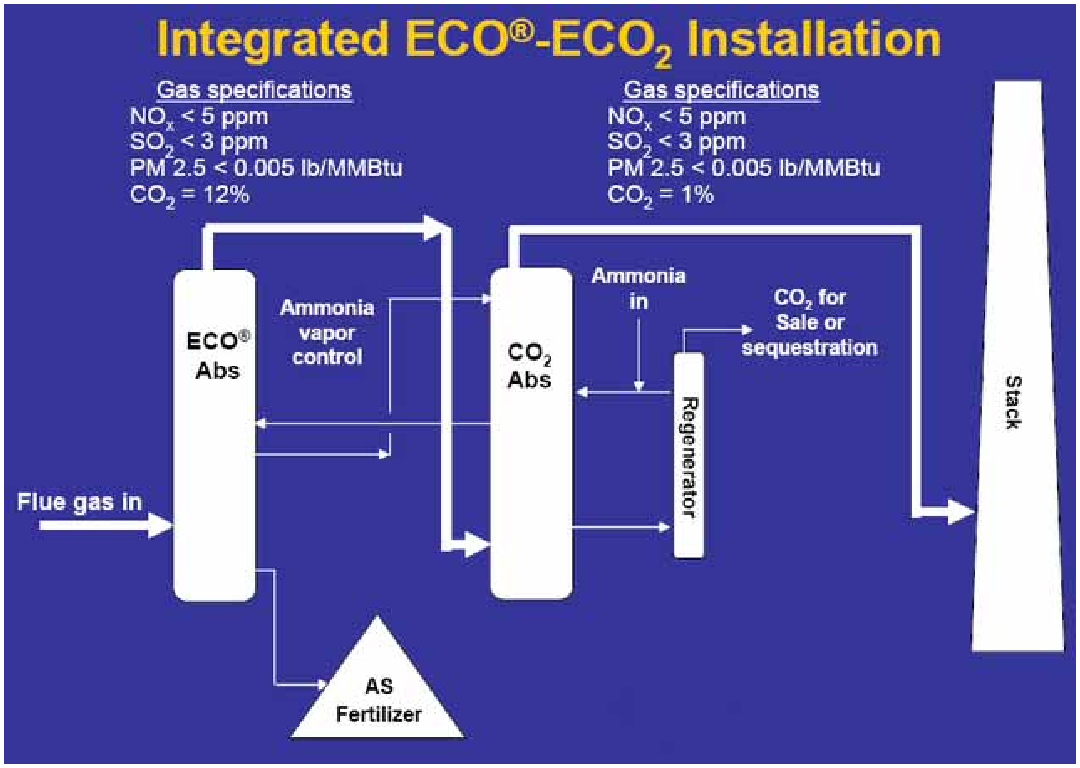
Powerspan ECO and ECO$_2$



The ECO$_2$ process is integrated after the ECO process, which provides NO$_x$, SO$_x$, and particulate control.

Powerspan Bench and Pilot Testing

- Bench testing – Powerspan and DOE
  - 90% CO_2 removal with ammonium carbonate solutions.
  - Parametric testing under way – absorption rates, ammonia vapor management, absorptive capacity.
- Pilot testing
  - Planned for FirstEnergy's R.E. Burger Plant.
  - 1-MW slipstream (20 ton/day).
  - Testing scheduled to begin in 2008.

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 NO_x, Hg, and CO_2 absorption.
- Commercialization focus in 2005–2007: heat integrating/optimizing processes:
  - CO_2–SO_2
  - SO_2–NO_{xx}–mercury

CO_2 Capture

- Cansolv absorbents are designed to exhibit:
  - Fast kinetics – similar to 1° amines.
  - Very low degradation – similar to 3° amines.
  - High resistance against oxidation and free radical attack.
  - Lowest possible regeneration energy – similar to formulated amines.

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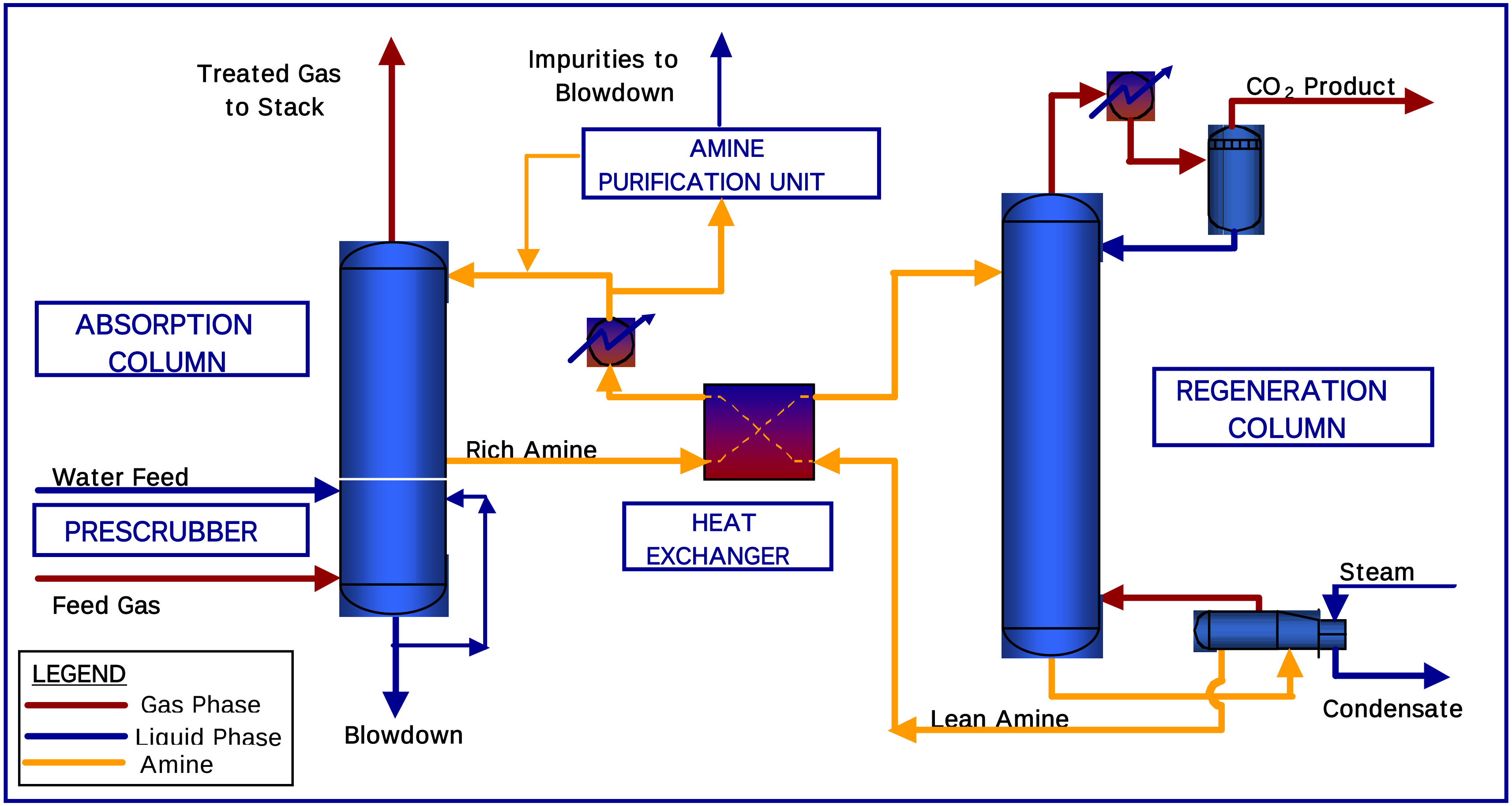
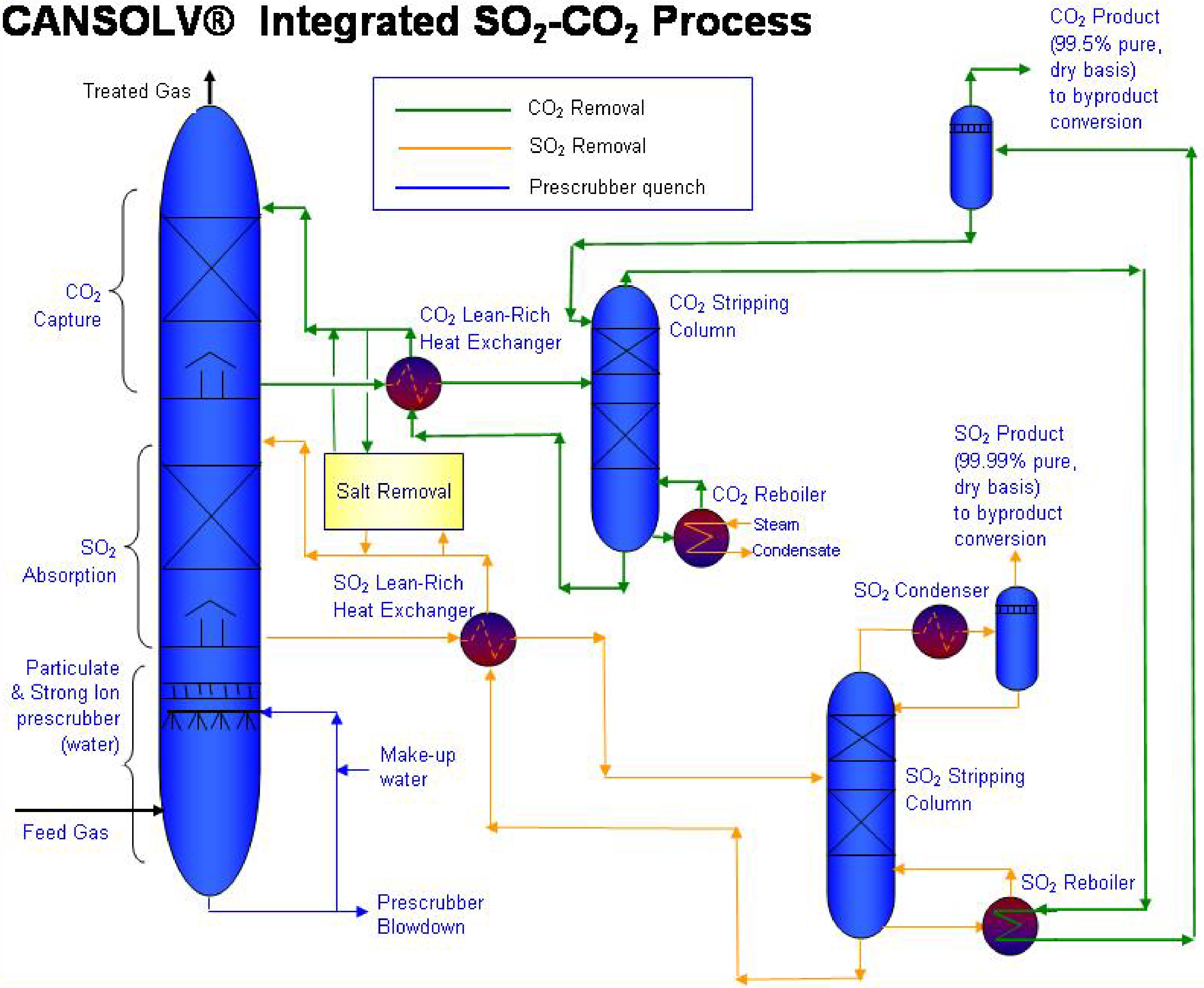
Cansolv CO_2 Capture Flow Sheet



CANSOLV® Integrated SO_2-CO_2 Process



Absorption

Physical

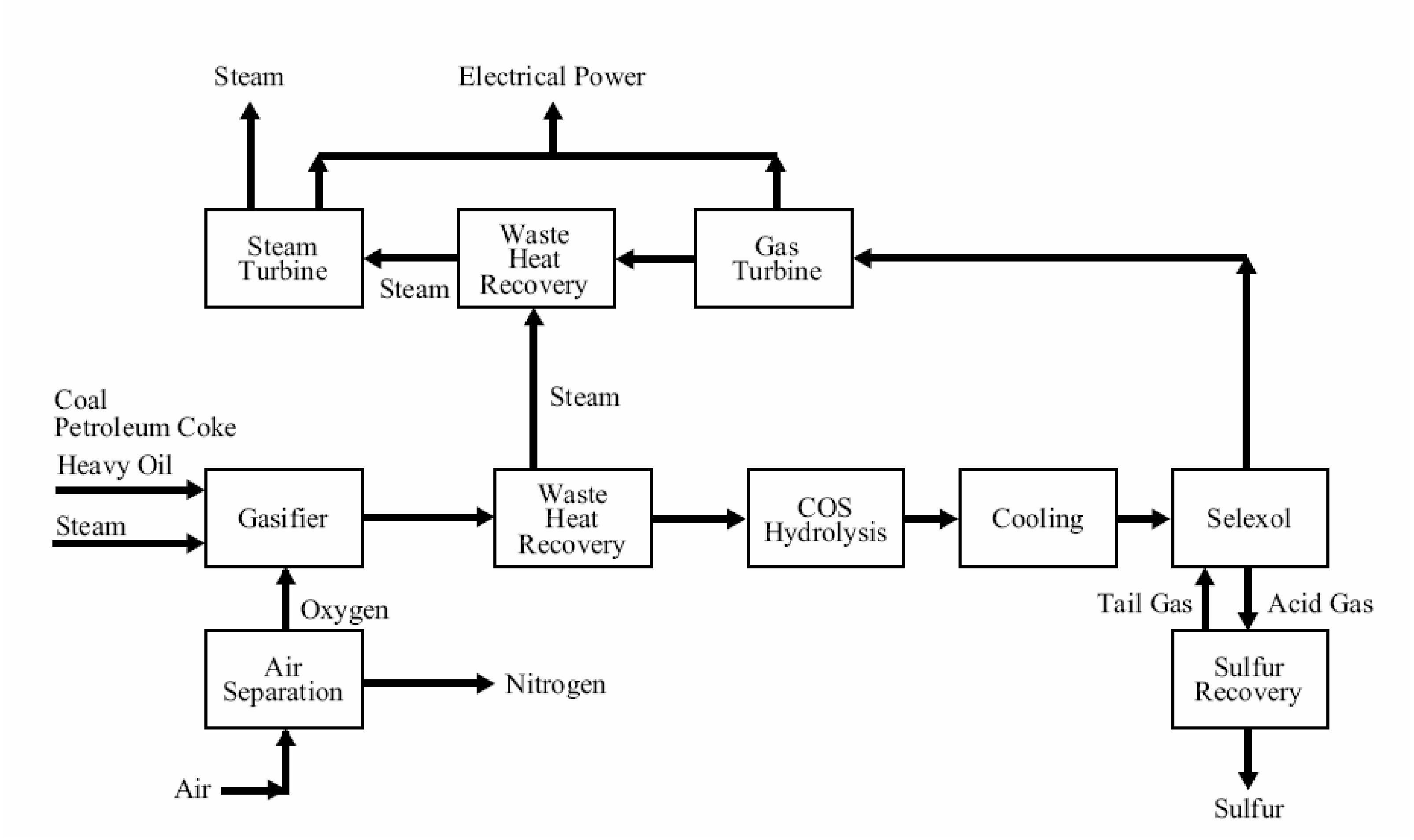
Physical Absorption

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

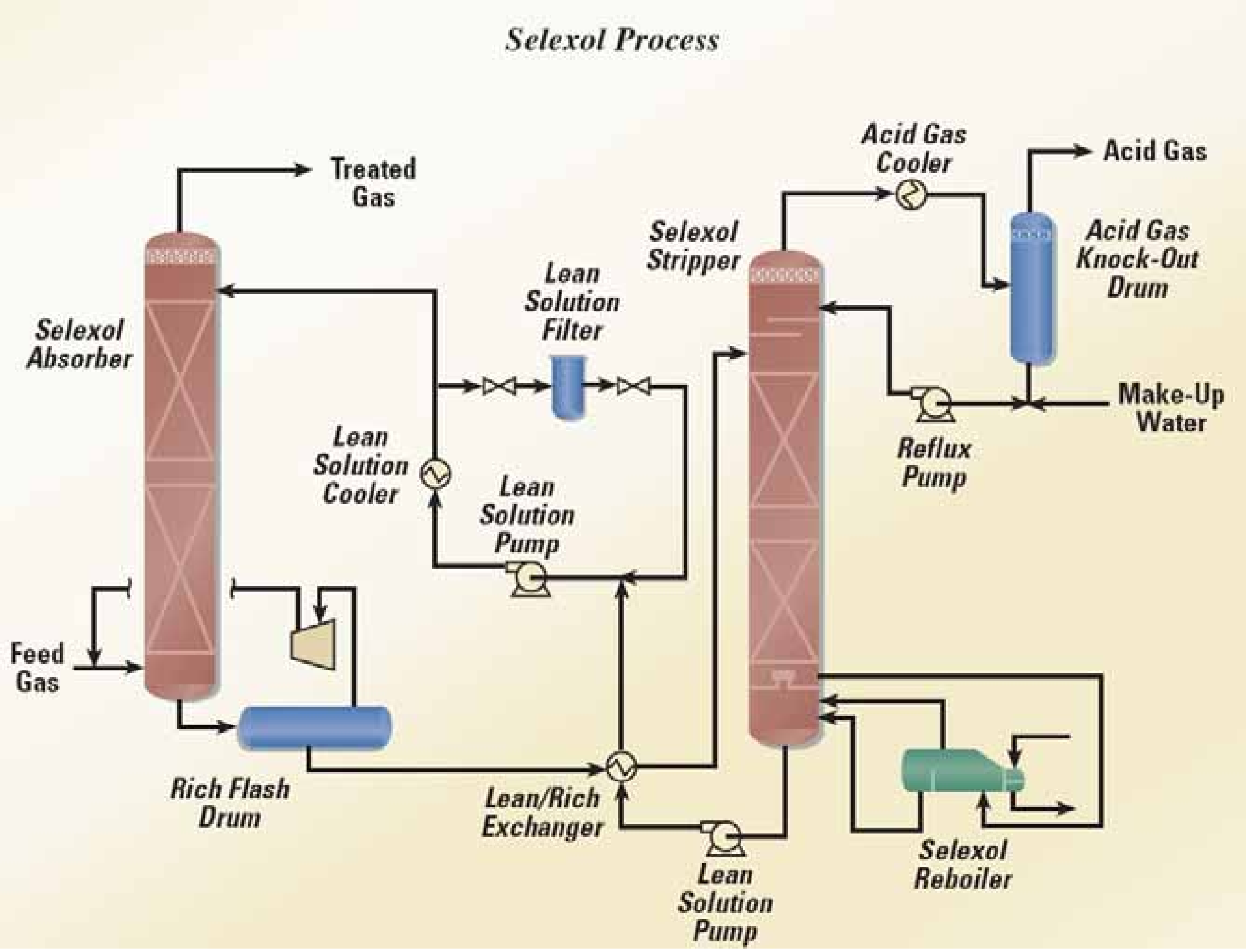
Selexol™

- Selexol™ is a liquid physical solvent developed over 30 years ago and currently owned by UOP.
- The solvent removes H_2S, CO_2, and mercaptans and is for both hydrocarbon and water dew point control.
- The Selexol™ solvent is a mixture of dimethyl ethers of polyethylene glycol, and has the formulation of CH_3 $(CH_2CH_20)nCH_3$, where n is between 3 and 9.
- Selexol™ solvents are true physical solvents and do not react chemically with the absorbed gases.
- The solvent has high selectivity for sulfur compounds over CO_2 and produces a highly enriched feed to the Claus unit. It also provides maximum CO_2 for any downstream process.

IGCC with Selexol™



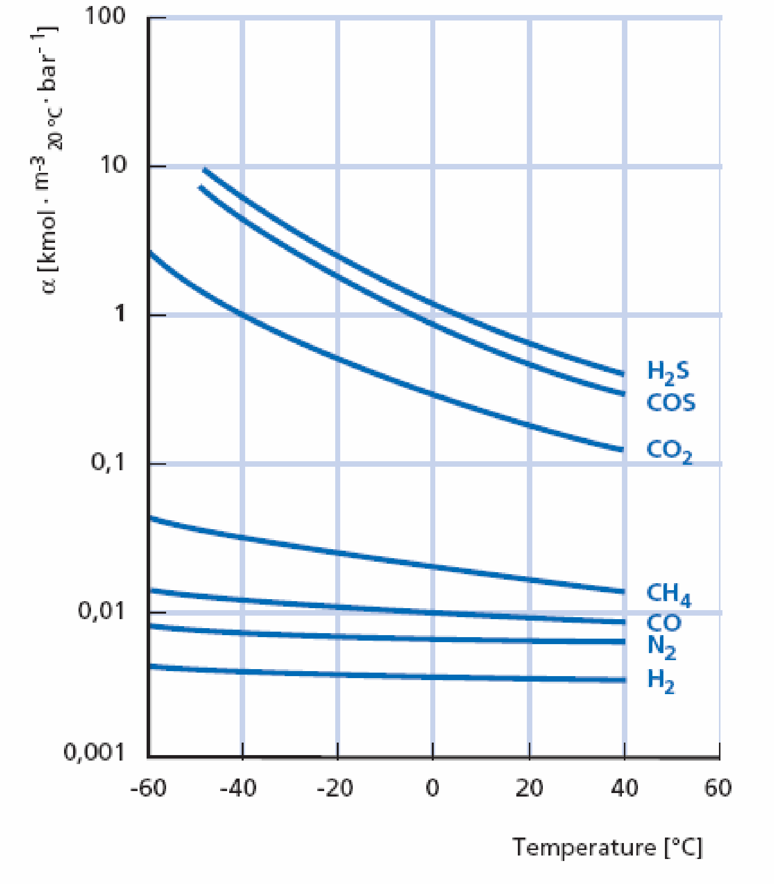
Selexol™ Process Schematic



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



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.

Other Technologies

- Alkali carbonate system (Research Triangle Institute [RTI]).
- Warm-gas sodium-based solid sorbents (NETL) have been developed for pressure swing adsorption (PSA)/thermal swing adsorption (TSA) application for removal from integrated gasification combined cycle (IGCC) syngas streams. They rely on chemical reaction for CO_2 capture. Regeneration temperatures are currently too high at 1292°F.
- Ionic liquids (University of Notre Dame, Sachem Inc., Merck) can dissolve gaseous CO_2 and are stable at temperatures up to several hundred degrees Celsius. Little heat is required for CO_2 recovery.

Adsorption

Chemical/Physical

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Adsorption

- Adsorbent beds typically comprise alumina, zeolite, or activated carbon.
- Regenerate by
  - PSA
  - Vacuum PSA (VPSA)
  - TSA
  - “Washing” of adsorbent bed by CO_2-free fluid
- Other adsorption techniques
  - Electrical swing adsorption (ESA)
  - Sorption-enhanced water–gas shift process
  - Metal organic frameworks (MOFs)

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Other Adsorption Techniques

- ESA (Oak Ridge National Laboratory) uses carbon-bonded activated carbon fiber as adsorption material. Adsorbed gas is removed by a low-energy electric current.
- Sorption-enhanced water–gas shift process (Air Products), in which a water–gas shift catalyst is combined with CO_2-selective hydrotalcite adsorbent. Multiple adiabatic fixed beds are used for cyclic reaction/adsorption and regeneration.
- Metal organic frameworks (UOP, UCLA, University of Michigan, Northwestern University) consist of large molecules with engineered macromolecular cavities that can adsorb CO_2. A high storage density is possible, and low heat is required for CO_2 recovery.

C-Quest Technologies

- C-Quest is a chemical sorbent system designed to significantly reduce CO_2 emissions from utility and industrial boilers.
- The sorbent ingredients are widely available.
- The by-product is a safe, recyclable solid which can be safely disposed of (as opposed to a gas which may be difficult to dispose of).
- Laboratory testing at the EERC reflects CO_2 capture rates as high 90%.
- Capture rates are dependent on several factors including gas-to-sorbent ratios, temperatures, and retention times.
- The sorbent captures other pollutants as well. In the lab, capture rates as high as 99% SO_2, 90% mercury, and 15% NO_x have been observed concurrently with the CO_2 capture.
- Further testing is currently being performed to determine capture efficiencies and other information which will be required to determine ultimate cost per ton of CO_2 captured; however, current results are extremely promising.

All reductions are from baseline emissions.

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.

Membranes

Organic/Inorganic

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Gas Separation Membranes

- Use partial pressure as the driving force for separation – most effective at high CO_2 concentrations and pressure.
- Differences in physical or chemical interaction between the components present in a gas mixture with the membrane material cause one component to permeate through the membrane faster than the other component.
- The gas component dissolves into the membrane material and diffuses through it to the other side.
- The membrane divides the feed gas stream into the permeate stream and the retentate stream.

New Membrane System – I

- Enzymatic liquid membranes (Carbozyme) are enzyme-based systems that achieve CO_2 capture and release by mimicking the mammalian respiratory mechanism. Its fast kinetics can lower system size and cost.
- CO_2 selective membrane (Media and Process Technology, University of Southern California), a membrane reactor that combines water–gas shift with CO_2 removal. It employs a tubular ceramic membrane, permeable only to CO_2, inside a water–gas shift reactor.
- Membrane water–gas shift reactor (Eltron Research/SOFCo/Chevron Texaco) is a catalytic membrane reactor (CMR) that utilizes oxygen transport membrane technology to facilitate in situ partial oxidation reforming. Syngas passes to a dense metal alloy membrane reactor to facilitate selective permeation of H_2 and enhanced shift. H_2 permeabilities are one order of magnitude higher than palladium and two orders of magnitude less expensive. This process requires sweet syngas, however.

