Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers

John L. Marion
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers

presented at
28th International Technical Conference on Coal Utilization & Fuel Science
March 10-13, 2003
Clearwater, FL

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ALSTOM Power Inc.
&
Scott Klara
DOE National Energy Technology Laboratory
Outline of Talk

- CO2 Mitigation from Fossil Power
- Oxy-fuel firing strategy
- Oxy-fuel fired CFB
- Study Cases
- Testing results
- next steps

Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers
Technology Response: CO₂ Mitigation Options - for Power

- Conservation
- Increase efficiency  
  [ of fossil fuel energy conversion ]
- Fuel Switch  
  - nuclear
  - renewables
  - natural gas
- CO₂ Sequestration  
  - Capture
  - Sequestration

Needed in the long run if we continue to use fossil fuels and commit to CO₂ emissions stabilization
Technology Response: CO₂ Capture Approaches-for Power

- Post Capture
  - Adsorption
  - Absorption
- Oxy-fuel Firing
  - external oxygen supply
  - integrated membrane-based
  - oxygen carriers
- Decarbonization
  - reforming (fuel decarbonization)
  - carbonate reactions (combustion decarbonization)

Innovative technology options just now emerging
CO₂ Capture by Oxy-fuel Combustion

Coal Combustion in O₂/Recycled Flue Gas (with High CO₂ Concentration) without CO₂ Separation

Air → [Air Separation Unit (ASU)] → [O₂] → [Boiler] → [Condenser] → [Compressor]

- Fuel
- H₂O

CO₂ Recycle

CO₂ Sequestration or Use
CO$_2$ Capture by Oxy-fuel Combustion

COMPLICATIONS!!

- **Air Separation Unit (ASU)**
  - Air in-leakage
  - 9000 ton/day O$_2$
  - 96 Mwe (21% gen. Output)

- **Boiler**
  - CO$_2$ Recycle
  - O$_2$, N$_2$
  - Fuel

- **Condenser**
  - H$_2$O

- **Compressor**
  - 2000 psi CO$_2$
  - 97.8%
  - 1.2% N$_2$
  - 215 ppm SO$_2$
  - 0.93% O$_2$
Oxygen Fired CFB

Fuel Flexible

- PET Coke
- Coal
- Biomass

Circulating Fluidized Bed Boiler

- 1,550 °F (850 °C)

Recirculation

Emissions Control

Recycled cooled solids in CFB control combustor temperature

Future - O2 Membranes
“Greenhouse Gas Emissions Control By Oxygen Firing in Circulating Fluid Bed (CFB) Boilers”

Study of nine (9) alternate novel CO2 capture from combustion systems technologies and comparison to three (3) IGCC cases - coal and petcoke fired

US DOE cofunded

ALSTOM Power
Parsons (A/E)
ABB Lummus
Praxair
Plasma
Project Objectives

To determine if carbon dioxide can be recovered at an avoided cost of $10/ton (or less) of carbon avoided, using a newly constructed coal fired plants

- Performance and economic analyses of an existing design 210-MWe air-fired CFB plant to provide Base Case information

- Design an O₂-fired CFB, for the same steam cycle parameters as Base Case CFB, and carry out performance and economic analyses

- Design several other advanced “CFB-based” and novel CO₂ capture plants for