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New Membrane System – II

- Hydrogen membrane reformer (Norsk Hydro, SINTEF, and UiO) is a two-reactor process that combines reforming, water–gas shift reaction, and H_2 separation. It utilizes a dense, mixed-conducting membrane (MCM). Since the transport process is based on ion diffusion, the selectivity of the membrane is infinite as long as the membrane is gas impervious (barring any defects).
- Palladium membrane reactor (NETL). This reactor system combines a palladium-based membrane with the water–gas shift reaction. The high temperature (1652°F) and pressure of operation and the catalytic effect of the membrane eliminate the need for a separate water–gas shift catalyst. A sulfur-tolerant membrane is possible.
- Hybrid alumina/organosilane membrane (NETL). In this system, organic molecules are grafted onto a substrate surface to attain higher selectivity toward CO_2 permeation.

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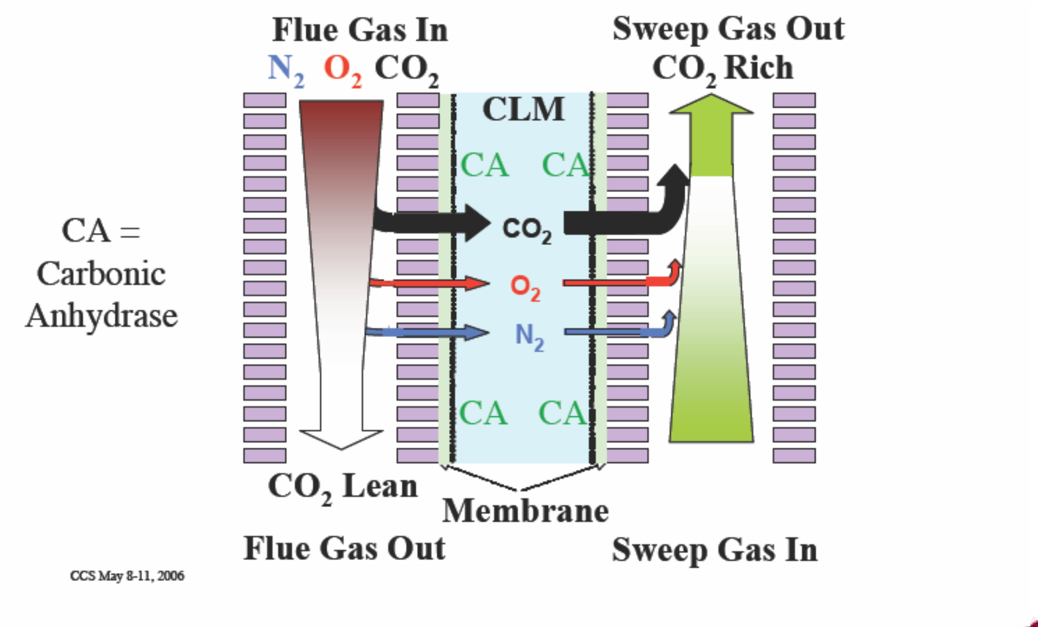
New Membrane System – III

- Thermally optimized polymer membrane (LANL, INEEL, Pall Corporation, University of Colorado, Shell Oil Company), in which polymer-based membranes exhibit high selectivity because of size-based exclusion and solubility variances of molecules within the polymer matrix. Polymer membranes have been commercially successful for a number of industrial applications. The intent of additional research is to increase the temperature of application.
- Inorganic nanoporous membrane (ORNL) with pore sizes of less than 1 nm. Composite membranes made of a ~2-µm membrane (e.g., alumina) layer on a ~450-µm porous support structure can allow operation at temperatures up to 1852°F.
- Molecular gate membrane (Research Institute of Innovative Technology for the Earth [RITE]), a cardo polyimide membrane that is selective to CO_2 permeation.
- Kvaerner hybrid membrane absorption system (Kvaerner Process Systems), a gas–liquid membrane contactor that replaces a traditional absorber. CO_2 diffuses through a microporous, hydrophobic solid membrane into liquid flow. The solvent, rather than the membrane, provides the selectivity. Compared to a conventional absorber, it weighs 70% less and has a 65% smaller footprint.

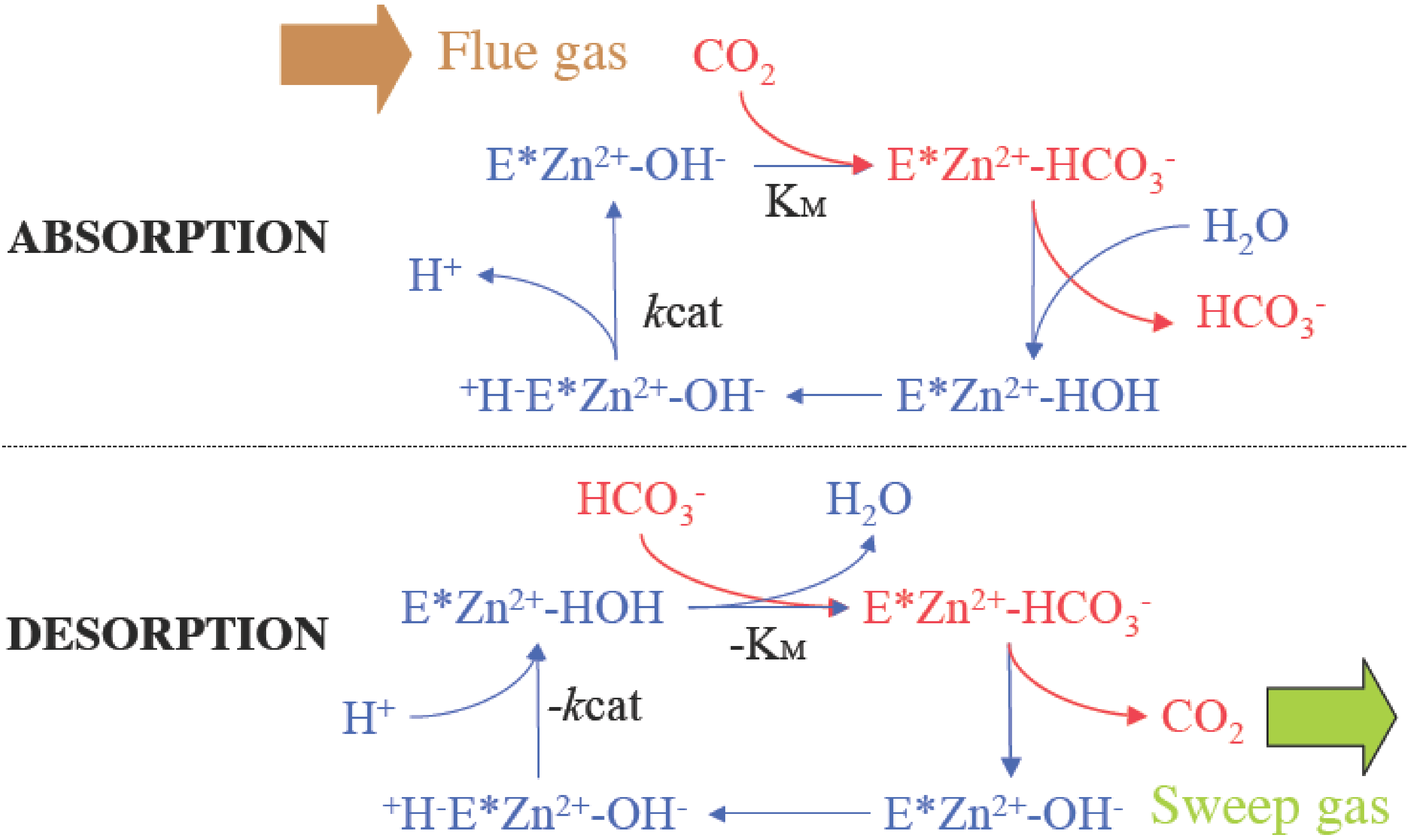
Carbozyme Technology

Carbozyme, Inc.

- Developing process to capture and separate CO_2
- Uses catalyzed liquid membrane reactor/separator
- Demonstrated at lab scale



Carbozyme Chemistry



Flue gas

CO_2

ABSORPTION

E^*Zn^{2+}-OH^- $\xrightarrow[K_M]{}$ E^*Zn^{2+}-HCO_3^-

H_2O

HCO_3^-

H^+

*k*cat

^+H-E^*Zn^{2+}-OH^- ← E^*Zn^{2+}-HOH

DESORPTION

HCO_3^-

H_2O

E^*Zn^{2+}-HOH $\xrightarrow[-K_M]{}$ E^*Zn^{2+}-HCO_3^-

H^+

-*k*cat

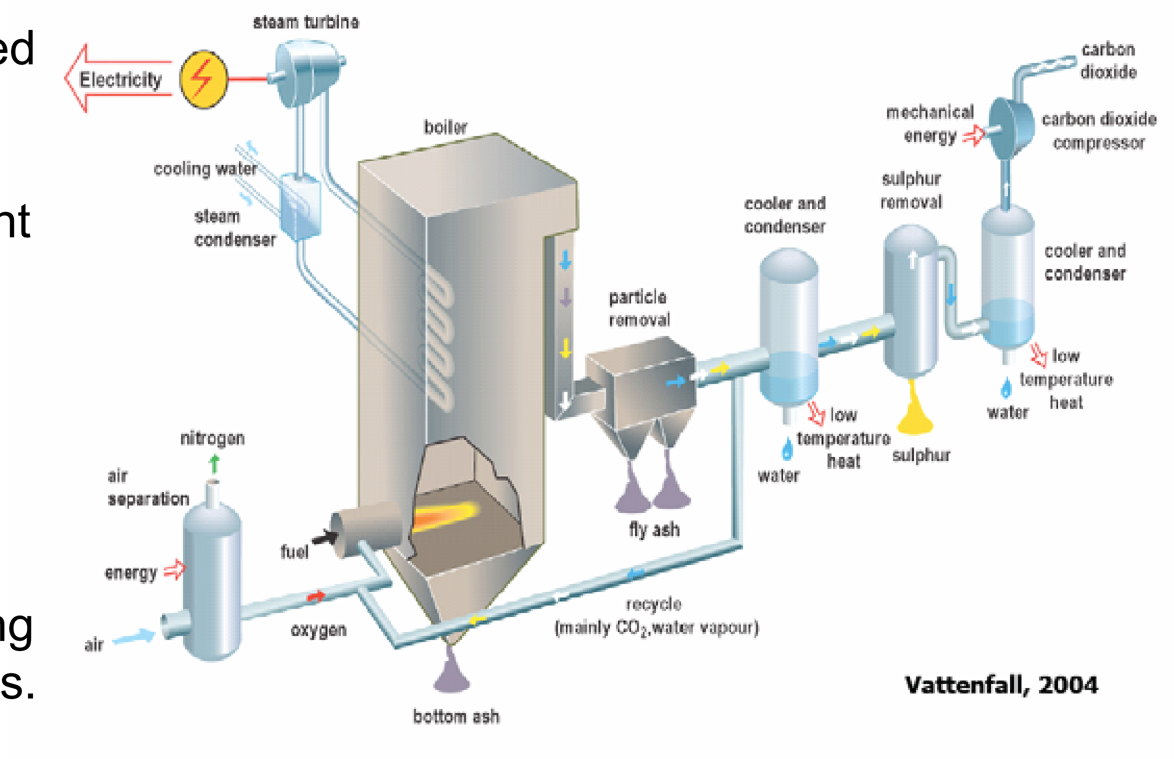
CO_2

^+H-E^*Zn^{2+}-OH^- ← E^*Zn^{2+}-OH^-

Sweep gas

Oxycombustion

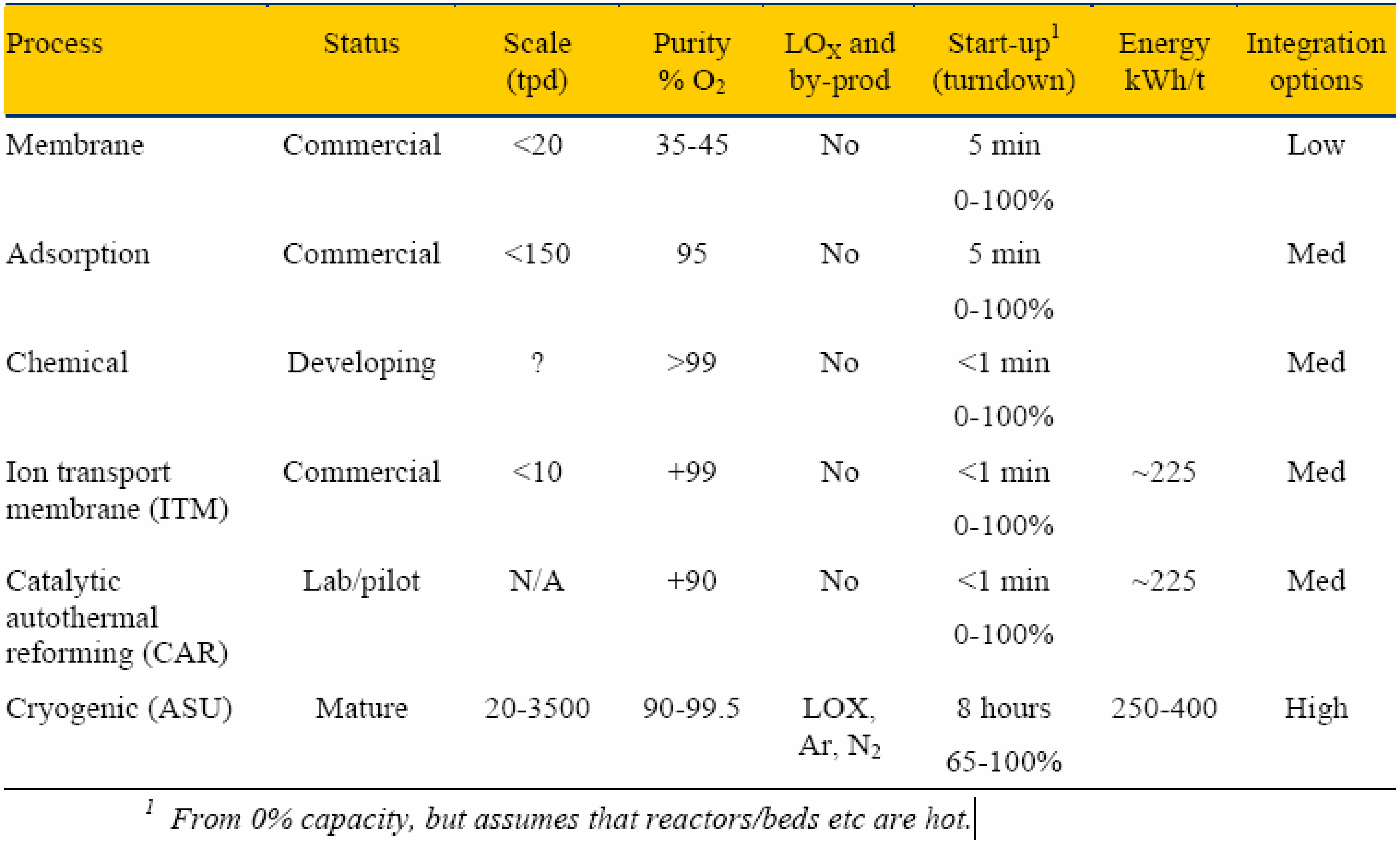
- Combustion in O_2/recycled flue gas.
- Produce high-CO_2-content (>80 vol%) flue gas.
- Shown to significantly reduce NO_x.
- Potential for zero emissions by sequestering all components in flue gas.
- Major cost component is air separation (cryogenics).



Vattenfall, 2004

Oxygen Separation

- State-of-the-art cryogenic distillation air separation has little room for improvement or cost reduction.



Process	Status	Scale (tpd)	Purity % O_2	LO_X and by-prod	Start-up[1] (turndown)	Energy kWh/t	Integration options
Membrane	Commercial	<20	35-45	No	5 min 0-100%		Low
Adsorption	Commercial	<150	95	No	5 min 0-100%		Med
Chemical	Developing	?	>99	No	<1 min 0-100%		Med
Ion transport membrane (ITM)	Commercial	<10	+99	No	<1 min 0-100%	~225	Med
Catalytic autothermal reforming (CAR)	Lab/pilot	N/A	+90	No	<1 min 0-100%	~225	Med
Cryogenic (ASU)	Mature	20-3500	90-99.5	LOX, Ar, N_2	8 hours 65-100%	250-400	High

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[1] *From 0% capacity, but assumes that reactors/beds etc are hot.*

Oxygen Separation (cont.)

- 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]).

Other Capture Methods

- Regenerative carbonate process
- Chemical looping gasification
- Chemical looping combustion
- ZEC technology
- Unmixed fuel processor
- CO_2 hydrate formation
- CO_2 hybrid process
- Water cycle
- Graz cycle
- MATIANT cycle

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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*℠ – 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 Janiero, 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℠* – 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 – one
- Australia – one

Technologies being investigated run the gamut:

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

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Summary

- Commercial technologies for CO_2 capture are available.
- Work is continuing to enhance performance.
- Limited data on the impact of impurities on cost and performance of CO_2 capture strategies.
- CO_2 management is a critical part of the future for many industries worldwide.

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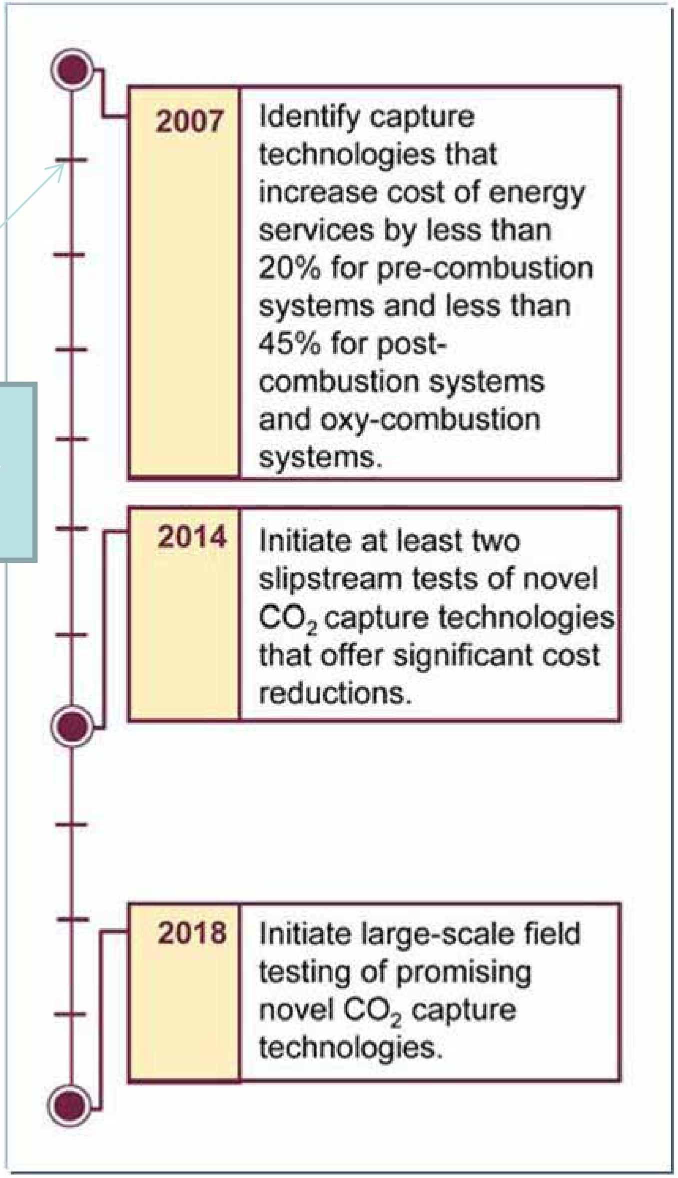
CO_2 Capture Challenges

Brandon Pavlish

Time Lines

NETL has set a goal that a technology portfolio of safe, cost-effective, commercial-scale GHG capture, storage, and mitigation technologies be available by 2012.



2007 Identify capture technologies that increase cost of energy services by less than 20% for pre-combustion systems and less than 45% for post-combustion systems and oxy-combustion systems.

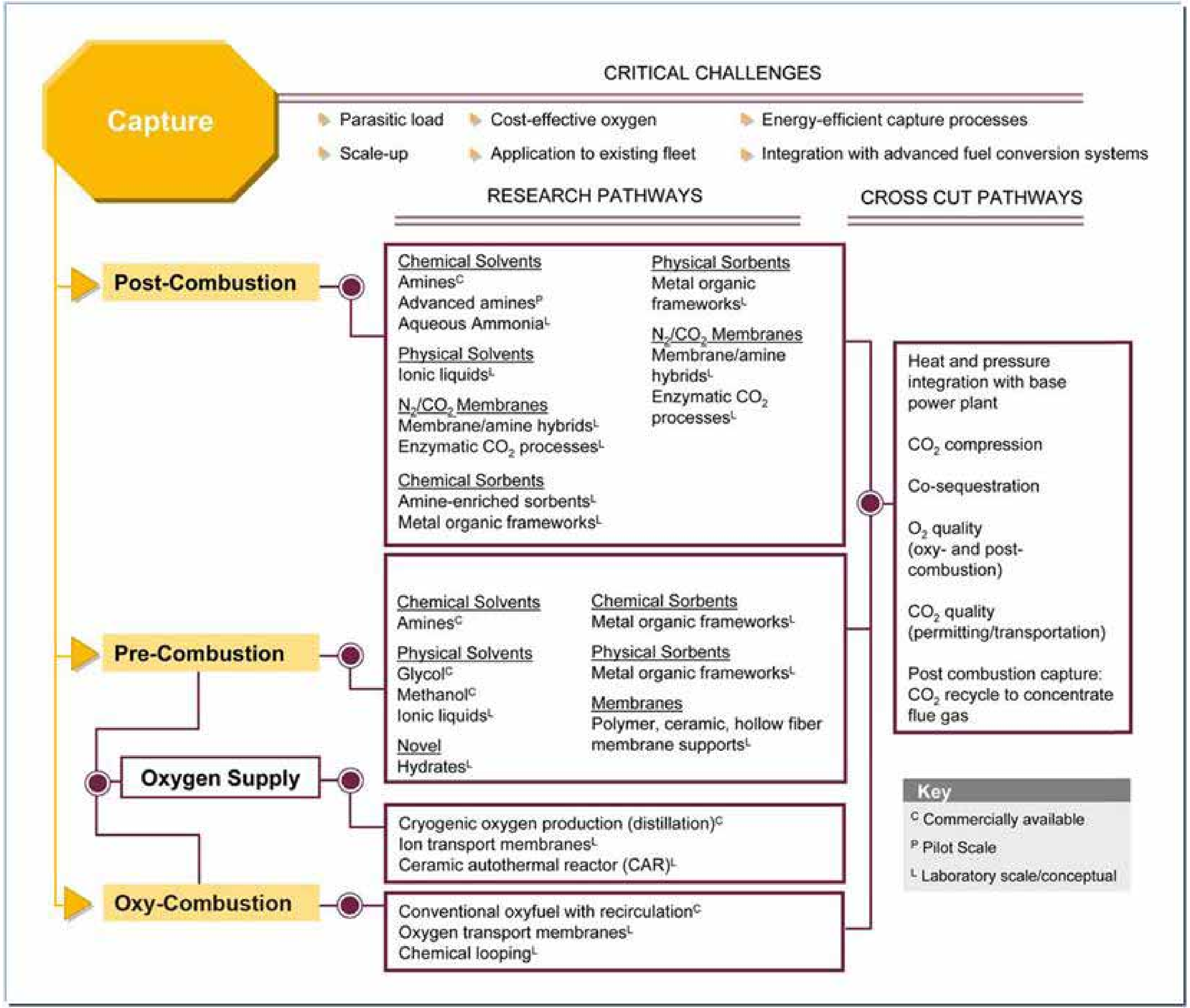
2014 Initiate at least two slipstream tests of novel CO_2 capture technologies that offer significant cost reductions.

2018 Initiate large-scale field testing of promising novel CO_2 capture technologies.

The Partnership for CO_2 Capture

Source: NETL DOE, "Carbon Sequestration Technology Roadmap and Program Plan 2007", www.netl.doe.gov Accessed March 2008

DOE NETL Identified Challenges



Capture

CRITICAL CHALLENGES

- Parasitic load
- Scale-up
- Cost-effective oxygen
- Application to existing fleet
- Energy-efficient capture processes
- Integration with advanced fuel conversion systems

RESEARCH PATHWAYS

CROSS CUT PATHWAYS

Post-Combustion

Chemical Solvents
Amines^{C}
Advanced amines^{P}
Aqueous Ammonia^{L}

Physical Solvents
Ionic liquids^{L}

N_2/CO_2 Membranes
Membrane/amine hybrids^{L}
Enzymatic CO_2 processes^{L}

Chemical Sorbents
Amine-enriched sorbents^{L}
Metal organic frameworks^{L}

Physical Sorbents
Metal organic frameworks^{L}

N_2/CO_2 Membranes
Membrane/amine hybrids^{L}
Enzymatic CO_2 processes^{L}

Pre-Combustion

Chemical Solvents
Amines^{C}

Physical Solvents
Glycol^{C}
Methanol^{C}
Ionic liquids^{L}

Novel
Hydrates^{L}

Chemical Sorbents
Metal organic frameworks^{L}

Physical Sorbents
Metal organic frameworks^{L}

Membranes
Polymer, ceramic, hollow fiber membrane supports^{L}

Oxygen Supply

Cryogenic oxygen production (distillation)^{C}
Ion transport membranes^{L}
Ceramic autothermal reactor (CAR)^{L}

Oxy-Combustion

Conventional oxyfuel with recirculation^{C}
Oxygen transport membranes^{L}
Chemical looping^{L}

Heat and pressure integration with base power plant

CO_2 compression

Co-sequestration

O_2 quality (oxy- and post-combustion)

CO_2 quality (permitting/transportation)

Post combustion capture: CO_2 recycle to concentrate flue gas

Key
^{C} Commercially available
^{P} Pilot Scale
^{L} Laboratory scale/conceptual

Source: NETL DOE, "Carbon Sequestration Technology Roadmap and Program Plan 2007", www.netl.doe.gov Accessed March 2008

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Challenges

- Solvent Systems
  - Impurities in flue gas streams
  - Integration and energy penalty
  - Footprint
  - Solvent availability
  - Waste management/new product streams
  - Unintended consequences
    - Environmental
    - Health and safety
- Oxy-firing
  - Air separation unit (ASU)
    - Footprint
    - Energy consumption
    - Equipment availability
  - Retrofit and new plant issues
    - Fouling and slagging
    - Flame stability
    - Heat transfer
    - Corrosion
    - Pollution control equipment

- Unknowns
- Product stream
- Costs

Solvent System Challenges

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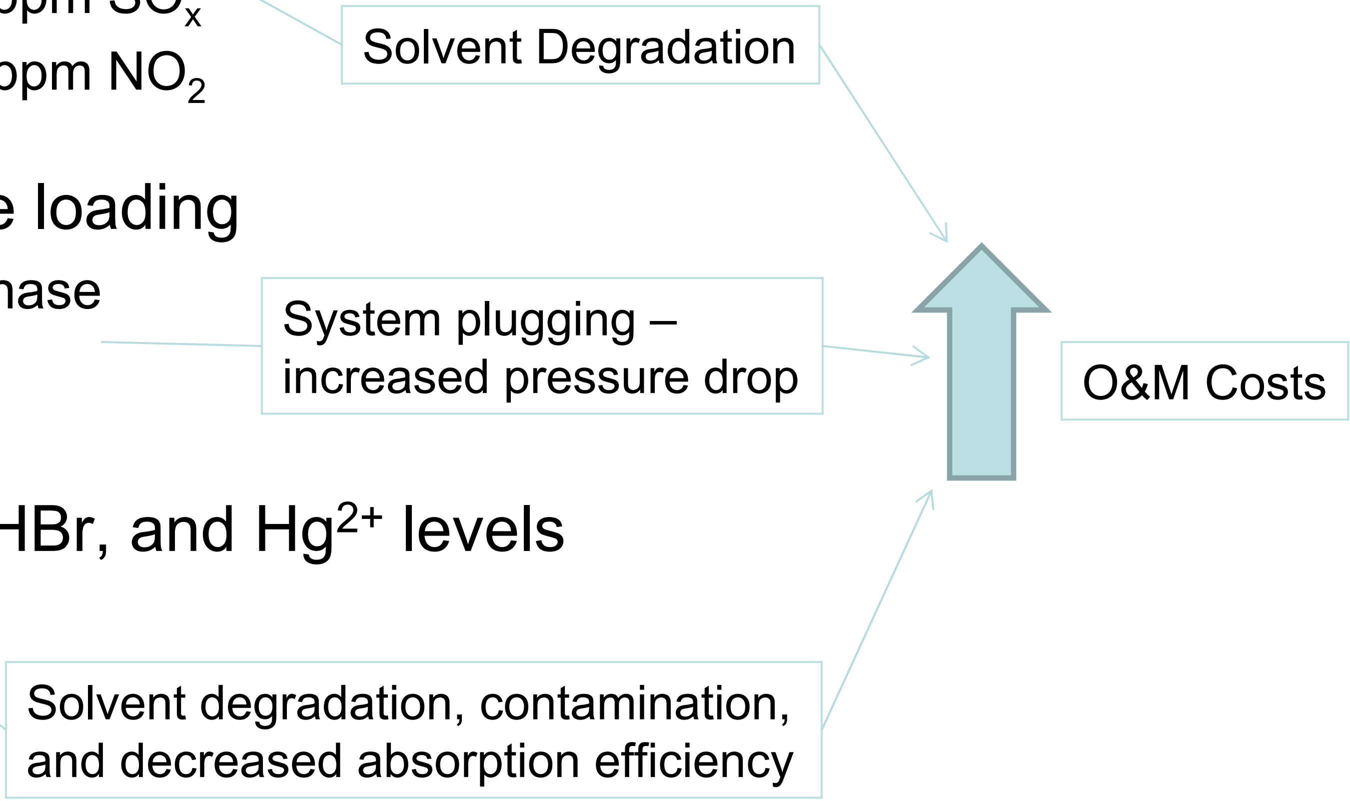
Impurities in Flue Gas

Capture Technology Flue Gas Requirements

- Ultralow SO_x and NO_x (especially SO_3 and NO) levels
  - Less than 10 ppm SO_x
  - Less than 20 ppm NO_2
- Low particulate loading
  - Condensed phase
  - Aerosols
- Low HF, HCl, HBr, and Hg^{2+} levels



Solvent Degradation

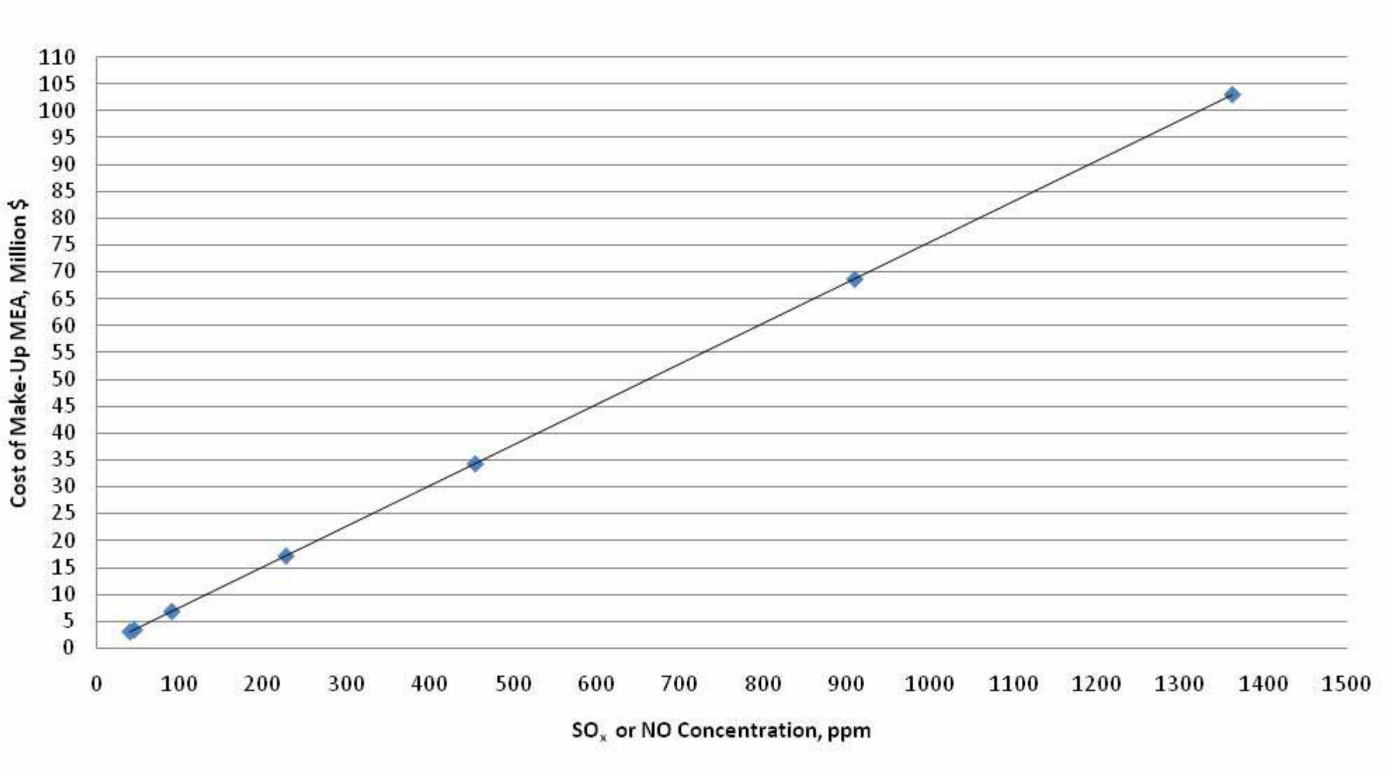
System plugging – increased pressure drop

Solvent degradation, contamination, and decreased absorption efficiency

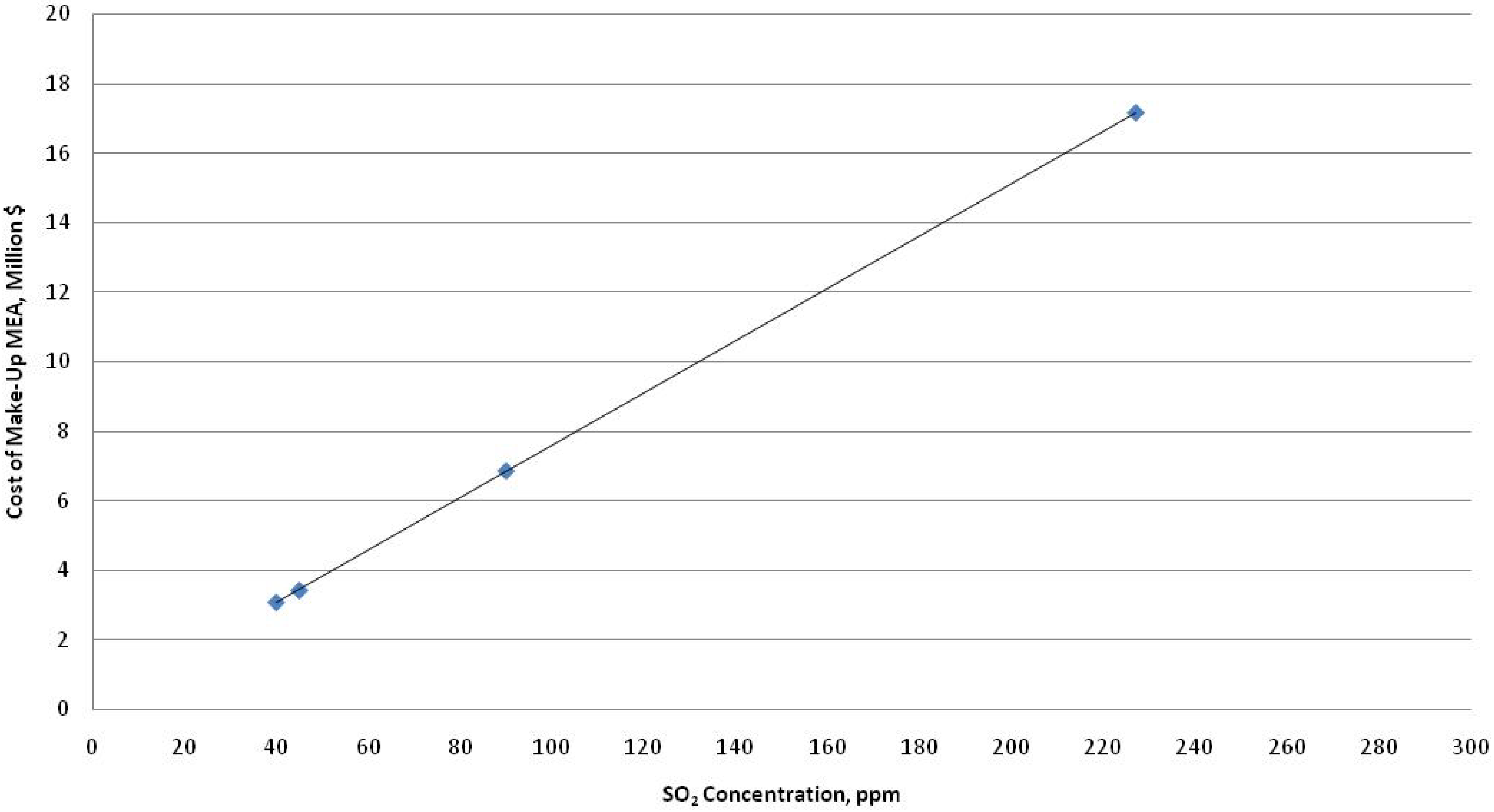
O&M Costs

Solvent Degradation

- Conventional wet and dry scrubber outlets have 40–60 ppm SO_2.
- 1 mole of SO_2/NO_2 consumes 2 moles of solvent to form heat-stable salts.

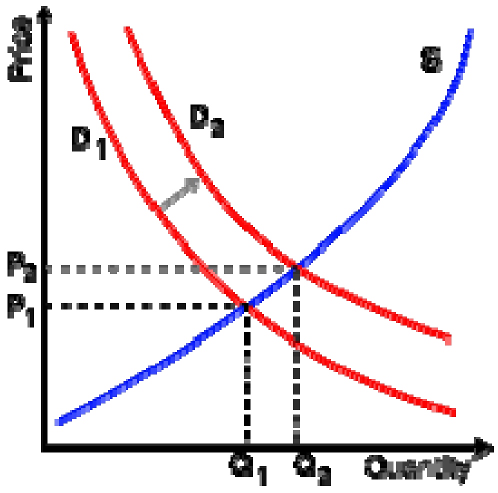


Effect of SO_x



Solvent Availability

- A significant amount of solvent will be required.
- Reliability from vendors.
- Cost
  - Ammonia produced from natural gas
    - Current cost ~ $300–$400 per ton.
    - Cost could become highly variable based on natural gas prices.
  - Amines produced from ammonia
    - Current cost ~ $1500 per ton.
    - Cost could become highly variable based on ammonia prices.
  - Supply vs. demand

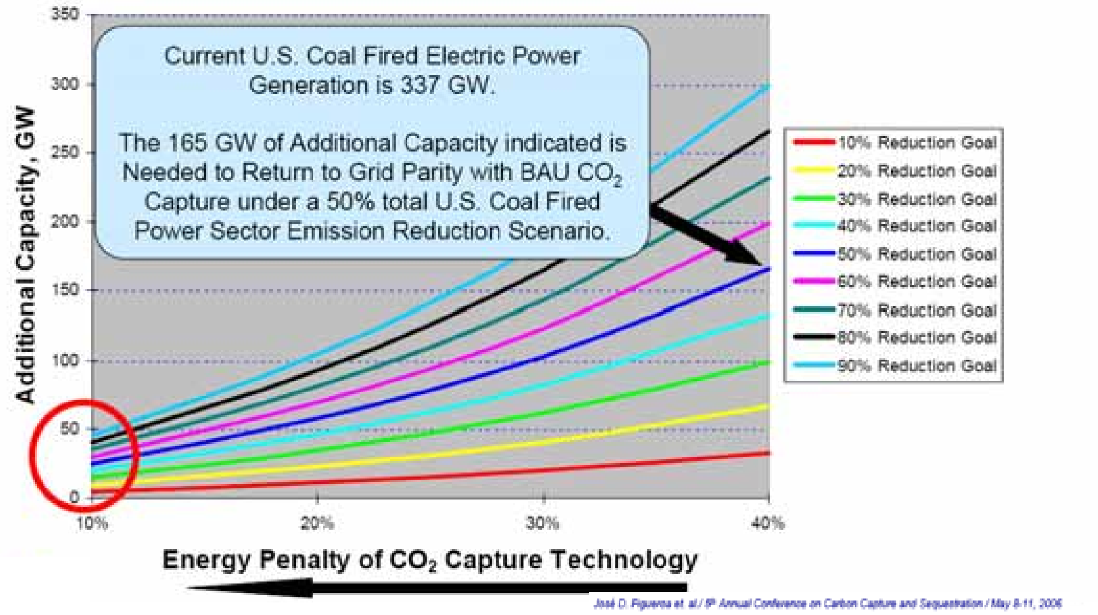


Energy Penalties

- The energy penalty for a typical MEA system is 30% to 50% of plant load for a retrofit.

- Example of energy penalty for ammonia systems.
  - Alstom’s Chilled Ammonia – 30% to 40%
  - Powerspan?

- Others?



José D. Figueroa et. al / 5th Annual Conference on Carbon Capture and Sequestration / May 8-11, 2006

Energy Penalties

A technology and economic analysis was performed by NETL comparing MEA and the chilled ammonia process:

550-MW Base Plant

Property	**Base-no CO_2 capture**	**MEA**	**Chilled Ammonia**
Electric load, MW	37.3	121	164
Lost generating capacity (due to steam consumption), MW	--	187	101
Total Energy Penalty, MW	--	**271**	**228**
Additional Capital Investment (millions)	--	$236	$276
HHV efficiency, i.e., energy fuel in – power output	39.5%	27.0%	28.4%
Cost of electricity, per kWh	$0.0510	$0.0808	$0.0808
CO_2 captured (tons/hr)	--	636	603
CO_2 capture efficiency	--	95%	90%
Capture cost, per ton CO_2	Avoided	$33.87	$33.54
	Removed	$25.77	$27.13

A 550-MW base plant is derated to a 279-MW plant for MEA or a 322-MW plant for chilled ammonia.

CO_2 Capture Retrofit Challenges Using Solvents

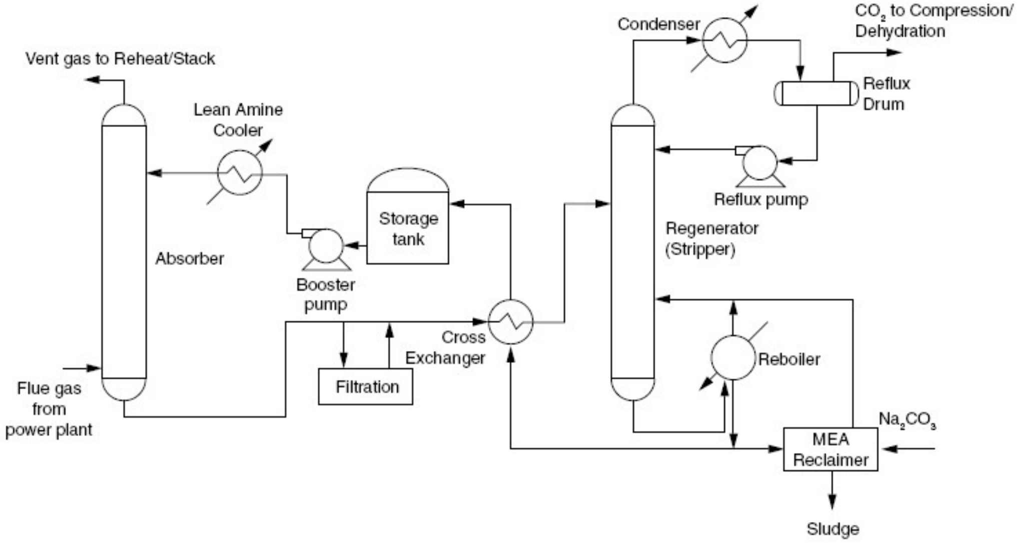
- Sufficient space (usually at least 2 to 6 acres) must be available within and around the plant for the chosen capture technology (footprint).
- Balance-of-plant equipment must be (re)sized to meet the requirements of not only the power block but the capture plant as well (larger sulfur removal equipment or new equipment).
- Waste and wastewater treatment needs will increase.
  - HSS, hazardous wastes, cooling water, process water
- Parasitic power load must be taken into account.
  - Replacement power requirements

Footprint

Fluor Daniel Econamine FGSM Retrofit at a gas-processing plant.

New Streams Due to CO_2 Removal

- Insoluble salts (amines = waste, ammonia = fertilizer). The production of fertilizer from one 500-MW plant would consume 13% to 27% of the present U.S. consumption of ammonium sulfate (fertilizer).
- Increased waste from further reductions in SO_x, NO_x, and particulate matter (PM).
- Large quantities of solvents on-site (MEA, ammonia, others)
- Others: wastewater, etc.



Unintended Consequences

- Effluent streams – vapors, slip, characteristics??
- Production of solvents produce CO_2 (1.65 ton CO_2/ton ammonia)
- By-products – hazardous waste potential from reclaiming HSS

Chemical-processing plant

Ammonia Plant

What Does It All Mean?

- Impurities in the flue gas
  - Increased solvent use through degradation
    - Increased O&M
    - Decreased absorption efficiency
- Solvent availability
  - Increased cost
  - Decreased reliability
- Energy penalties
  - Increased cost
  - Increased replacement power needs
- Footprint
  - Retrofit applicability
  - Larger space requirements for new plants

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What Does It All Mean? (cont.)

- New streams
  - Increased waste
  - Increased safety hazards
  - Increased water needs

Increased Cost

- Unintended consequences
  - Other environmental impacts
  - Large solvent use requires more energy and increased CO_2 emissions from chemical processes

Solvent Technology Status: Pros and Cons

MEA Challenges

- Significant amount of power to operate pumps and blowers for gas and solvent circulation.
- The largest parasitic load to the power cycle is associated with the steam used for solvent regeneration. Energy consumption as steam can be as high as 3.6 to 4.5 million Btu/ton CO_2 recovered.
- Additional issues:
  - Corrosion
  - Solvent degradation caused by the presence of dissolved O_2 and other impurities
  - Solvent reactions with SO_2, SO_3, and NO_x to produce nonregenerable, heat-stable salts
    - Requires SO_2 levels below 10 ppm, NO_2 levels below 20 ppm, and NO_x below 400 ppm.

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Tailored Amines/Designer Amines

- Pros
  - Lower heat of regeneration over MEA
  - Lower corrosion issues over MEA
  - Higher CO_2 absorption loading in some designer amines

- Cons
  - Still require large amounts of regeneration energy
  - Solvent degradation remains an issue
  - Solvent availability (less produced) and greater cost
  - Unknowns

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Pros and Cons of Ammonia Processes

- **Pros**
  - Lower heat of regeneration than MEA
  - Higher net CO_2 transfer capacity than MEA
  - Lower stripping steam requirement
  - Offers multipollutant control
- **Cons**
  - Ammonium bicarbonate decomposes at 140°F, so temperatures in the absorber must be lower.
  - 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.
  - Considerable energy required for chilled ammonia.
  - Unknowns.

Activated Hot Potassium Carbonate Processes: Gasification (precombustion)

- Pros
  - Absorbs CO_2 at a relatively high temperature.
  - Solvent regeneration is accomplished through pressure reduction with some heating.
- Cons
  - Solvent stream must be split before entering the absorber, with a portion cooled to increase CO_2 solubility.
  - The CO_2 partial pressure should be at least 30 to 50 psi.

Pros and Cons of Physical Absorbents: Gasification (precombustion)

- **Pros**
  - Low utility consumption.
  - Rectisol® uses inexpensive, readily 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.

Oxygen-Fired Combustion Challenges

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Oxyfuel Combustion Challenges

- Air separation unit
  - Footprint
  - Energy consumption
  - Oxygen purity
  - Equipment availability
- Retrofit and new plant issues
  - Fouling and slagging
  - Existing pollution control devices
  - Air leaks
  - Thermal properties change
  - Corrosion

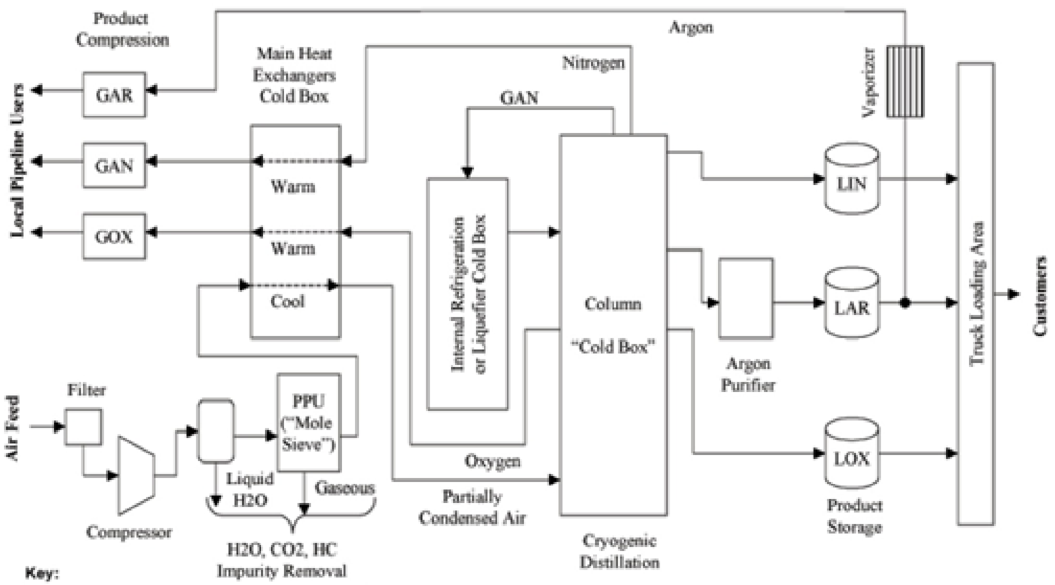
Air Separation Unit

- A 500-MW oxy-fired plant would consume 9000 ton/day of O_2.
- A cryogenic ASU of this size would require 5 to 6 acres of space.
- Cryogenic ASUs require between 250 and 450 kWh of electricity per ton of O_2.
- The ASU alone will consume 15% to 20% of the plants generation, with compression 25% to 30%.

Air Separation Unit (cont.)

- Operating flexibility: requires liquid oxygen storage.
- Unit scale: the current scale of cryogenics is around 4000 ton/day.
- Nitrogen contamination.
- Equipment availability.

EERC BP27566.CDR



Key:

Gaseous	Product	Liquid
GAN	Nitrogen	LIN
GAR	Argon	LAR
GOX	Oxygen	LOX
CO2	Carbon Dioxide	-
H2O	Water	H2O
HC	Hydrocarbons	-

Generic Air Separation Unit (ASU)

- Shows inter-relationship of major components
- Specific plants will vary

Oxyfuel Retrofit Issues

- Fouling and slagging differences.
- Existing pollution control equipment:
  - Will be oversized.
- Air leaks:
  - Systems will need to be sealed in order to prevent nitrogen contamination.
- Thermal properties will change which may affect steam cycle.

Oxyfuel Retrofit Issues (cont.)

- Flue gas recycle
  - Elevated concentrations of SO_2/SO_3 (corrosion).
  - Reliability.
  - High moisture concentrations (corrosion).
- Altered ash (oxy-firing)
  - Ash chemistry may change, making ash no longer salable.

Combustion and Ash Behavior During O_2/CO_2 Firing of Coal

- Flame radiation intensity increases up to 30% for the gas-fired O_2/CO_2 as compared to air-fired conditions due to gas emissivity and possible soot formation for gas-fired tests (Andersson, K.; Johnsson, F. *Fuel* **2007**, *86,* 656–668).

- Radiative heat transfer has been shown to increase but literature is limited.

- Unknowns:
  - Impact on partitioning of inorganic impurities (vapors, liquids, solids), slag flow behavior, ash deposition, corrosion and erosion is unknown.

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Key Issues – Impacts of Oxy-Firing

- Formation of intermediate ash species
  - Inorganic gases, liquids, and solids
  - Particle-size and composition evolution
- Deposit sticking and growth
  - Steel characteristics (oxide layer–deposit interface)
  - Liquid-phase formation (initial particle stickiness and captive surface)
- Deposit strength development
  - Sintering with a low-viscosity liquid phase (reactive and nonreactive)
- These issues depend on coal composition, system design, and operating conditions (temperature, oxygen concentration, and gas-cooling rate)

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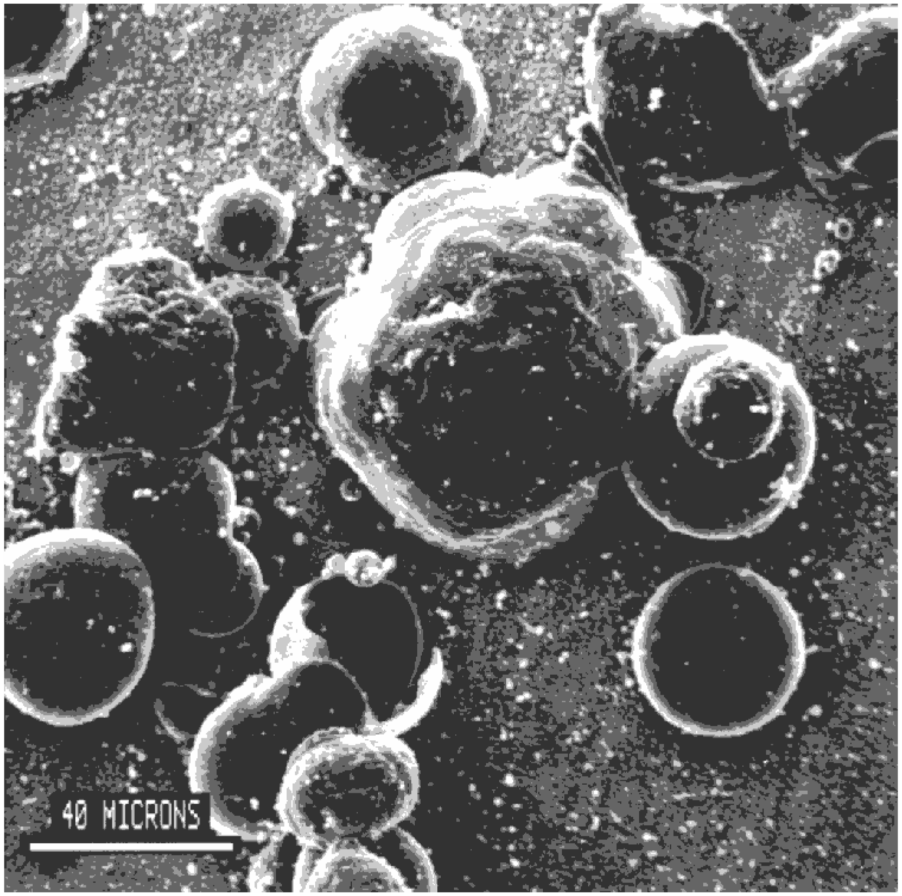
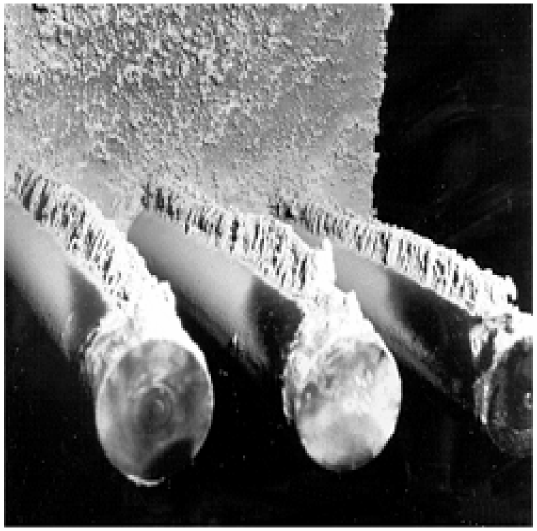
Ash Particle Impact and Bonding

- Substrate is stainless steel.
- Note flattened appearance of ash, indicative of being in a molten state on impact.

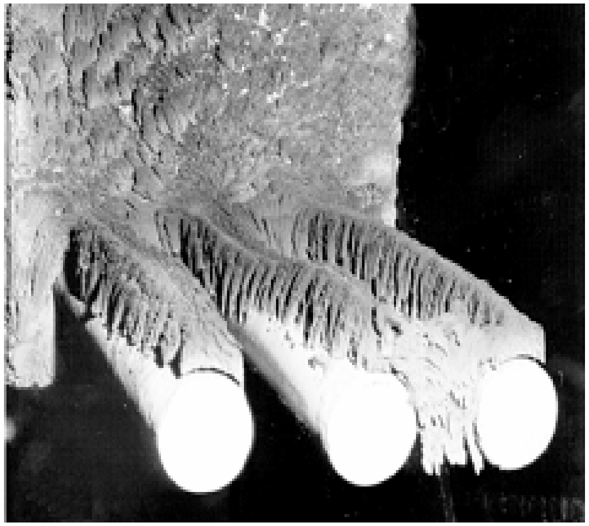


High-Temperature Ash-Fouling Probe Test Results
Sinter Deposit at 1200°C (2200°F)

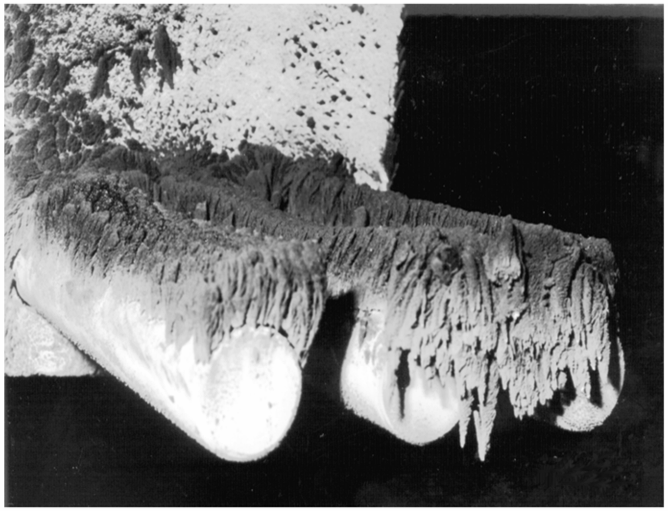
Bailey



Black Thunder



Antelope



Product Stream

Product Stream Composition Targets

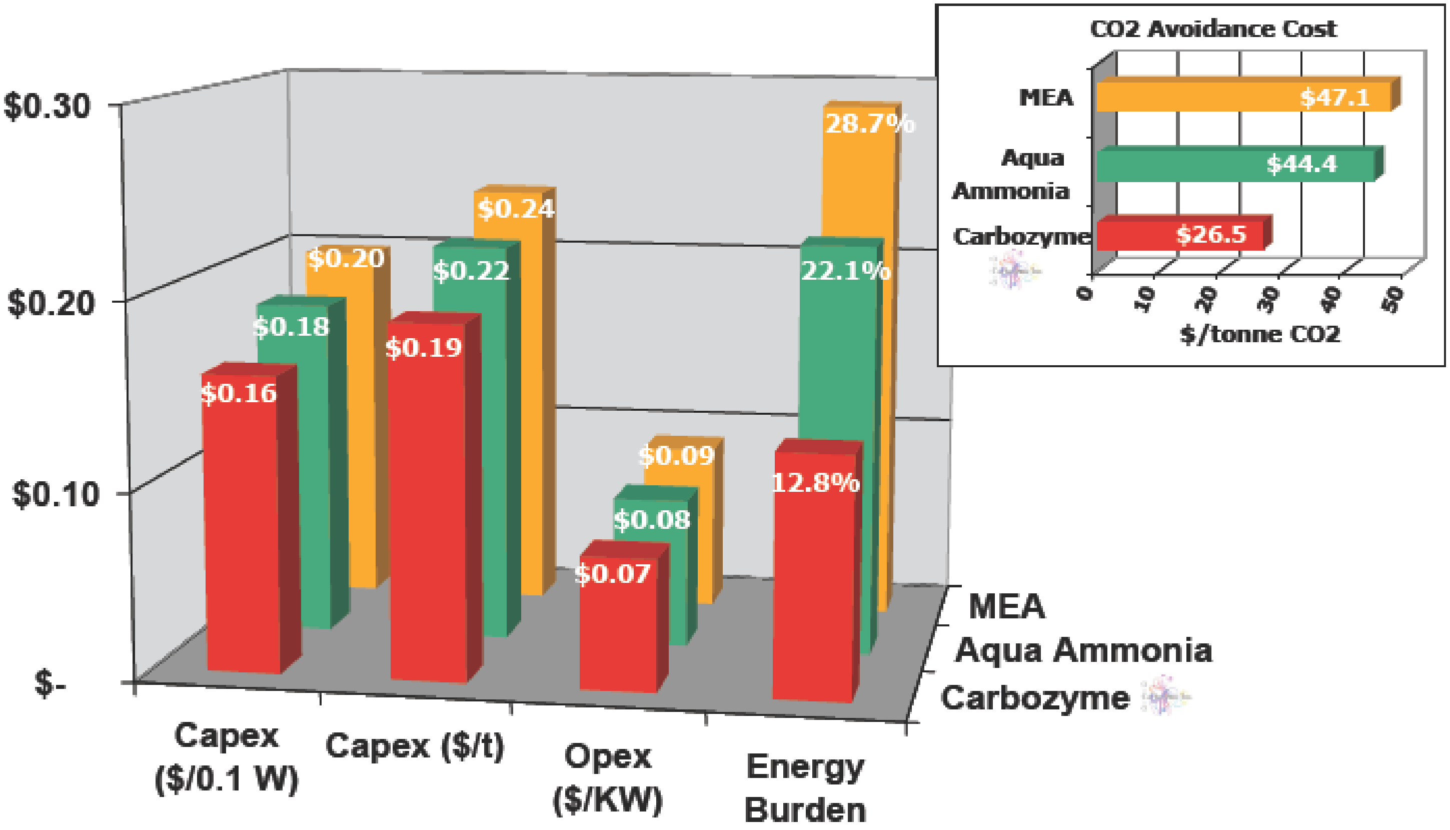
CO_2	95%	Min.	MMP concern
Nitrogen	4%	Max.	MMP concern
Hydrocarbons	5%	Max.	MMP concern
Water	30 lbs/MMcf*	Max.	Corrosion
Oxygen	10 ppm	Max.	Corrosion
H_2S	10–200 ppm	Max.	Safety
Glycol	0.3 gal/MMcf	Max.	Operations
Temperature	120°F	Max.	Materials

- Kinder Morgan pipeline requirements for EOR applications

* MMcf = million cubic feet at 1 atm and 60°F.

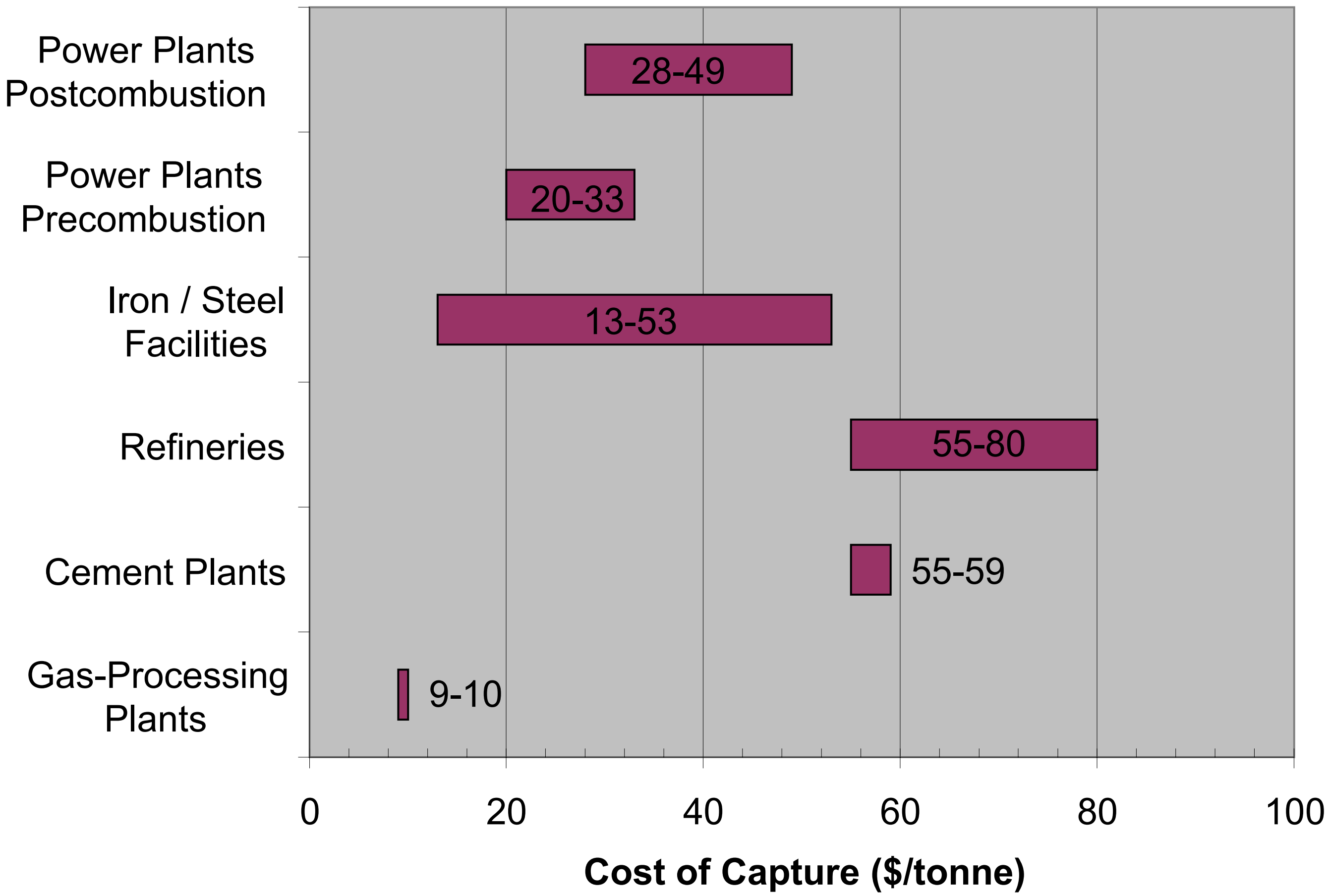
Costs

Cost Comparisons – Carbozyme Reports

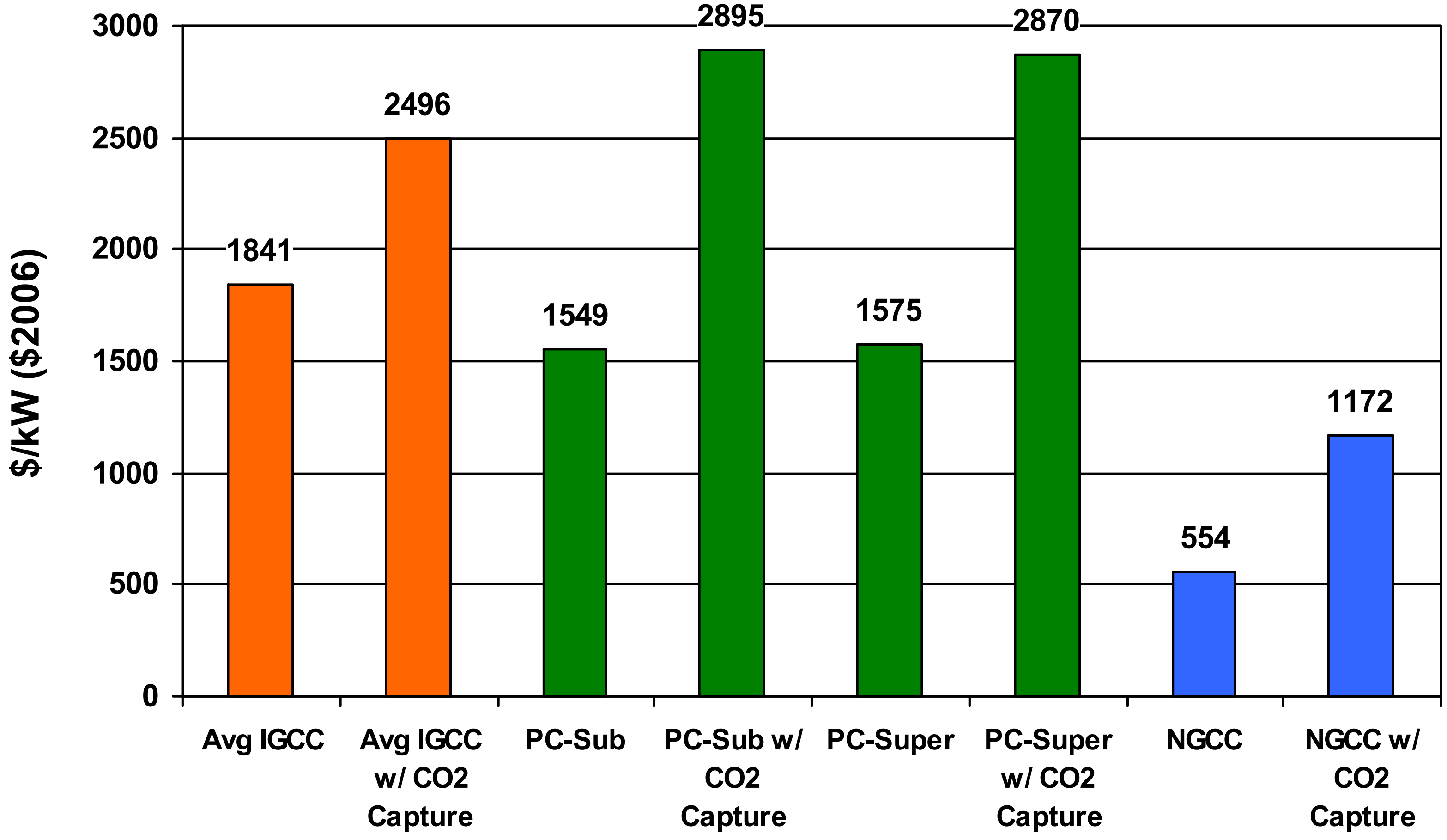


Based on EPRI, 2000

Cost of Capture Technologies (as of 2005)



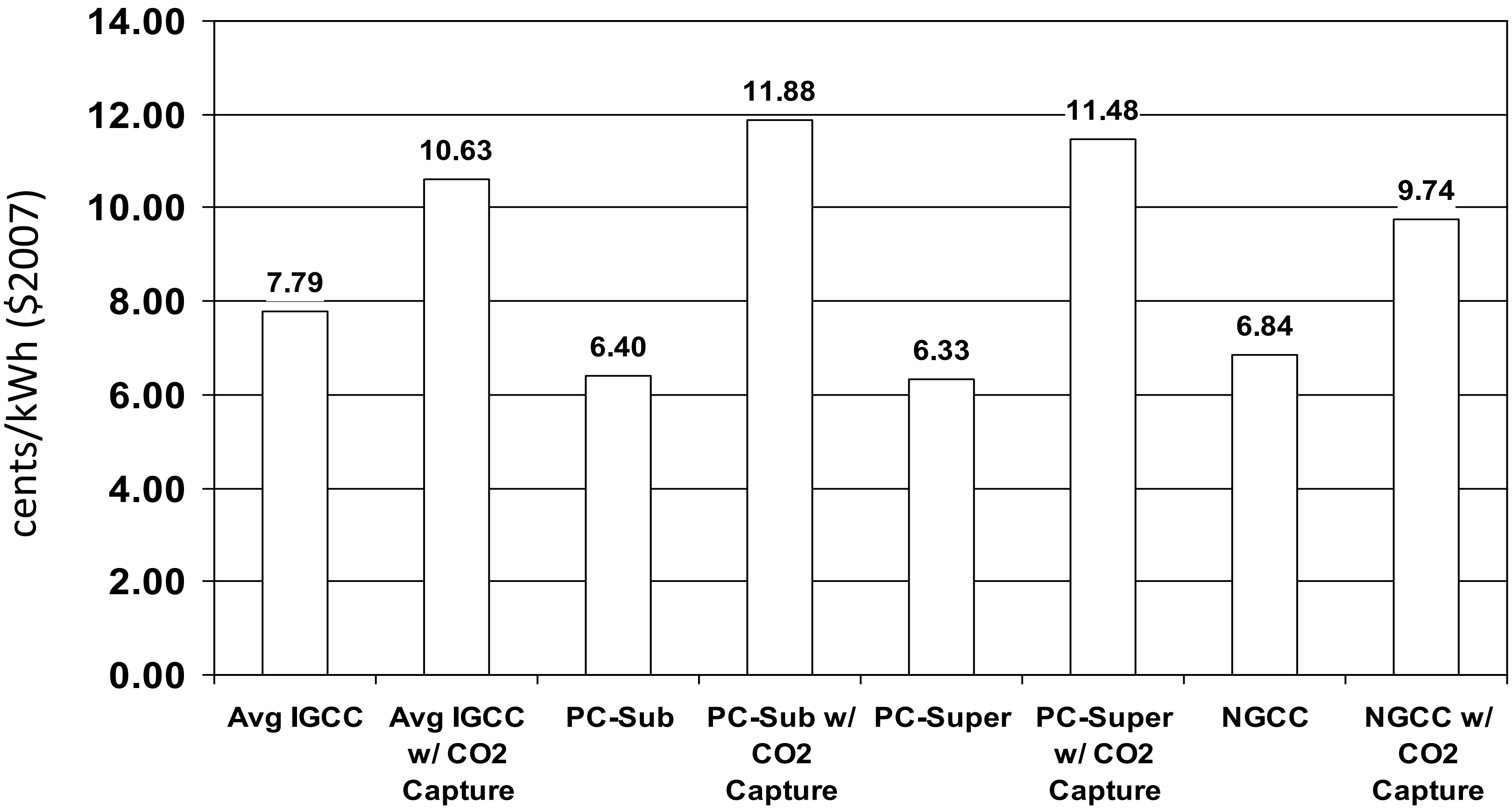
Total Plant Cost Comparison



Total Plant Capital Cost includes contingencies and engineering fees

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

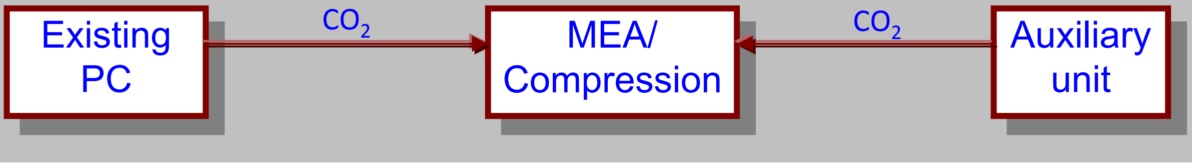
Cost of Electricity (COE) Comparison

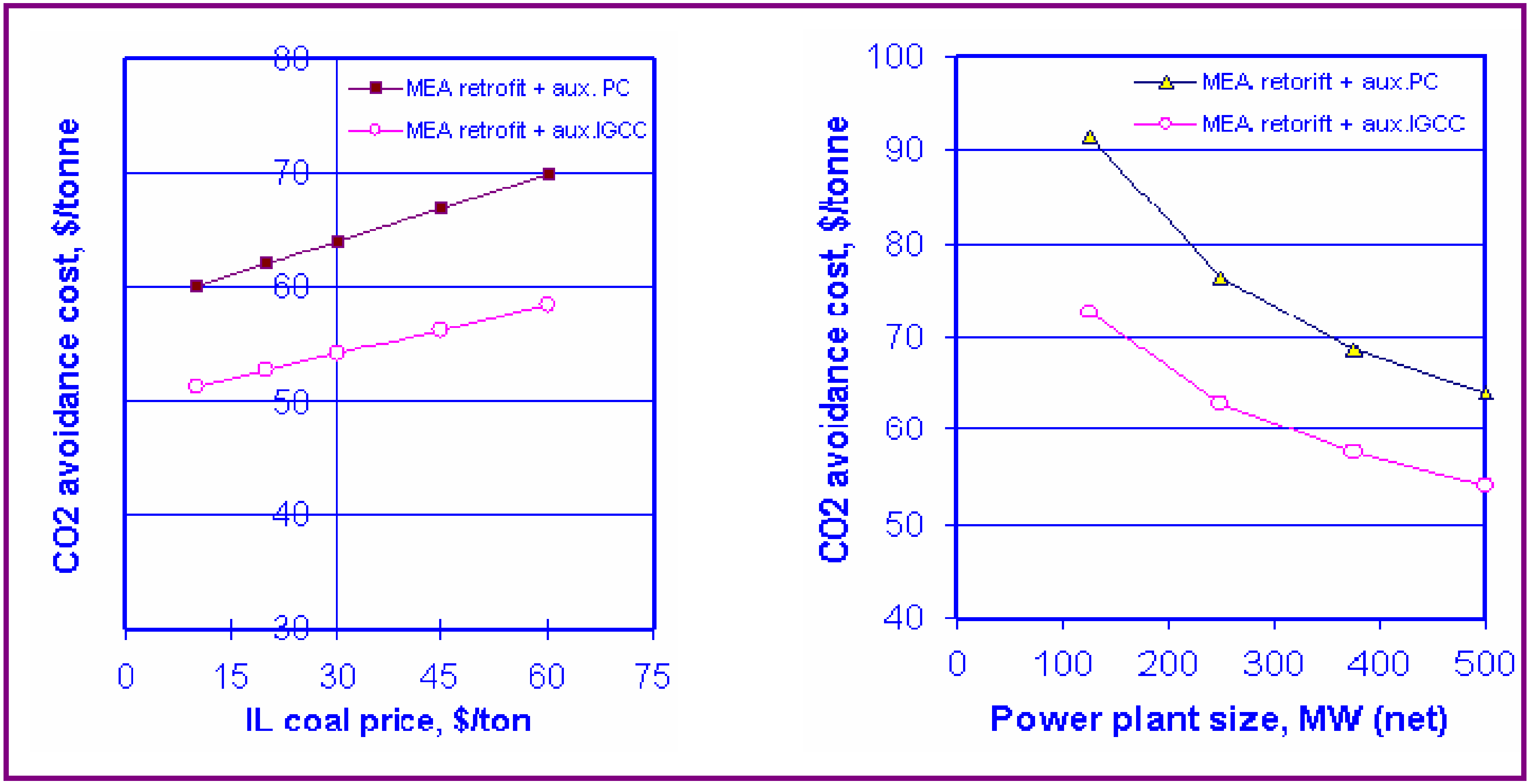


January 2007 Dollars, Coal cost $1.80/10^6Btu. Gas cost $6.75/10^6Btu

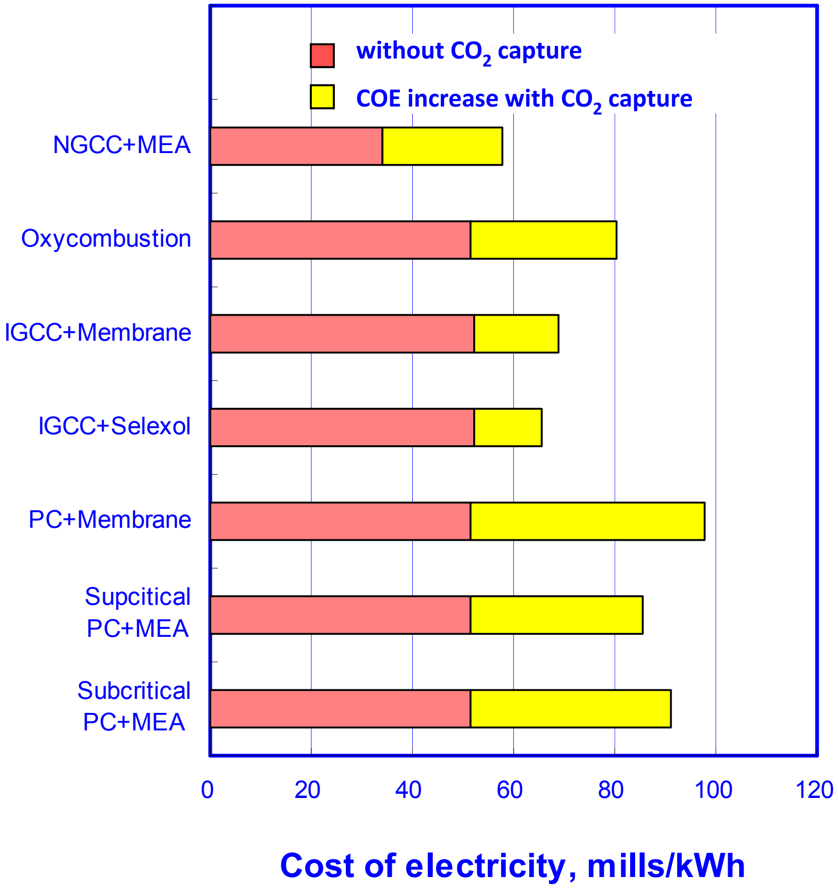
http://www.netl.doe.gov/energy-analyses/baseline_studies.html

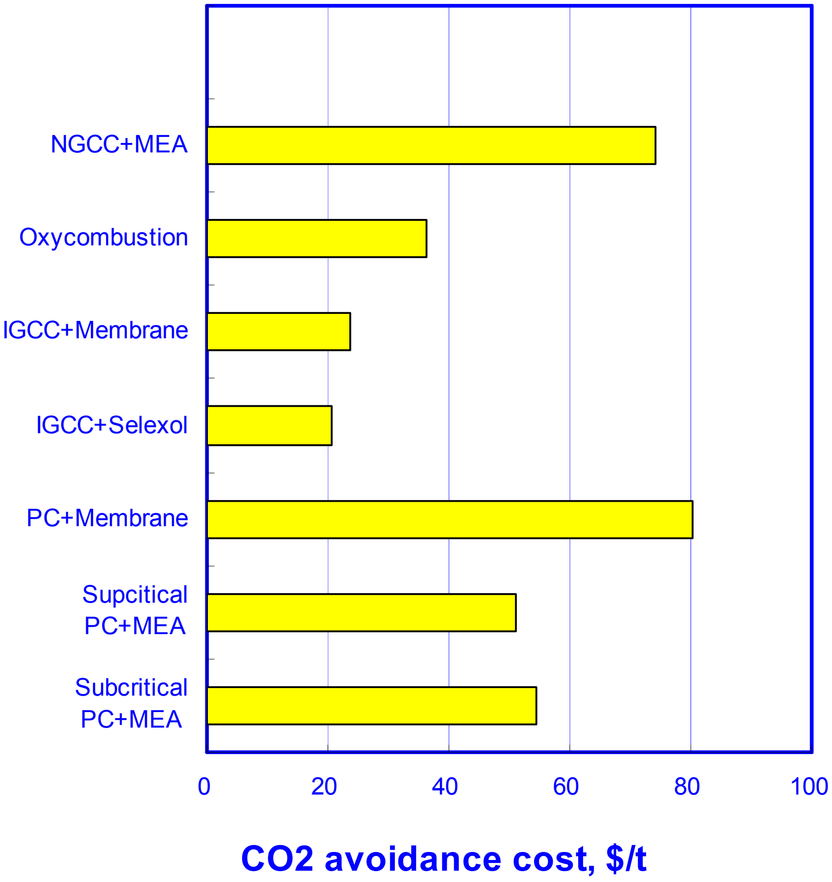
MEA Retrofit with Energy Loss Supplemented by Installing an Auxiliary Unit





Source: Assessment of Carbon Capture Options for Power Plants. Illinois By Massoud Rostam-Abadi, Shiaoguo Chen, and Yongiqi Lu





(All data in 2000 dollar; PC+ Membrane: 80% CO_2 recovery and 68% purity)

Data sources:

1. *Hendriks C., Carbon Dioxide Removal from Coal-fired Power Plants, Kluwer Academic Publishers, The Netherlands, 1994.*
2. *Parsons Energy and Chemicals Group Inc., Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal, DOE Interim Report 1000316, 2002*
3. *Chen S.G., Lu Y. and Rostam-Abadi M., Assessment of Geological Carbon Sequestration Options in the Illinois Basin - Task 2: Assess Carbon Capture Options for Illinois Basin Carbon Dioxide Sources, DE-FC26-03NT41994, March 2005.*
4. *Assessment of Carbon Capture Options for Power Plants. By Massoud Rostam-Abadi, Shiaoguo Chen, and Yongqi Lu*

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)

- Breakeven 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

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

Costs

- Very hard to find comparative cost estimates all on the same basis for other technologies:
  - Powerspan
  - Cansolv
  - MHI
  - Alstom’s Chilled Ammonia
  - Others
    - Solid sorbents
    - Membranes
    - Etc.

Challenges

- Several challenges have been identified.
- Larger demonstrations have been initiated and are critical to reaching the targets set by DOE and others.
- Smaller-scale studies will continue to enhance the performance of larger demonstrations leading to more cost effect and efficient strategies for CO_2 capture.
  - Minimize key challenges
    - Increase energy efficiencies
    - Decrease costs

The Partnership for CO_2 Capture Overview

Brandon Pavlish

The Partnership for CO_2 Capture

- Time line
- Project goals
- Project objectives
- Project tasks
  - Task 1: Postcombustion Capture System Design and Construction
  - Task 2: Oxygen-Fired Retrofit(s)
  - Task 3: Shakedown and Testing
  - Task 4: System Engineering Studies
  - Task 5: Deliverables, Schedule, and Management

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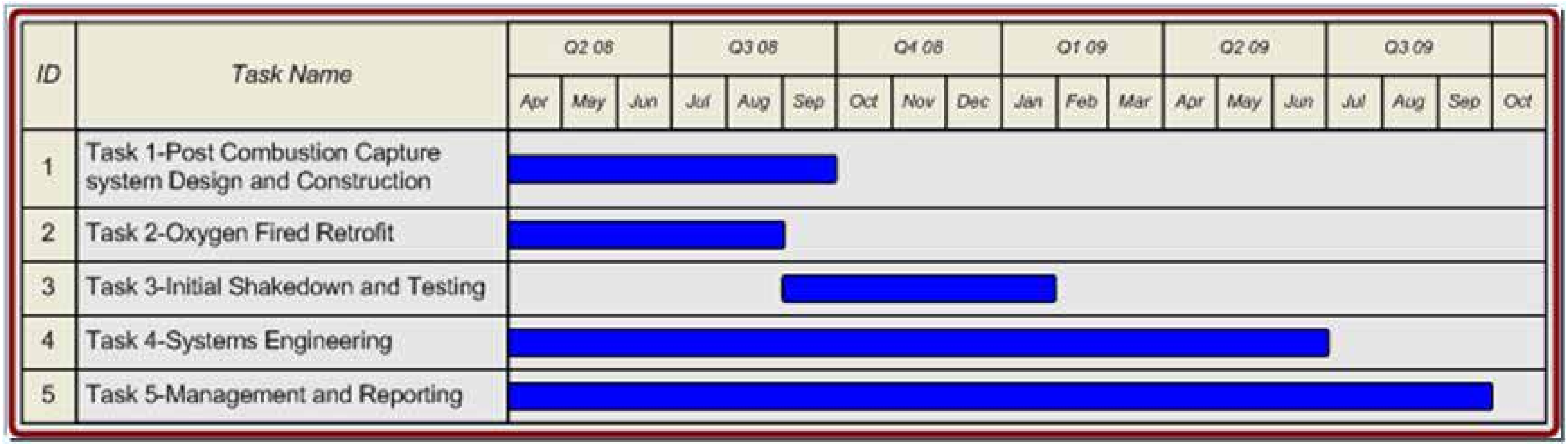
Time Line



ID	Task Name	Q2 08			Q3 08			Q4 08			Q1 09			Q2 09			Q3 09			
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	Task 1-Post Combustion Capture system Design and Construction	■	■	■	■	■	■													
2	Task 2-Oxygen Fired Retrofit	■	■	■	■	■														
3	Task 3-Initial Shakedown and Testing						■	■	■	■	■									
4	Task 4-Systems Engineering	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
5	Task 5-Management and Reporting	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	

The Partnership for CO_2 Capture: Goals

The overall goal of this program is to demonstrate a wide range of CO_2 capture technologies to identify the key challenges associated with each in order to develop strategies for cost-effective and efficient implementation at the commercial scale.

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The Partnership for CO_2 Capture: Objectives

- Gain a thorough understanding of the state of CO_2 capture technologies in order to move toward the development of strategies to enhance efficiencies and decrease costs.
  - Identify the key issues involved with several CO_2 capture technologies.
  - Test a wide range of back-end configurations (electrostatic precipitator [ESP], baghouse, selective catalytic reduction [SCR], wet flue gas desulfurization [WFGD], etc.) to mimic several CO_2 capture applications.
  - Determine effects of various fuel types and flue gas components on CO_2 capture efficiencies.
  - Begin to develop strategies to minimize or eliminate key issues.
  - Perform an overall technical and economic study on several CO_2 capture technologies to form a base to compare and improve upon the state of the technology.

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The Partnership for CO_2 Capture: Tasks

- Modifications of pilot-scale and slipstream systems for postcombustion testing.
  - Flexible postcombustion CO_2 capture system(s)
  - Flexible flue gas cleanup and conditioning system(s)
- Oxygen-fired retrofit of existing EERC pilot systems.
- Conduct initial shakedown and testing of selected fuels, system configurations, and CO_2 capture technologies.
- Perform systems engineering analysis of selected systems (for multiple CO_2 technologies).
- Conduct overall project management and reporting.

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Questions?

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Task 1: Postcombustion Test Systems

Scott Tolbert

Postcombustion Test Systems

Bridging the gap between models, commercial designs, and challenging implementations

- Task 1: Postcombustion systems
  - Flexible CO_2 capture system
  - Flexible flue gas cleanup and conditioning system
    - Design ideas
    - Implementation
- Schedule
  - Critical path analysis

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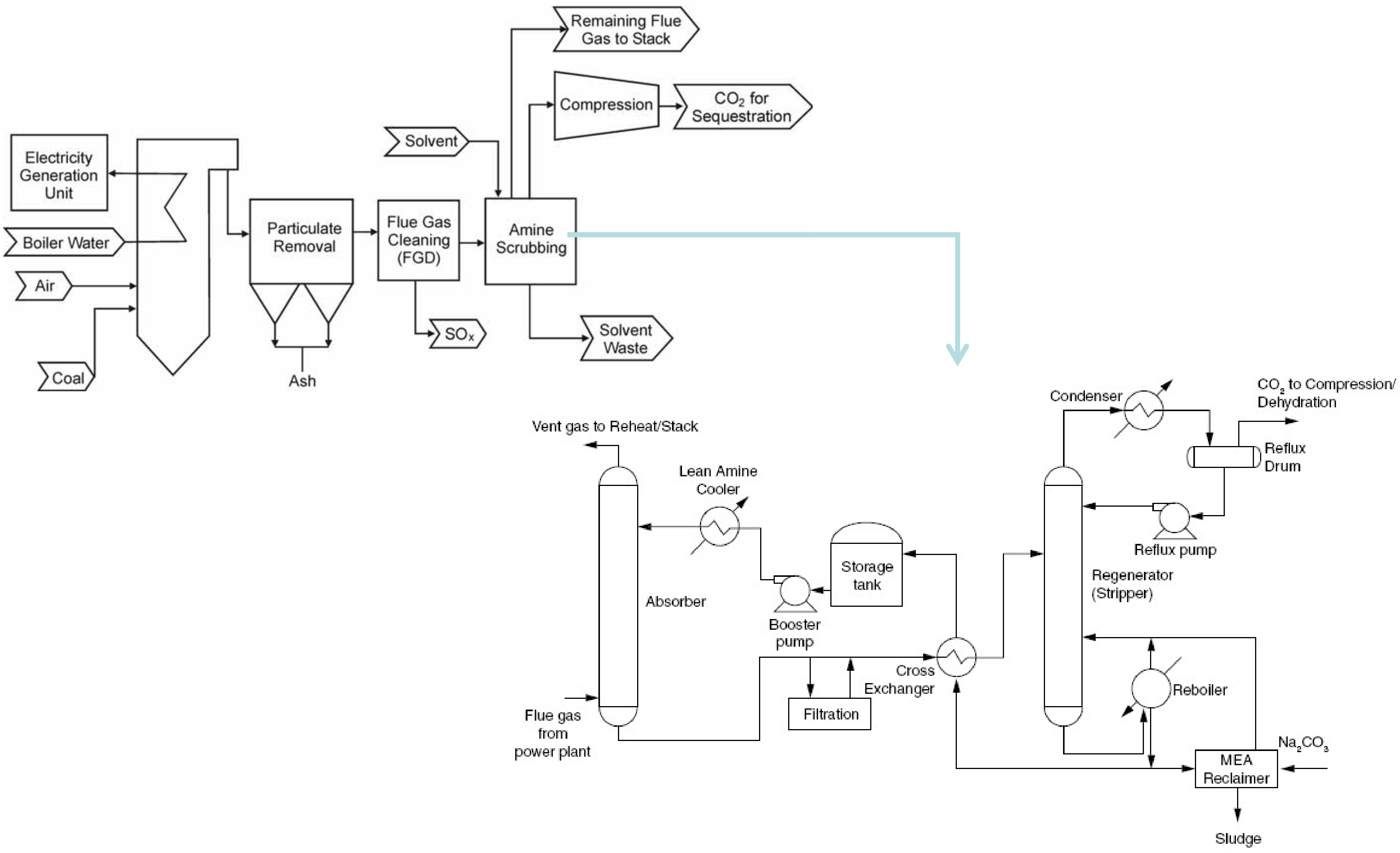
Flexible CO_2 Capture System

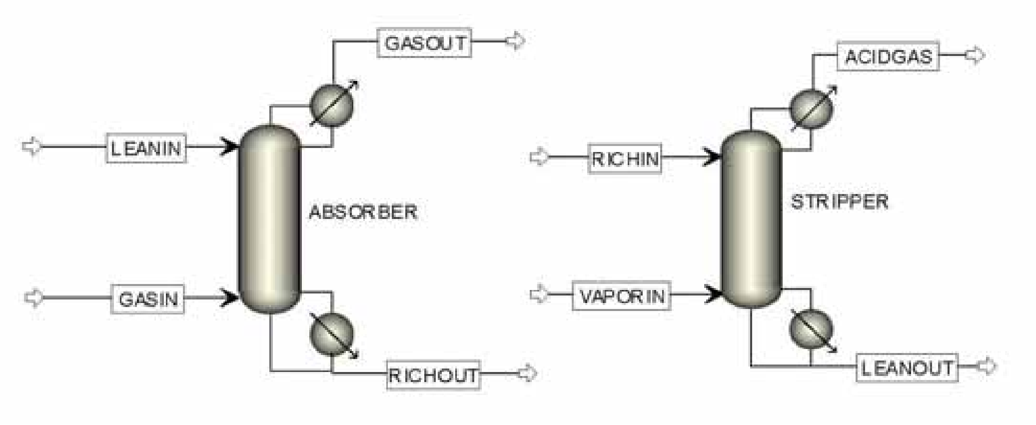
- Designed to be a postcombustion absorption CO_2 capture system.
- Will be able to mimic typical solvent systems.
- Design will be as flexible as possible to allow for easy scaleup and for several design modifications.
- Design will allow for the unit to be portable to test on different test systems:
    - Combustion test furnace (CTF)
    - Slagging furnace system (SFS)
    - Others (potential to trailer mount)

Flexible CO_2 Capture System (cont.)



Equipment Design

- Specific equipment will be designed with the help of Aspen.
  - Pumps
  - Heat exchangers
  - Columns
    - Absorber
    - Stripper
  - Tanks



- Where Aspen is not available, engineering design equations and firsthand experience will be used.

Flexible CO_2 Capture System

- Special design considerations for adequate measurements to determine:
  - Heat of regeneration
  - Solvent flows
  - Temperatures
  - Energy consumption
  - Flue gas components
  - Final CO_2 purity
  - Others to be determined
- Columns will be designed in sections to be able to change out internals easily.
  - Spray nozzles/spray sections
  - Internal packing

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Flexible Flue Gas-Conditioning System

- The flue gas-conditioning system will be design to enable the control of the incoming flue gas conditions to the absorption system.
  - Particulate loading
  - HF, HCl, and Hg^{2+} levels
  - Temperatures
  - Flow rates
  - Concentrations of SO_x
  - Concentrations of NO_x
  - Moisture levels

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Flexible Flue Gas-Conditioning System (cont.)

- Equipment may include, but is not limited to:
  - Heat exchangers
  - Flow control loops
  - SO_x polishing equipment
  - Wet ESP
  - NO_x control system (other than existing SCR)
  - Others to be determined

Pilot-Scale Testing Units

		Combustion Test Facility	Slagging Furnace System	Particulate Test Combustor
COMBUSTION MODE DATA	mBtu/hr	0.55	2.50	0.55
	Exhaust Flow (scfm)	130	530	130
	Exhaust Temperature (°F)	2500	2800	1800
	Air Fired	X	X	X
	Flue Gas Recycle	R $	X	R $
	O_2 Fired	R $	X	R $
	Air Separation Unit	R $	R $$$	R $
	Staged Combustion	X	R $$$	R $
	Low NOx Burner	X	X	X
	Daily Operational Cost	$	$$$	$
FUELS	Bituminous	X	X	X
	Subbituminous	X	X	X
	Lignite	X	X	X
	Petroleum Coke	X	R $$$	R $
	Coal Slurry	X	R $$$	R $
	Municiple Solid Waste	X	R $$$	R $
	Municiple Sludge	X	R $$$	R $
	Biomass	X	R $$$	R $
	Fuel Oil	X	R $$$	R $
	Residual Oil	X	R $$$	R $
	Crude Oil	X	R $$$	R $
	Natural Gas	X	X	X
	Other	X		

		Combustion Test Facility	Slagging Furnace System	Particulate Test Combustor
STUDIES	Ash Fouling	X	X	
	Heat Flux	X	X	R $
	Flame Stability Tests	X	X	X
EXHAUST CLEANUP	Multi-Port Sorbent Injection	X	R	
	Cyclone	X	X	X
	Wet ESP	R $	R $$$	R $
	Hot ESP	X	R $$$	R $
	Cold ESP	X	R $$$	X
	Baghouse	X	X	X
	Spray Dryer Adsorber	X	R $$$	X
	Dry Flue Gas Desulfurization	R $ Slip stream	R $$$	R $ Slip stream
	Wet Flue Gas Desulfurization	X	X	R $
	Selective Catalytic Reduction	X	R $$$	X
	Ammonia CO_2 Scrubber	R $	R $$$	R $
	MEA CO_2 Scrubber	R $	R $$$	R $
INSTRUMENTATION	SO_x	X	X	X
	NO_x	X	X	X
	CO	X	X	X
	CO_2	X	X	X
	O_2	X	X	X
	Hg	X	X	X

X - Presently capable
R - Retrofit possible
$ - Relative costs for operation and retrofits

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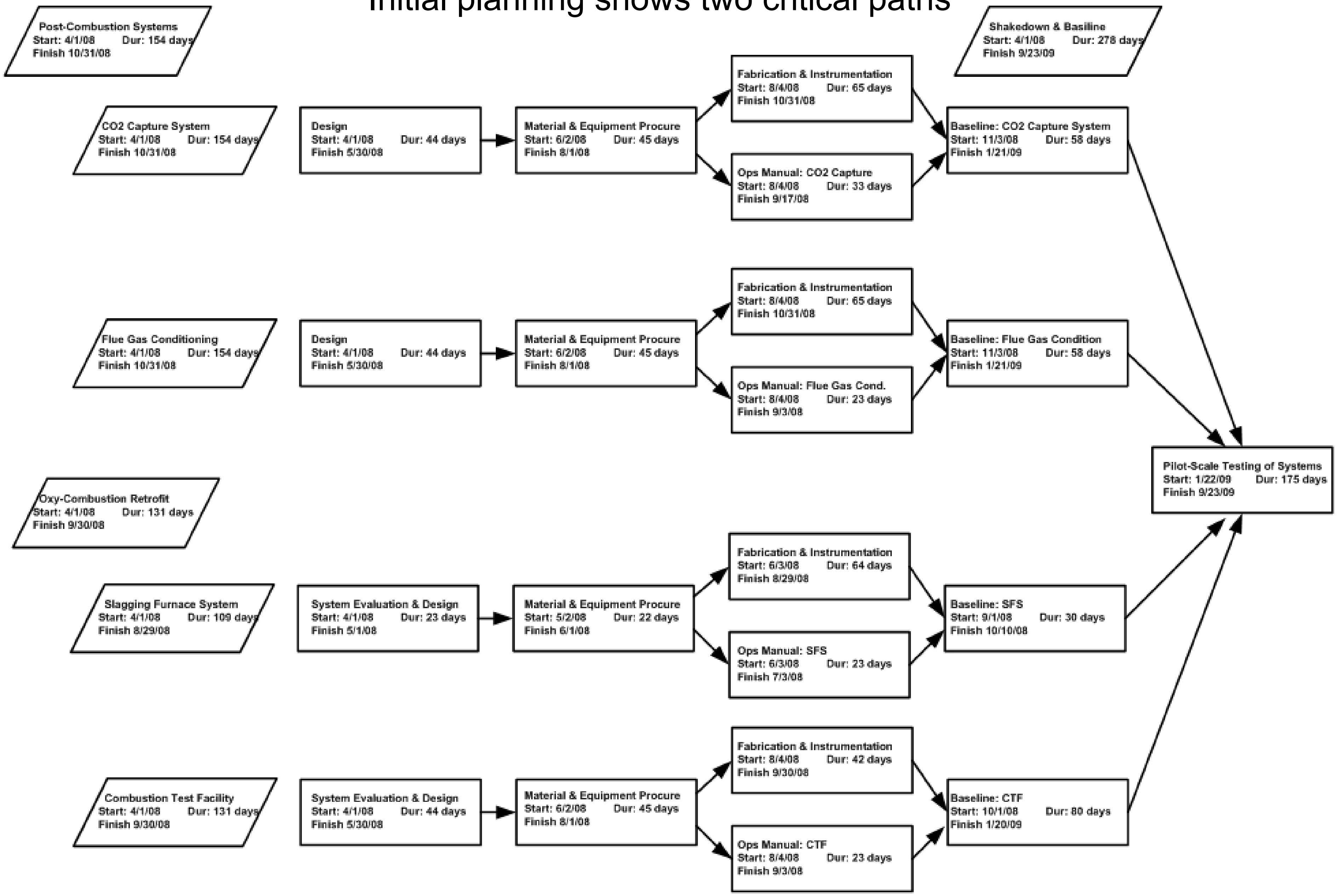
Tasks 1 and 2: Critical Path Analysis

Initial planning shows two critical paths



Post-Combustion Systems
Start: 4/1/08 Dur: 154 days
Finish 10/31/08

CO2 Capture System
Start: 4/1/08 Dur: 154 days
Finish 10/31/08

Design
Start: 4/1/08 Dur: 44 days
Finish 5/30/08

Material & Equipment Procure
Start: 6/2/08 Dur: 45 days
Finish 8/1/08

Fabrication & Instrumentation
Start: 8/4/08 Dur: 65 days
Finish 10/31/08

Ops Manual: CO2 Capture
Start: 8/4/08 Dur: 33 days
Finish 9/17/08

Baseline: CO2 Capture System
Start: 11/3/08 Dur: 58 days
Finish 1/21/09

Shakedown & Basiline
Start: 4/1/08 Dur: 278 days
Finish 9/23/09

Flue Gas Conditioning
Start: 4/1/08 Dur: 154 days
Finish 10/31/08

Design
Start: 4/1/08 Dur: 44 days
Finish 5/30/08

Material & Equipment Procure
Start: 6/2/08 Dur: 45 days
Finish 8/1/08

Fabrication & Instrumentation
Start: 8/4/08 Dur: 65 days
Finish 10/31/08

Ops Manual: Flue Gas Cond.
Start: 8/4/08 Dur: 23 days
Finish 9/3/08

Baseline: Flue Gas Condition
Start: 11/3/08 Dur: 58 days
Finish 1/21/09

Pilot-Scale Testing of Systems
Start: 1/22/09 Dur: 175 days
Finish 9/23/09

Oxy-Combustion Retrofit
Start: 4/1/08 Dur: 131 days
Finish 9/30/08

Slagging Furnace System
Start: 4/1/08 Dur: 109 days
Finish 8/29/08

System Evaluation & Design
Start: 4/1/08 Dur: 23 days
Finish 5/1/08

Material & Equipment Procure
Start: 5/2/08 Dur: 22 days
Finish 6/1/08

Fabrication & Instrumentation
Start: 6/3/08 Dur: 64 days
Finish 8/29/08

Ops Manual: SFS
Start: 6/3/08 Dur: 23 days
Finish 7/3/08

Baseline: SFS
Start: 9/1/08 Dur: 30 days
Finish 10/10/08

Combustion Test Facility
Start: 4/1/08 Dur: 131 days
Finish 9/30/08

System Evaluation & Design
Start: 4/1/08 Dur: 44 days
Finish 5/30/08

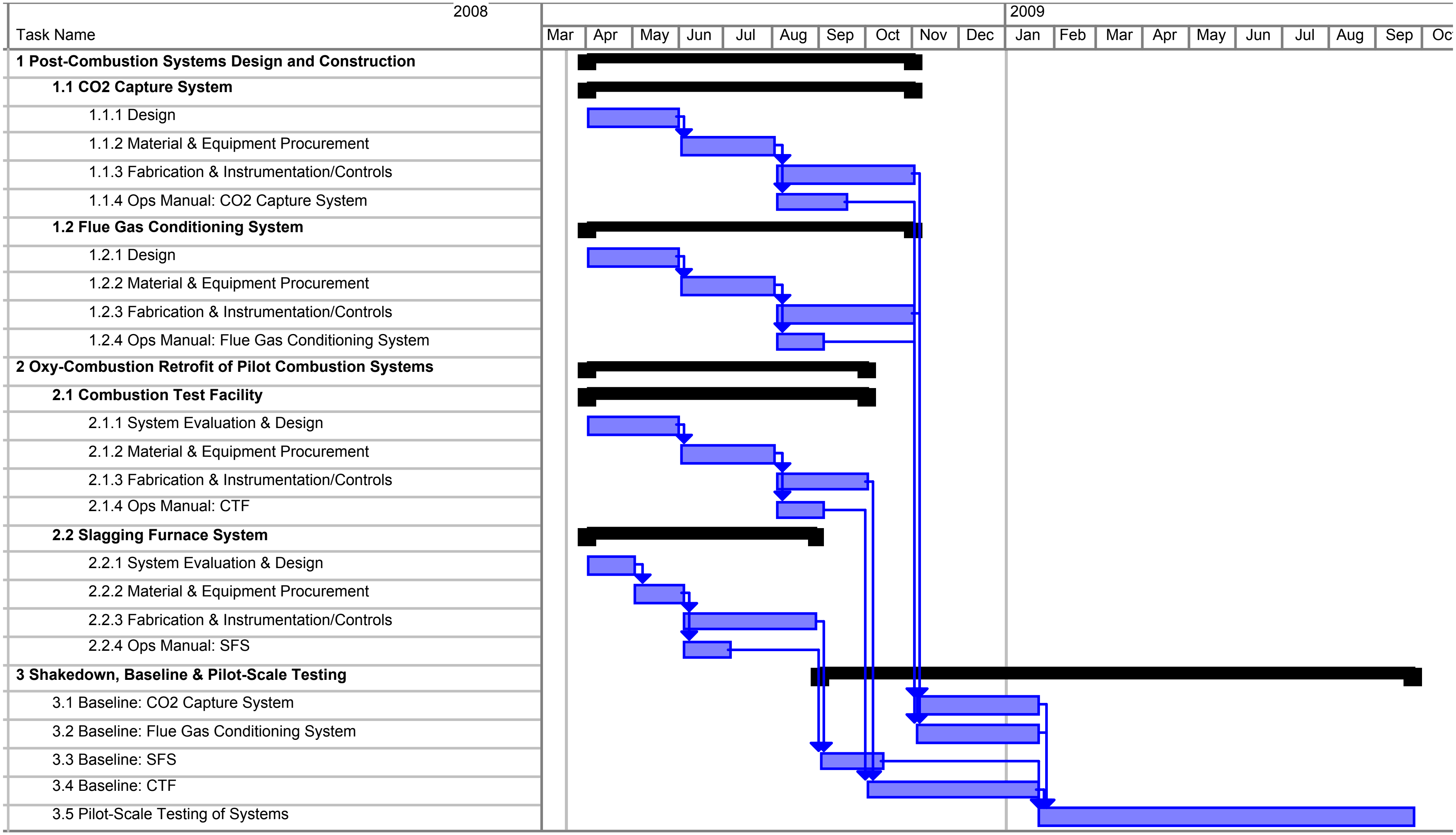
Material & Equipment Procure
Start: 6/2/08 Dur: 45 days
Finish 8/1/08

Fabrication & Instrumentation
Start: 8/4/08 Dur: 42 days
Finish 9/30/08

Ops Manual: CTF
Start: 8/4/08 Dur: 23 days
Finish 9/3/08

Baseline: CTF
Start: 10/1/08 Dur: 80 days
Finish 1/20/09

Tasks 1–3: Schedule



Task Name

1 Post-Combustion Systems Design and Construction
- **1.1 CO2 Capture System**
  - 1.1.1 Design
  - 1.1.2 Material & Equipment Procurement
  - 1.1.3 Fabrication & Instrumentation/Controls
  - 1.1.4 Ops Manual: CO2 Capture System
- **1.2 Flue Gas Conditioning System**
  - 1.2.1 Design
  - 1.2.2 Material & Equipment Procurement
  - 1.2.3 Fabrication & Instrumentation/Controls
  - 1.2.4 Ops Manual: Flue Gas Conditioning System

2 Oxy-Combustion Retrofit of Pilot Combustion Systems
- **2.1 Combustion Test Facility**
  - 2.1.1 System Evaluation & Design
  - 2.1.2 Material & Equipment Procurement
  - 2.1.3 Fabrication & Instrumentation/Controls
  - 2.1.4 Ops Manual: CTF
- **2.2 Slagging Furnace System**
  - 2.2.1 System Evaluation & Design
  - 2.2.2 Material & Equipment Procurement
  - 2.2.3 Fabrication & Instrumentation/Controls
  - 2.2.4 Ops Manual: SFS

3 Shakedown, Baseline & Pilot-Scale Testing
- 3.1 Baseline: CO2 Capture System
- 3.2 Baseline: Flue Gas Conditioning System
- 3.3 Baseline: SFS
- 3.4 Baseline: CTF
- 3.5 Pilot-Scale Testing of Systems

Task 2: Oxygen-Fired Retrofit(s)

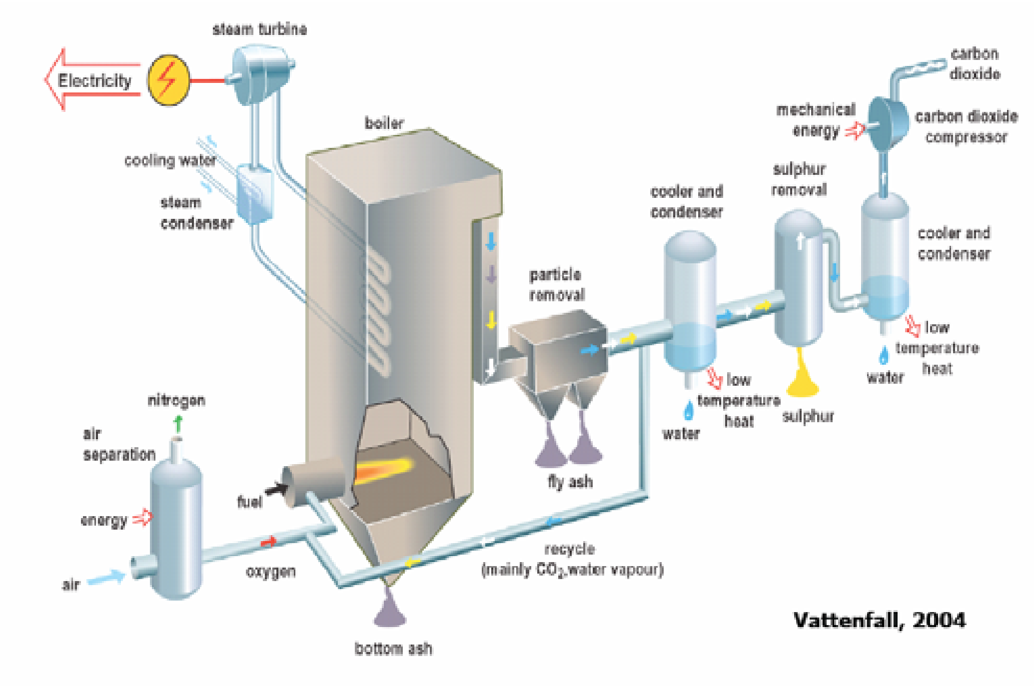
Jason Laumb

Energy & Environmental Research Center®

Oxygen-Fired Retrofit(s)

- Rationale
  - Reduced footprint.
  - Maturity of technology.
  - Reduced NO_x emissions.
  - SO_x, particulate, mercury
  - Sodium
- Challenges
  - Fouling/slagging
  - Materials
  - Flue gas recycle
  - ASU

Pilot-Scale Units:
  - CTF
  - SFS



Vattenfall, 2004

Combustion Test Facility

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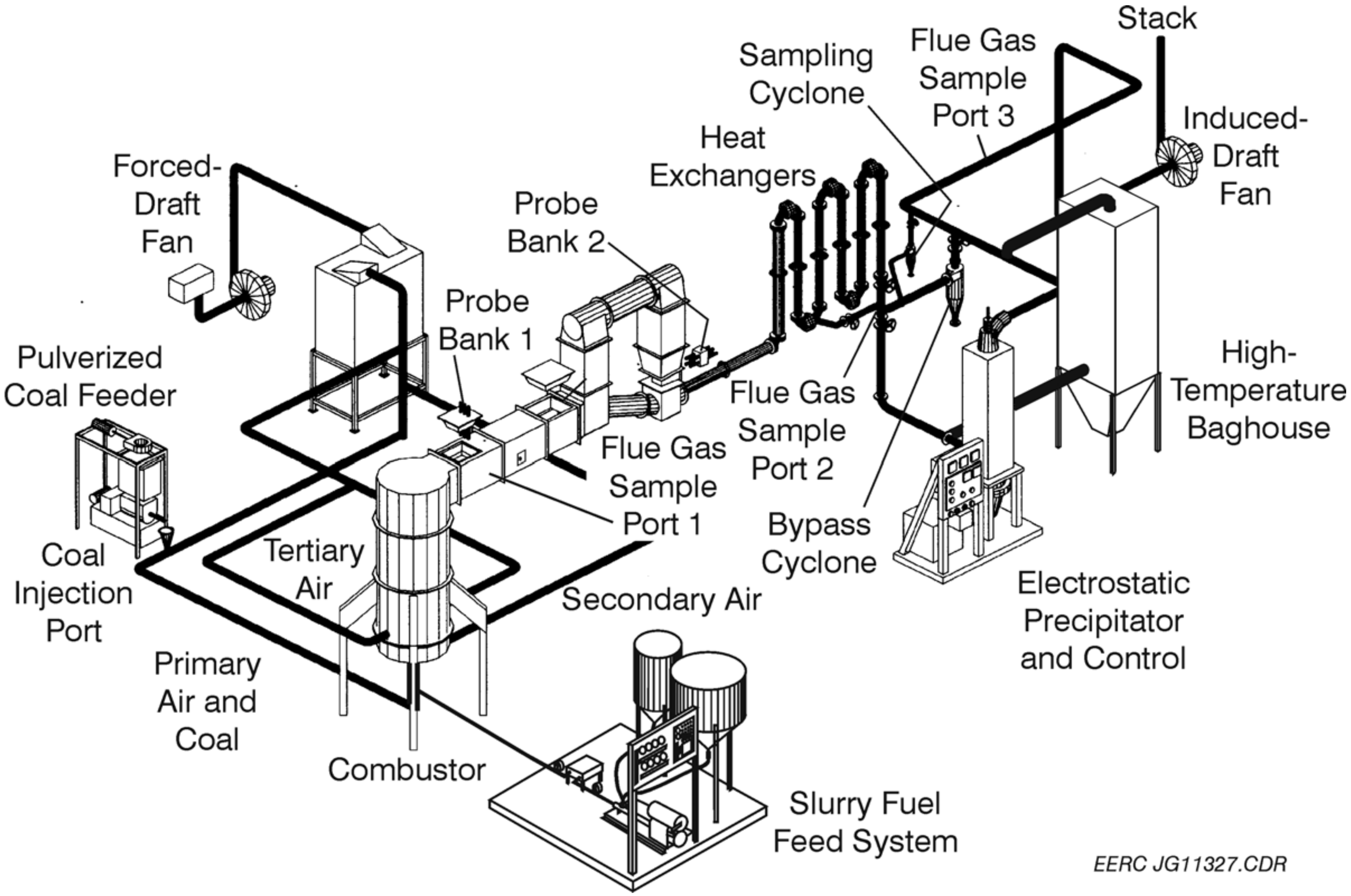
CTF (cont.)



EERC JG11327.CDR

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CTF (cont.)

- A 550,000-Btu/hr pulverized fuel pilot plant test furnace
- Furnace exit gas temperature as high as 2500°F
- Research applications:
  - Determine ash-fouling rates and the strength, composition, and structure of fouling deposits for coals of all rank.
  - Apply sophisticated analytical methods to characterize input coal, ash, and deposits.
  - Evaluate the combustion characteristics of coal–water fuels, biomass fuels, municipal solid waste, and petroleum coke.
  - Determine fly ash collection properties of various fuels by electrostatic precipitation or fabric filtration using a pulse-jet baghouse, including high-temperature applications.
  - Perform flame stability tests for comparing a particular fuel at full load and under turndown conditions.
  - Evaluate sorbent injection for SO_x and Hg control and assess integrated particulate and SO_x–NO_x control.
  - Furnace heat flux measurement

CTF (cont.)

- The CTF is fully instrumented for SO_x, NO_x, CO_2, CO, O_2, Hg, temperatures, pressures, and flow rates.
- Flue gas cleanup equipment:
  - SCR
  - CESP
  - HESP
  - Baghouse
  - Cyclone
  - SDA
  - WFGD

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Slagging Furnace System

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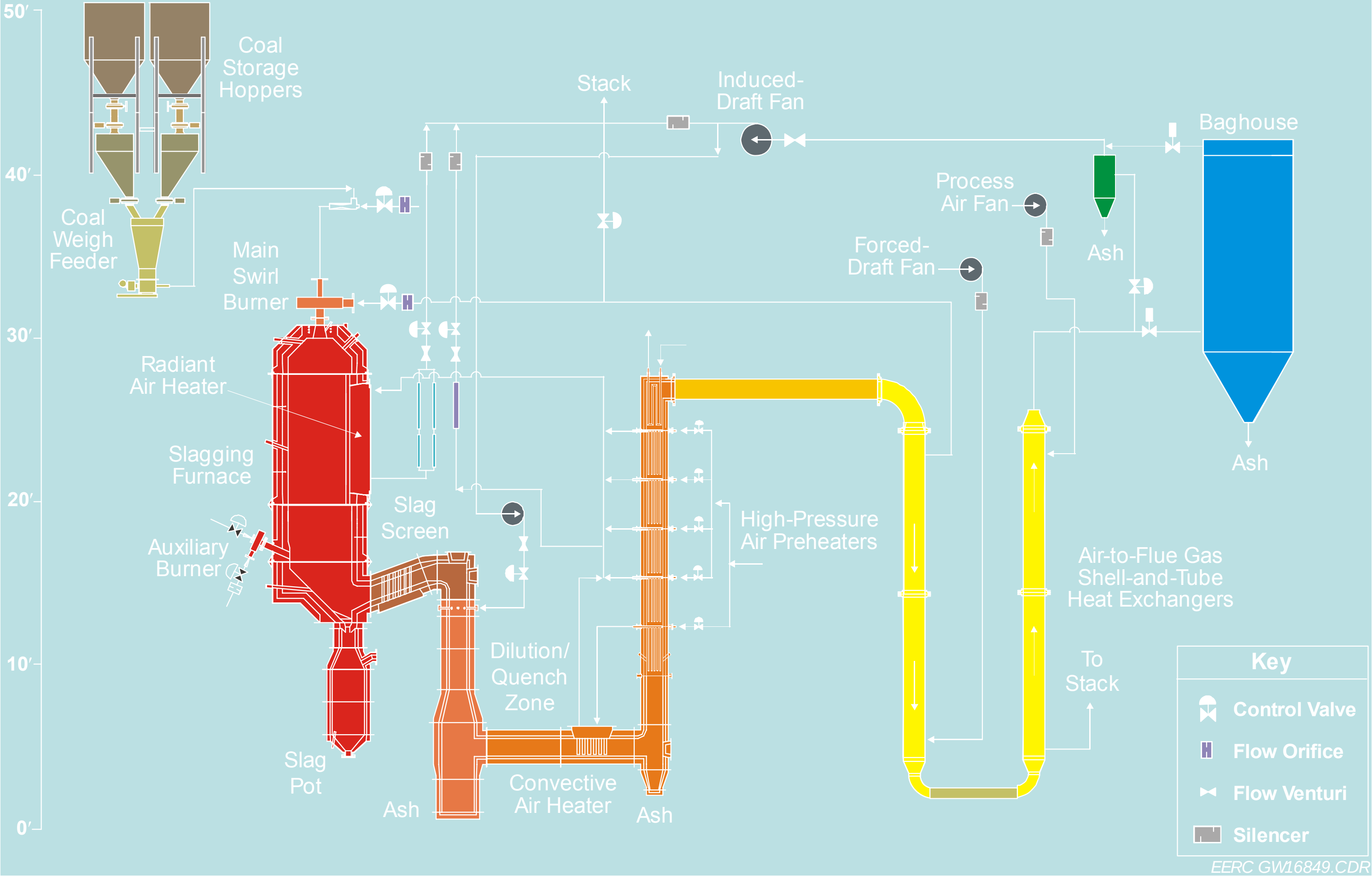
SFS (cont.)


50′
40′
30′
20′
10′
0′
Coal Storage Hoppers
Coal Weigh Feeder
Main Swirl Burner
Stack
Induced-Draft Fan
Baghouse
Process Air Fan
Forced-Draft Fan
Ash
Radiant Air Heater
Slagging Furnace
Auxiliary Burner
Slag Screen
High-Pressure Air Preheaters
Air-to-Flue Gas Shell-and-Tube Heat Exchangers
Ash
Dilution/ Quench Zone
To Stack
Slag Pot
Ash
Convective Air Heater
Ash
Key
Control Valve
Flow Orifice
Flow Venturi
Silencer
EERC GW16849.CDR

SFS (cont.)

- The SFS is a slagging design intended to be as fuel-flexible as possible.
- Maximum furnace exit temperature of 2900°F, but is typically run at 2800°F.
- The SFS has a nominal firing rate of 2.5 million Btu/hr and a range of 2.0 to 3.0 million Btu/hr using a single burner.
- Resulting flue gas flow rates range from roughly 425 to 640 scfm, with a nominal value of 530 scfm based on 20% excess air.

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SFS (cont.)

- Has been run in an oxygen-fired mode.
- Contains the necessary flue gas recycle loop.
- Flue gas cleanup equipment:
  - Baghouse
  - ESP
  - WFGD
  - Wet ESP

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Past Experience with Oxy-Firing

- SFS system operated in oxy-firing mode.
  - Flue gas recycle (20% primary, 80% secondary).
  - Automated oxygen injection system.
  - Oxygen levels up to 35% in secondary air.

Proposed Oxycombustion Work

- Determine proper scale for retrofit.
- Enhance current oxy-firing capability:
  - Flue gas recycle
  - Control systems
- Determine fouling/slagging issues associated with oxy-firing.
- Work with exotic metal alloys.

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Task 3: Initial Shakedown and Testing

John Kay

Initial Shakedown and Testing

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Initial Shakedown

- CO_2 postcombustion system, flue gas pretreatment/conditioning system, and oxy-fired retrofits
  - Develop proper start-up and shutdown procedures
  - Operational parameters verified and optimization of systems
    - Temperatures, pressures, flow rates, etc.
- Expected shakedown length of 1–2 weeks

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Baseline Testing – CO_2 Postcombustion System

- MEA
- Intended as standard for comparison
  - Determine regeneration energy required
  - Solvent degradation
  - Effects of flue gas constituents (SO_x, NO_x, Hg, particulate)
  - System optimization
  - CO_2 capture rate and purity
  - Energy penalty
- Utilize flue gas pretreatment/conditioning system
  - Vary the concentrations of SO_x, NO_x and other gas constituents to determine their effects
- Baseline testing of 1–2 weeks

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Baseline Testing – Oxy-Fired

- CTF
- SFS
- Baseline will be used to identify potential challenges:
  - Flame stability
  - Heat-transfer issues
  - Fouling and slagging
  - Effects of Hg capture
- Baseline testing of 1–2 weeks

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Beyond Baseline

- Develop detailed test plan
  - Content finalized by input from DOE and cost-share partners
- Possible technologies – postcombustion
  - MDEA
  - Ammonia
  - Tailored amines
  - Potassium bicarbonate
  - Other

Beyond Baseline – Oxy-Fired

- Additional parameters
  - Effects on Hg control
  - Fabric filter performance
  - ESP performance
  - WFGD performance
  - SDA performance
  - SCR performance
  - Other

Beyond Baseline – Small-Scale Slipstreams

- Carbozyme
- Solid sorbents (Zeolytes, MOFs, solid amines)
- Other membranes
- Other

- Test parameters
  - Determined on a technology basis
  - CO_2 capture rates and CO_2 purity
  - Energy penalty
  - Technology robustness
  - Other

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Potential Fuel Types

- Biomass
- Lignite
- Subbituminous
- Bituminous
- Petcoke
- Blends
- Fuels chosen by input from DOE and cost-share partners

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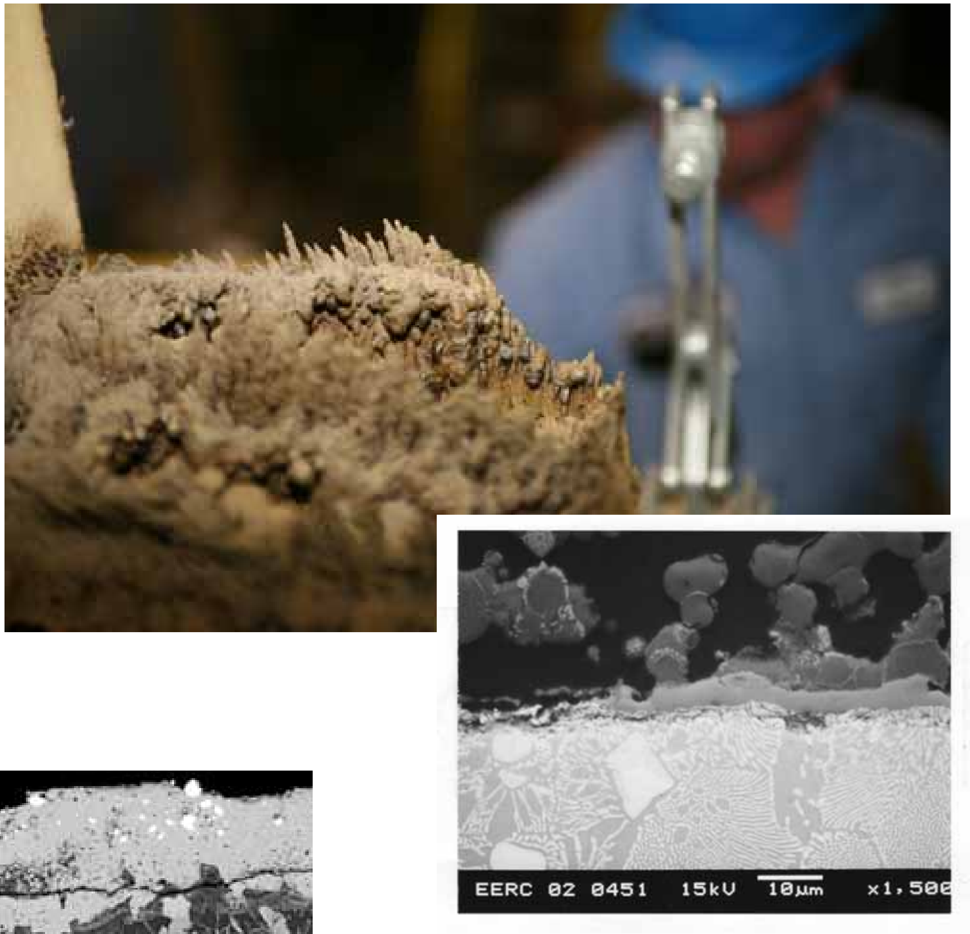
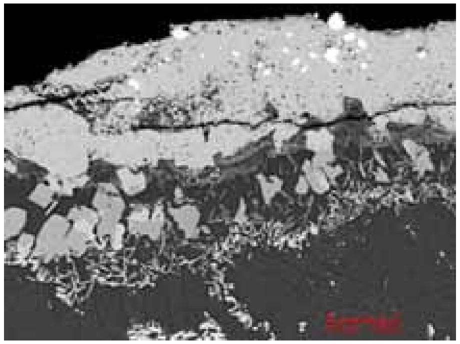
Analytical Toolbox

The EERC has more than 50 years of analytical experience.

Analytical tools provide key information in the characterization of fuels, deposits, slags, ashes, alloy corrosion, and mechanical components.

Advanced techniques provide that information quickly.





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Advanced Analysis

- Scanning electron microscopy and x-ray microanalysis
  - Coal mineral typing and sizing
  - Ash deposits and slag
  - Morphological examination
- Electron backscattered diffraction
  - Crystalline phases and composition
- Heated-stage x-ray diffraction
  - Changes of crystalline phases with time and/or temperature

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Scanning Electron Microscopy

- Morphological analysis
- Fuel impurity analysis— size, shape, and chemistry of several thousands of particles per sample.
- Slag and ash deposit liquid-phase identification and physical properties.
- X-ray elemental mapping.

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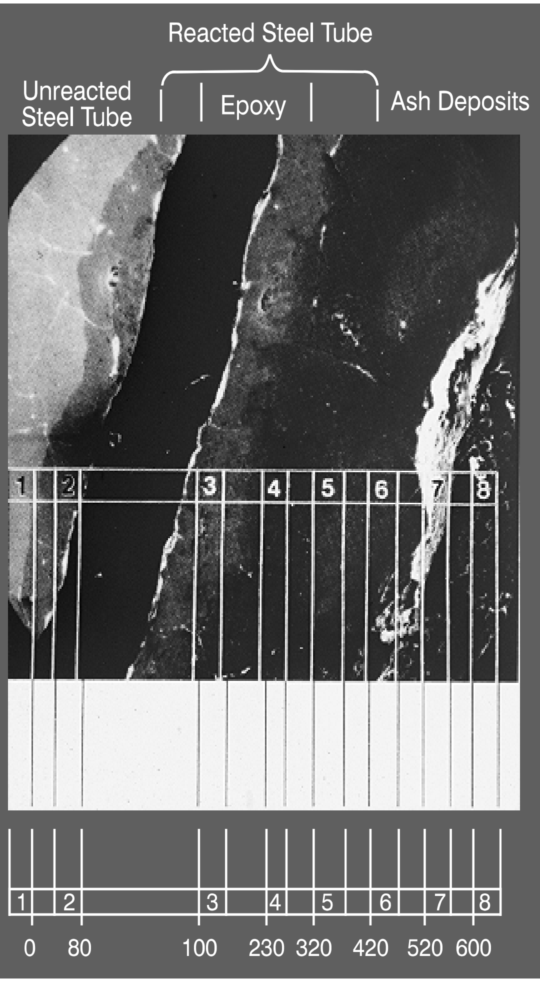
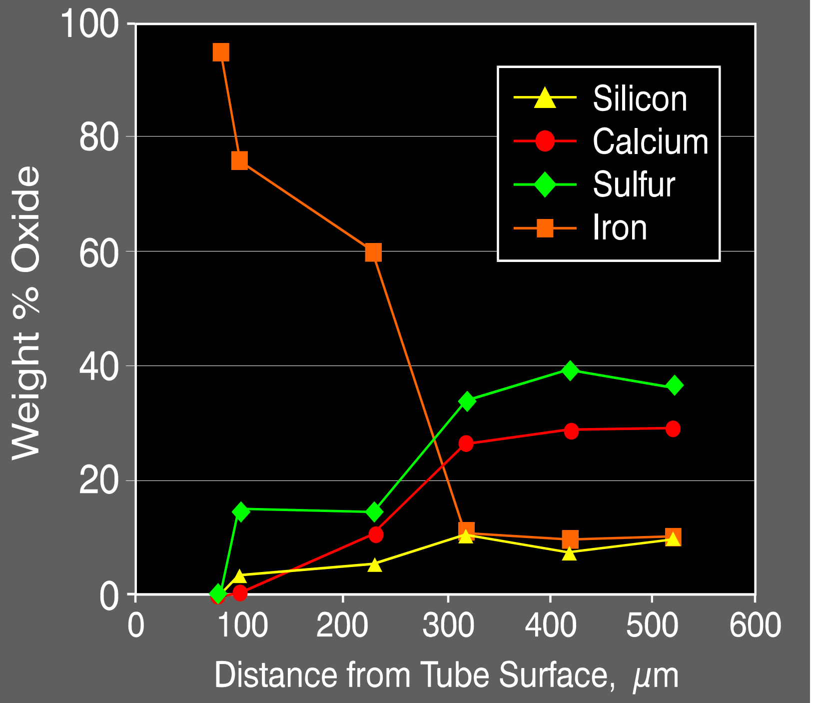
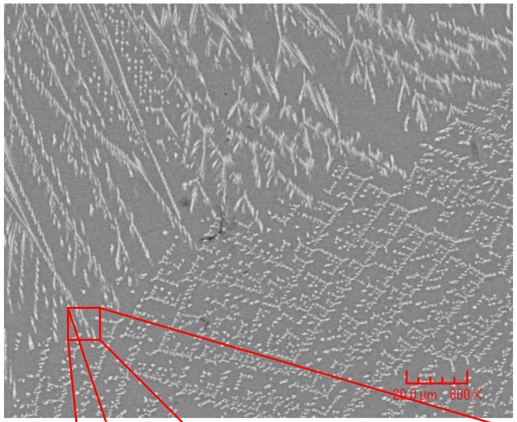
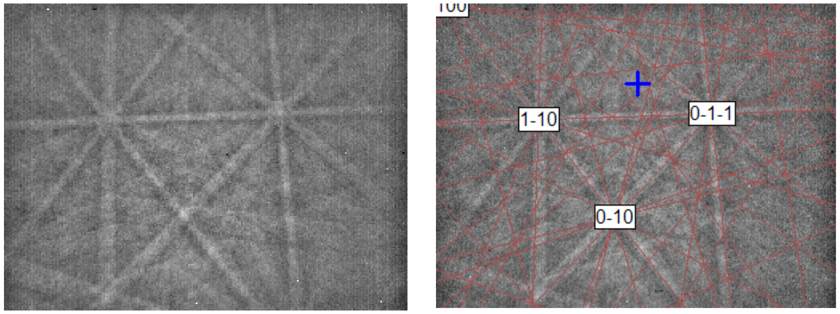
Relationship Between Corrosion and Deposit Adhesion

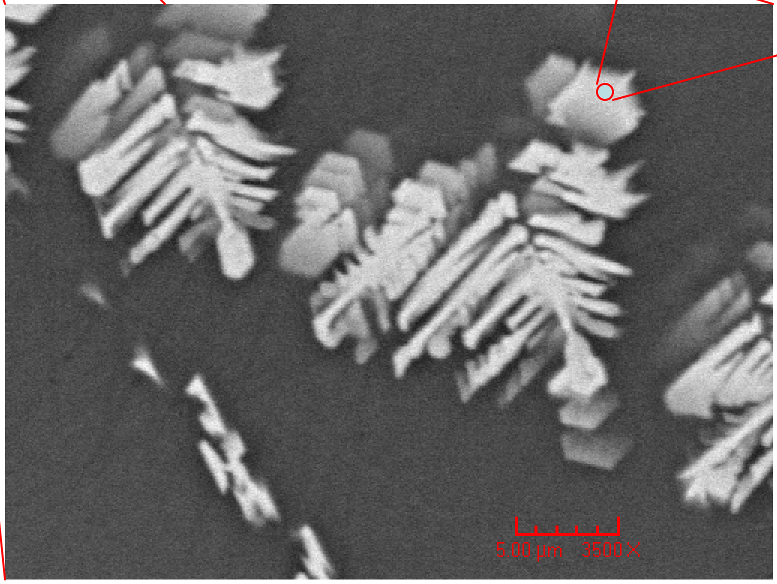




Electron Backscattered Diffraction (EBSD)

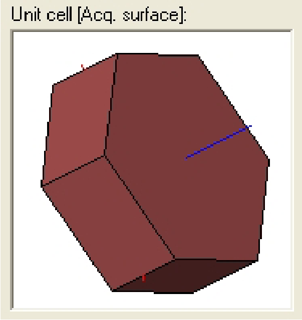




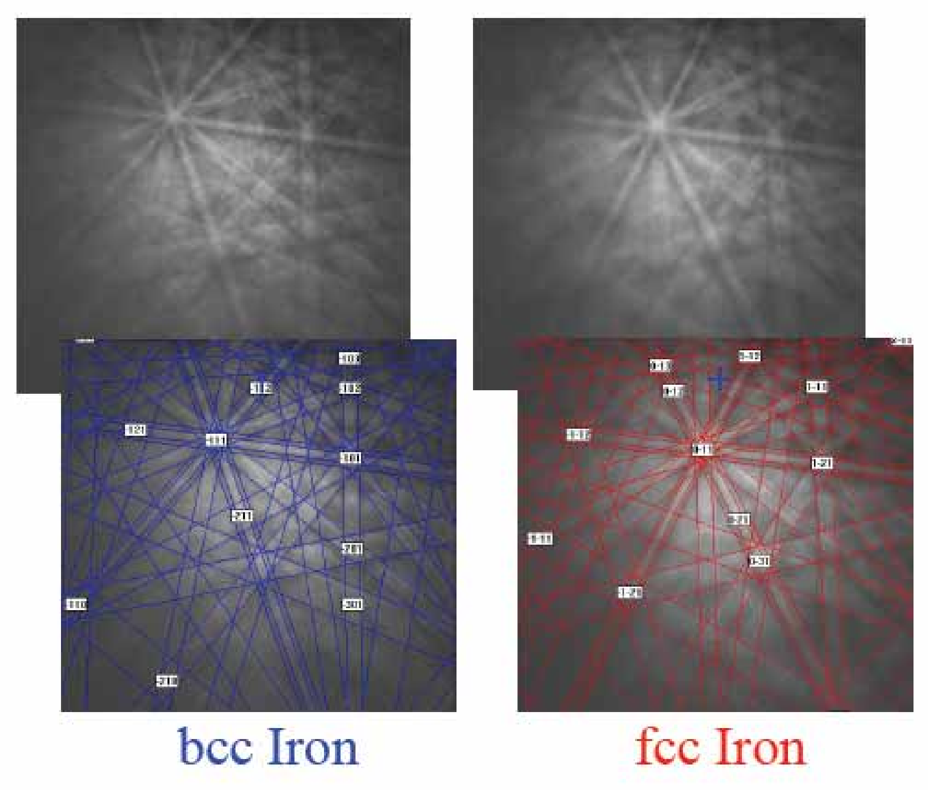


Identified Crystalline Phase:

Fe_5Si_3



Phase Discrimination



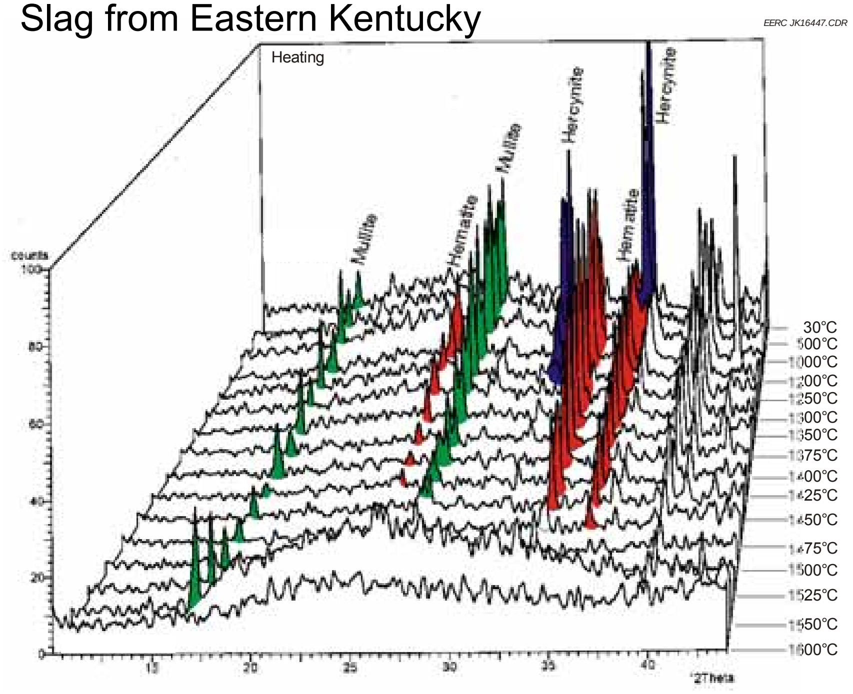
bcc Iron

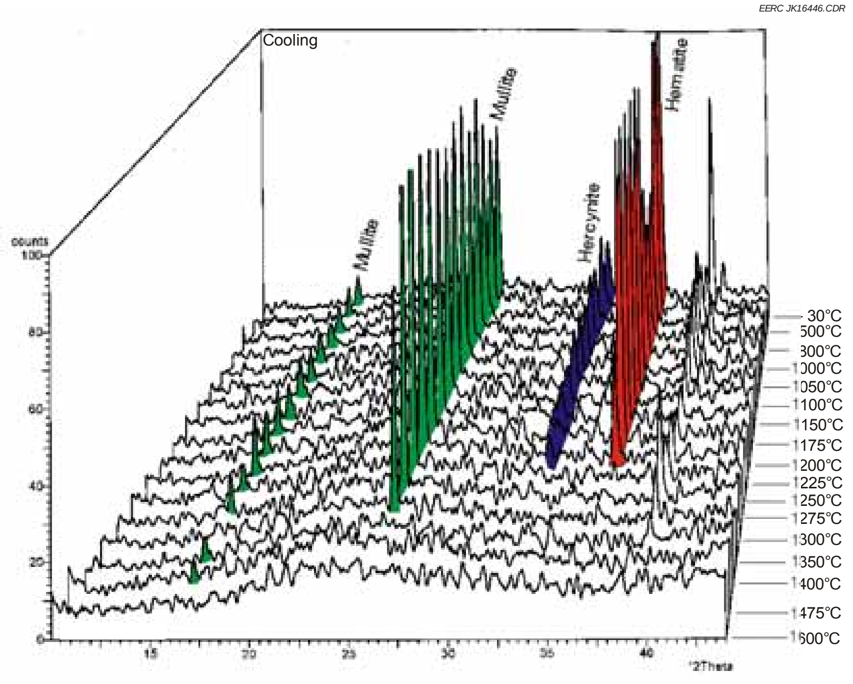
fcc Iron

Differences in interplanar angles allow similar EBSD patterns to be discriminately identified.

X-Ray Diffraction of Slags

Slag from Eastern Kentucky





Differences in crystallization can be detected and identified.

Summary of Task 3

- Shakedown and baseline testing of post-CO_2 combustion, flue gas pretreatment/conditioning system, and oxy-fired retrofits.
- Additional testing based on sponsor input.
- Utilization of EERC analytical experience and toolbox to provide vital information on fuel characterization, ash and deposit analysis, corrosion, and slagging/fouling mechanisms.

Task 4: Systems Engineering Studies

Josh Stanislowski

Systems Engineering Studies Overview

- Task 4 will utilize Aspen Plus process-modeling software to aid in design and evaluation of CO_2 capture systems.
  - Aspen Plus will be the design tool for pilot-scale equipment additions and upgrades in Tasks 1 and 2.
  - Develop postcombustion CO_2 capture models (retrofit technologies).
  - Gasification modeling with and without CO_2 capture (precombustion).
  - Economic studies and comparisons of CO_2 capture technologies.

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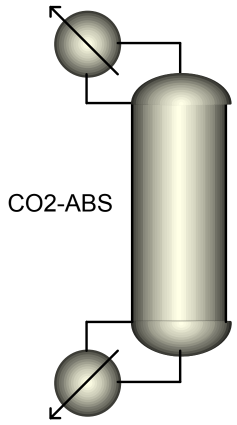
Systems Engineering with Aspen Plus®

- Aspen Plus® is a very versatile model for gasification systems engineering:
  - Heat and energy balances
  - Equipment sizing
  - Solids-handling capabilities
  - Accepts proximate–ultimate analysis to determine coal properties
  - Models for coal ash properties
  - Fluegas/syngas composition predictions
  - Particle-size modeling
  - Absorber-stripper modeling capabilities
  - NIST Chemical Properties Database



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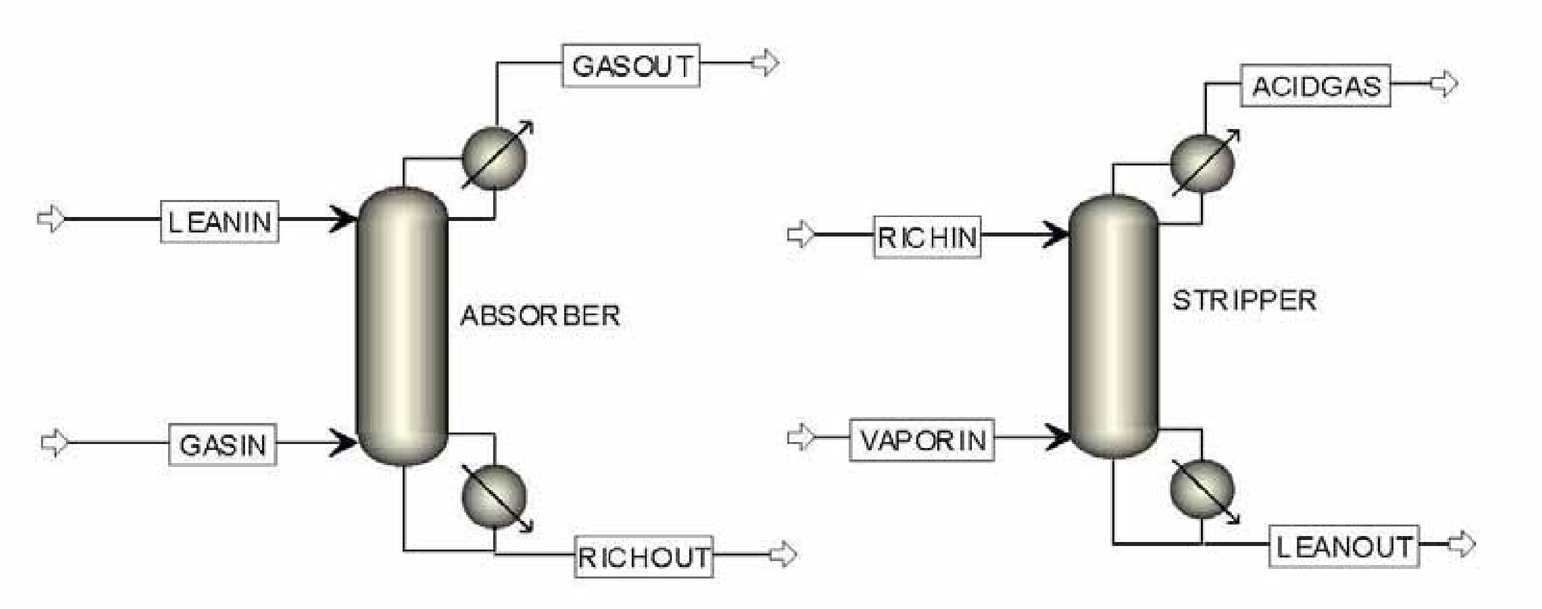
Aspen-Based CO_2 Capture Model



- Base model for various absorption and stripping column designs.
- Model details are contained within the modules:
  - Kinetics
  - Mass transfer
  - Chemical reaction and phase equilibrium
- User-specified models can be incorporated.

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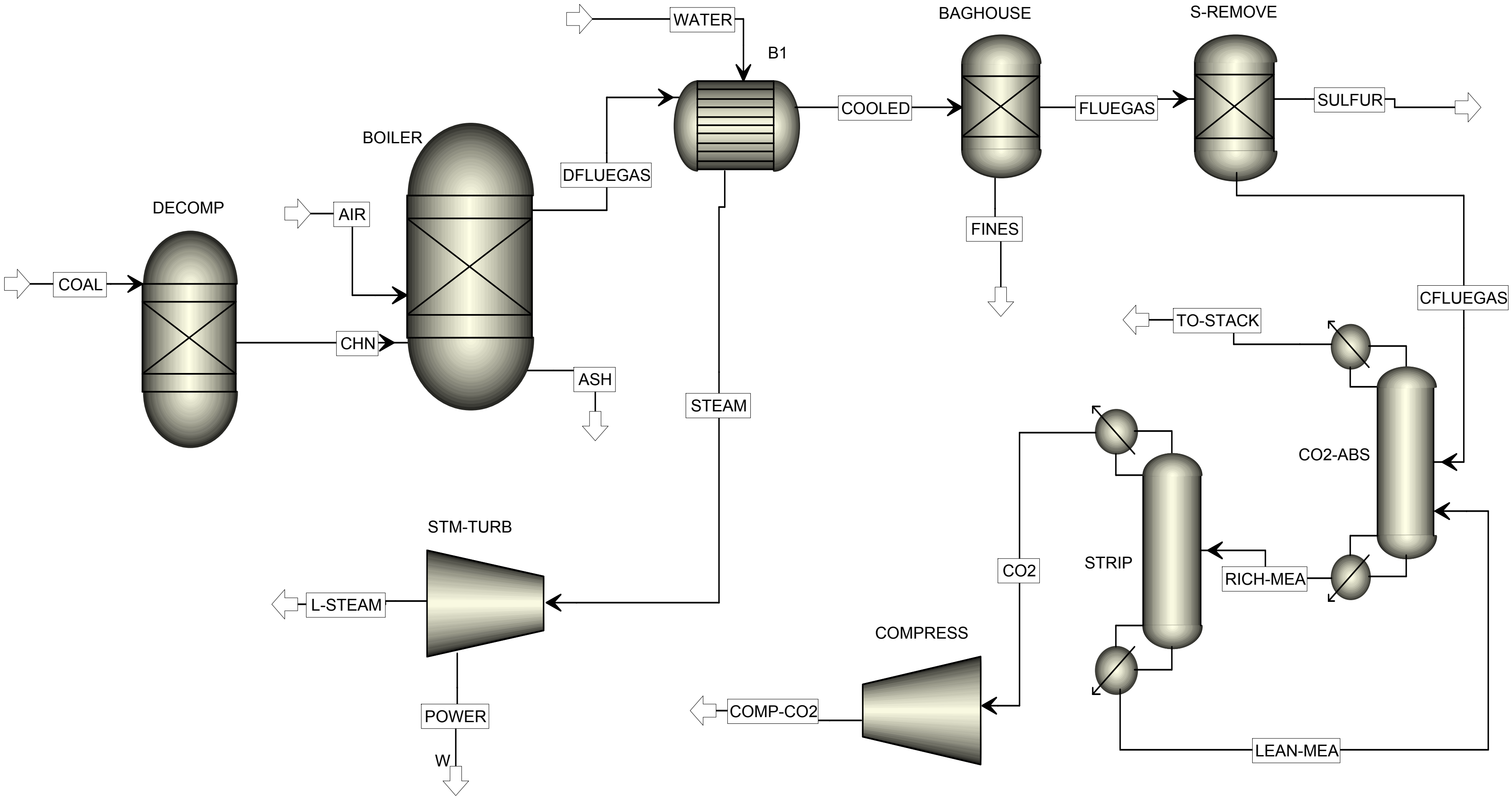
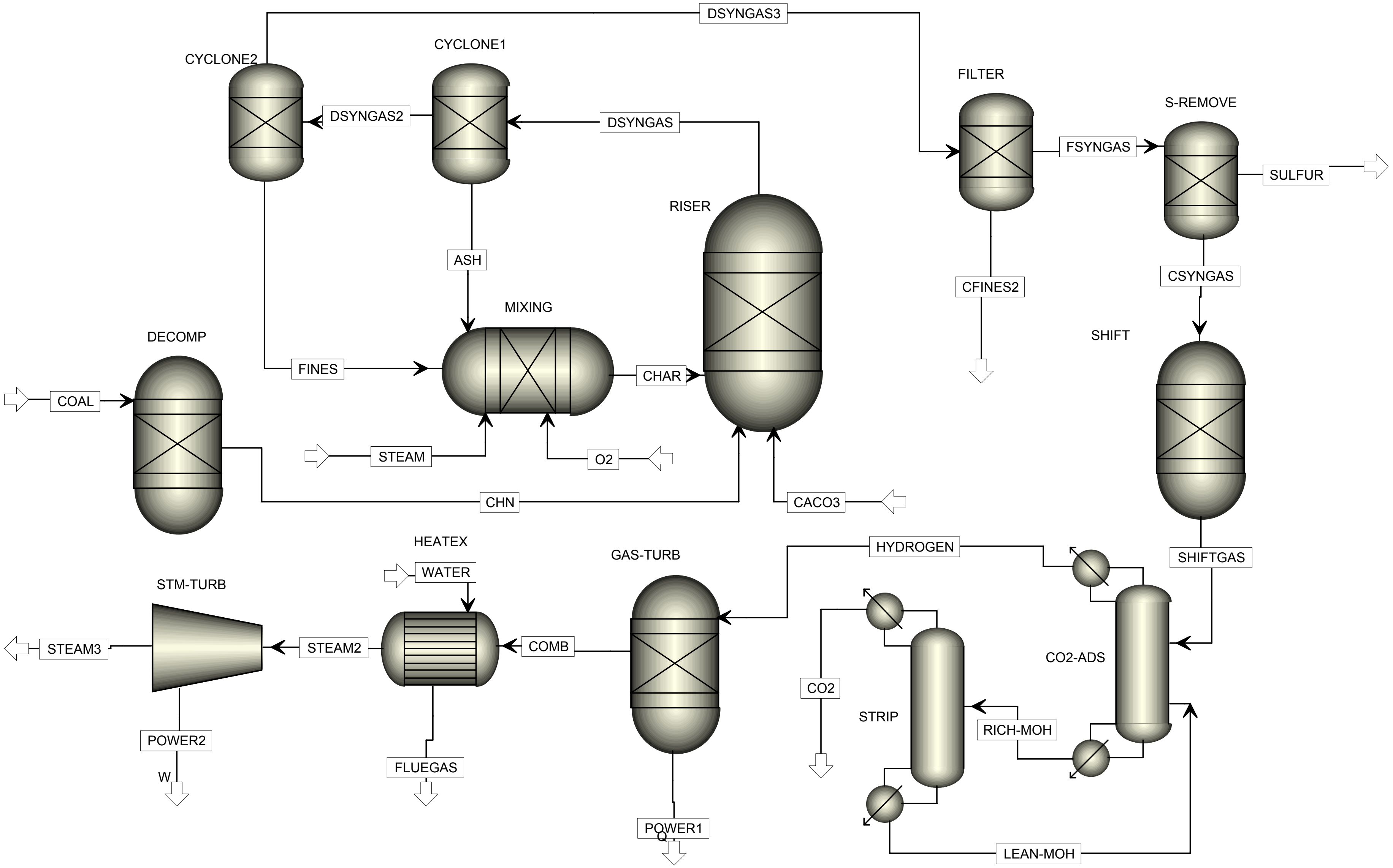
Postcombustion CO_2 Capture Model



Precombustion CO_2 Capture



Aspen Modeling Results Sample

		BIOMASS	C-FINES	CHN	DSYNGAS	DSYNGAS2	DSYNGAS3	O2	QSYNGAS	QSYNGAS2	SLAG	STEAM	WATER-Q	
From			CYCLONE	DECOMP	RGIBBS	SLAGTAP	CYCLONE		QUENCH	QUENCHE	SLAGTAP			
To		DECOMP		RGIBBS	QUENCH	CYCLONE		RGIBBS	QUENCHE	SLAGTAP		RGIBBS	QUENCH	
Substream: ALL														
Mass Flow	LB/HR	100	0.36	100	165.7	220.82	220.47	45.7	229.82	229.82	9	20	64.12	
Mass Enth	BTU/HR	-615601	169.68	-63755.11	-248945.8	-788214.7	-788384.3	-237.93	-688885.7	-788798.7	-584.09	-107770.9	-439939.9	
Substream: MIXED														
Phase:		Missing	Missing	Mixed	Vapor	Vapor	Vapor	Vapor	Vapor	Vapor	Missing	Vapor	Liquid	
Component Mole Flow														
H2O	LBMOL/HR	0	0	0.56	1.68	4.26	4.26	0	5.24	4.26	0	1.11	3.56	
N2	LBMOL/HR	0	0	0.16	0.16	0.16	0.16	0	0.16	0.16	0	0	0	
O2	LBMOL/HR	0	0	0.76	0	0	0	1.43	0	0	0	0	0	
S	LBMOL/HR	0	0	0.08	0	0	0	0	0	0	0	0	0	
NH3	LBMOL/HR	0	0	0	0	0	0	0	0	0	0	0	0	
C	LBMOL/HR	0	0	0	0	0	0	0	0	0	0	0	0	
H2	LBMOL/HR	0	0	2.23	2.14	1.58	1.58	0	2.14	1.58	0	0	0	
CO	LBMOL/HR	0	0	0	3.05	0.56	0.56	0	3.05	0.56	0	0	0	
CO2	LBMOL/HR	0	0	0	0.65	2.39	2.39	0	0.65	2.39	0	0	0	
COS	LBMOL/HR	0	0	0	0.01	0	0	0	0.01	0	0	0	0	
CH4	LBMOL/HR	0	0	0	0	0.76	0.76	0	0	0.76	0	0	0	
CL2	LBMOL/HR	0	0	0	0	0	0	0	0	0	0	0	0	
H2S	LBMOL/HR	0	0	0	0.08	0.08	0.08	0	0.08	0.08	0	0	0	
Component Mole Fraction														
H2O		0	0	0.15	0.22	0.43	0.43	0	0.46	0.43	0	1	1	
N2		0	0	0.04	0.02	0.02	0.02	0	0.01	0.02	0	0	0	
O2		0	0	0.2	0	0	0	1	0	0	0	0	0	
S		0	0	0.02	0	0	0	0	0	0	0	0	0	
NH3		0	0	0	0	0	0	0	0	0	0	0	0	
C		0	0	0	0	0	0	0	0	0	0	0	0	
H2		0	0	0.59	0.28	0.16	0.16	0	0.19	0.16	0	0	0	
CO		0	0	0	0.39	0.06	0.06	0	0.27	0.06	0	0	0	
CO2		0	0	0	0.08	0.24	0.24	0	0.06	0.24	0	0	0	
COS		0	0	0	0	0	0	0	0	0	0	0	0	
CH4		0	0	0	0	0.08	0.08	0	0	0.08	0	0	0	
CL2		0	0	0	0	0	0	0	0	0	0	0	0	
H2S		0	0	0	0.01	0.01	0.01	0	0.01	0.01	0	0	0	

Postcombustion Models – Calibration and Validation

- Performance data from Task 3 will be used to calibrate and validate the Aspen capture models.
  - Combine existing Aspen CO_2 capture models and pilot-scale data to build upon and improve capture models.
  - Run modeling scenarios and provide results to consortium.
  - Use models as a scale-up tool from pilot- to full-scale systems.
  - Evaluate other variables not tested including other feedstocks and boiler operating conditions.
  - Models can be tuned to closely simulate input flue gas conditions.

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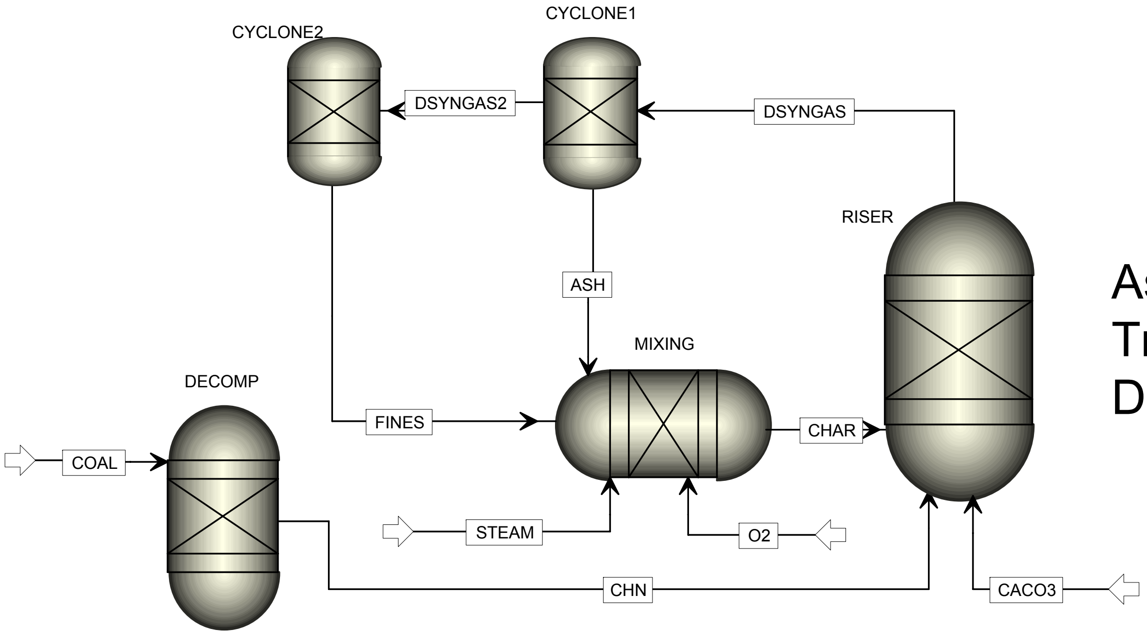
Gasification Studies

- Task 4 will evaluate CO_2 capture technologies with gasification systems.
- Data will be used to compare cost and performance to combustion systems.



Aspen Representation of Transport Reactor Development Unit (TRDU)

Economic Analysis

- Aspen Icarus Process Evaluator (IPE)
  - Vast database of costing information that is updated on a regular basis by receiving updates from Aspentech.
  - Costing information is customizable.
  - NETL CO_2 capture economic guidelines will be used to enhance comparability.
- QA/QC
  - The results obtained from IPE will be compared to current literature and to other models, where applicable, including the Integrated Environmental Control Model (IECM).

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Task 5: Deliverables, Schedule, and Management

Brandon Pavlish

Management and Reporting

- The project team will work in close cooperation with the project steering group, which will include the committed project sponsors and the U.S. Department of Energy.
- Regular updates of the overall project progress and results will be provided through quarterly and annual reports to the sponsors.
- Project information of a proprietary nature will be conveyed to the individual sponsors separately.
- A detailed final report that will include the following:
  - Results from testing the CO_2 capture system
  - Results from testing the pre-gas cleanup system
  - Results of testing the oxyfuel system retrofit
  - Advanced model simulations
  - CO_2 capture feasibility studies
  - CO_2 capture economic sensitivity analysis

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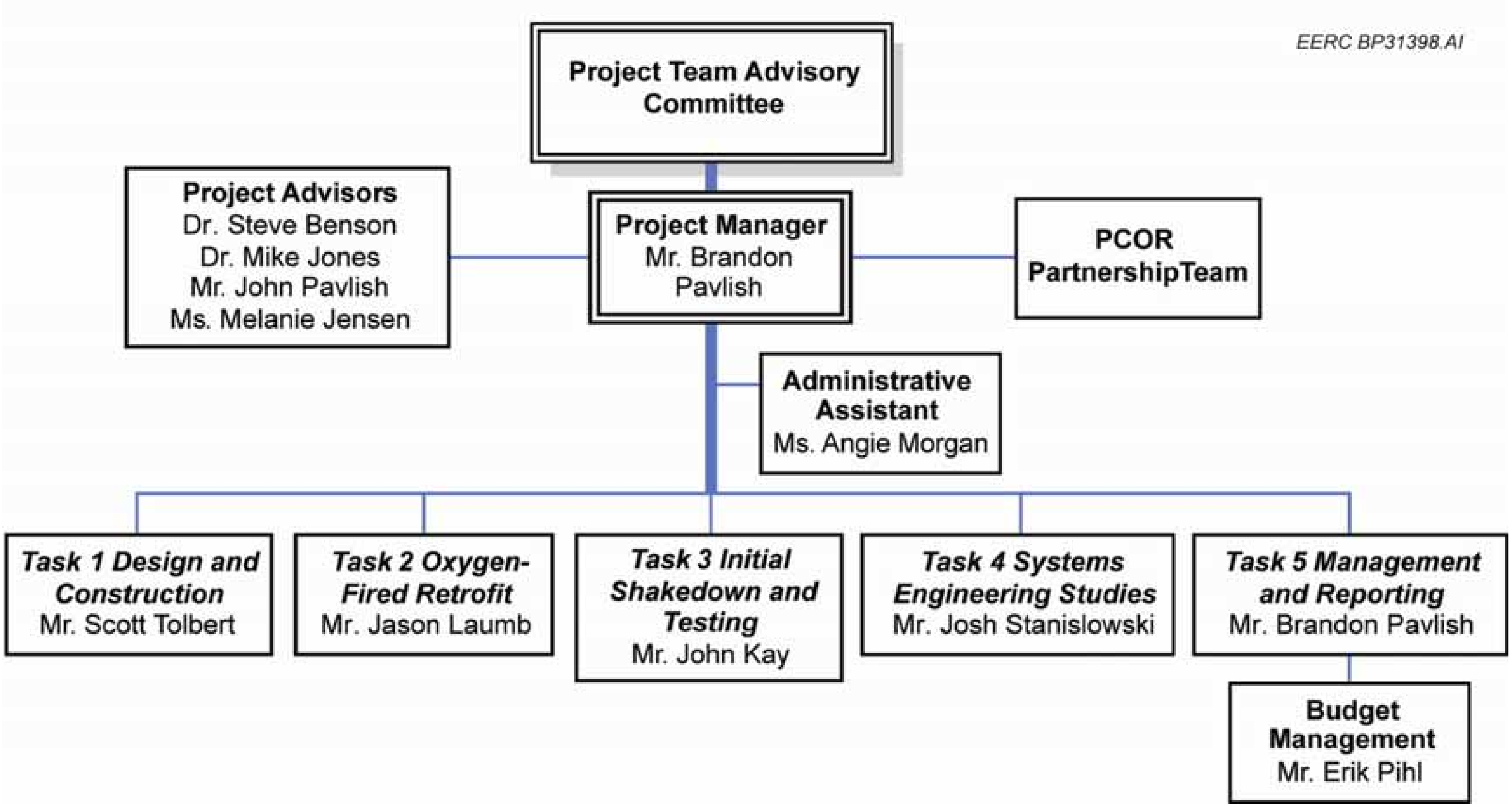
Management Structure



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Project Team Advisory Committee

Project Advisors
Dr. Steve Benson
Dr. Mike Jones
Mr. John Pavlish
Ms. Melanie Jensen

Project Manager
Mr. Brandon Pavlish

PCOR PartnershipTeam

Administrative Assistant
Ms. Angie Morgan

Task 1 Design and Construction
Mr. Scott Tolbert

Task 2 Oxygen-Fired Retrofit
Mr. Jason Laumb

Task 3 Initial Shakedown and Testing
Mr. John Kay

Task 4 Systems Engineering Studies
Mr. Josh Stanislowski

Task 5 Management and Reporting
Mr. Brandon Pavlish

Budget Management
Mr. Erik Pihl

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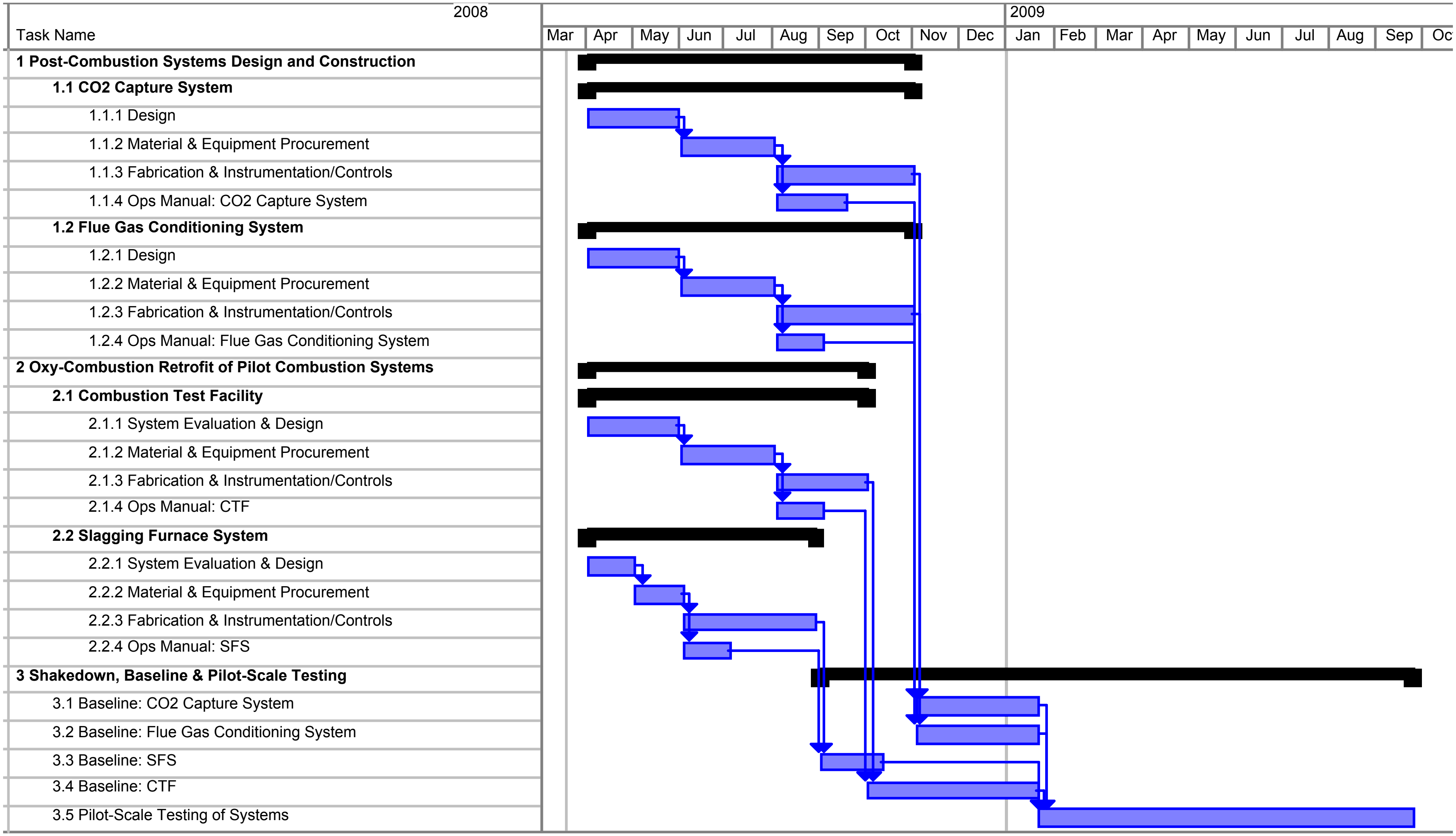
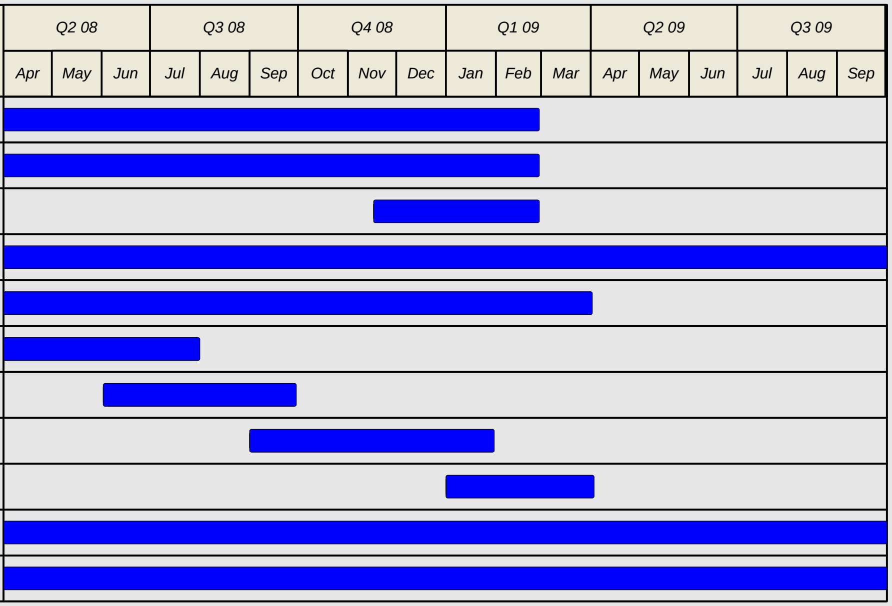
Schedule



Task Name
1 Post-Combustion Systems Design and Construction
1.1 CO2 Capture System
1.1.1 Design
1.1.2 Material & Equipment Procurement
1.1.3 Fabrication & Instrumentation/Controls
1.1.4 Ops Manual: CO2 Capture System
1.2 Flue Gas Conditioning System
1.2.1 Design
1.2.2 Material & Equipment Procurement
1.2.3 Fabrication & Instrumentation/Controls
1.2.4 Ops Manual: Flue Gas Conditioning System
2 Oxy-Combustion Retrofit of Pilot Combustion Systems
2.1 Combustion Test Facility
2.1.1 System Evaluation & Design
2.1.2 Material & Equipment Procurement
2.1.3 Fabrication & Instrumentation/Controls
2.1.4 Ops Manual: CTF
2.2 Slagging Furnace System
2.2.1 System Evaluation & Design
2.2.2 Material & Equipment Procurement
2.2.3 Fabrication & Instrumentation/Controls
2.2.4 Ops Manual: SFS
3 Shakedown, Baseline & Pilot-Scale Testing
3.1 Baseline: CO2 Capture System
3.2 Baseline: Flue Gas Conditioning System
3.3 Baseline: SFS
3.4 Baseline: CTF
3.5 Pilot-Scale Testing of Systems

Schedule (cont.)

ID	Task Name	Start	Finish	Duration
1	**Task 4 – Systems Engineering Studies**	4/1/2008	2/27/2009	239d
2	***Sub-Task 4.1 Modeling of CO2 Capture Systems***	4/1/2008	2/27/2009	239d
3	***Sub-Task 4.2 Economic Evaluation of CO2 Capture Systems***	11/17/2008	2/27/2009	75d
4	**Task 6 Reporting**	4/1/2008	10/1/2009	393d
5	***Sub-Task 6.1 Quarterly Reports***	4/1/2008	4/1/2009	262d
6	*6.1.1 DOE Quarterly*	4/1/2008	7/31/2008	88d
7	*6.1.2 DOE Quarterly*	6/2/2008	9/29/2008	86d
8	*6.1.3 DOE Quarterly*	9/1/2008	1/30/2009	110d
9	*6.1.4 DOE Quarterly*	1/1/2009	4/2/2009	66d
10	***Sub-Task 6.2 Final Report DOE***	4/1/2008	10/1/2009	393d
11	***Sub-Task 6.3 Final Report Industrial***	4/1/2008	10/1/2009	393d



Benefits of Sponsorship

- Membership on the project's Advisory Committee.
- Information on mechanisms of CO_2 capture and interactions with fly ash and flue gas components.
- Detailed fuel characterization information.
- Results of CO_2 emissions and capture potential for various capture technologies.
- Performance and cost data for various CO_2 capture technologies to assist in developing an overall capture strategy. Data available will be directly applicable to coals and plants that are part of this project.

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Benefits of Sponsorship (cont.)

- Collaborative research between stakeholders with an interest in developing cost-effective CO_2 capture technologies.
- Cost-effective research at a fraction of the cost available to a single company.
- Effective transfer of information and data through consultation with EERC staff and sponsor personnel.
- Interaction with other sponsors and with personnel interested in CO_2 capture problems and potential solutions.

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Test Plan Development

- Questionnaire
  - Fuel types
  - Capture technologies
  - Critical test parameters
  - Unit configurations
  - Modeling efforts

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Questionnaire

- Task 1: Postcombustion Test Systems
  - Design considerations
    - Scale
    - Temperature capabilities
    - Parameters of importance
    - Measurement capabilities
- Task 2: Oxygen-Fired Retrofit(s)
  - Design considerations
    - Scale
    - Measurement capabilities
    - Others

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Questionnaire (cont.)

- Task 3: Initial Shakedown and Testing
  - Fuel types
  - Capture technologies
  - Parameters of interest
  - Suggested tests to consider
  - Others
- Task 4: Systems Engineering Studies
  - Systems to model
  - Parameters of interest
  - Others

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Questionnaire (cont.)

- Task 5: Management and Reporting
  - Meeting(s)/conference calls to discuss work plans, results, accomplishments, and directions:
    - Frequency
      - Every 6 months
      - Every 3 months
      - Every other month
      - Other
    - Location – preference
      - EERC for all meetings
      - EERC once per year of project and off-site at sponsors' suggested location

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Contact Information

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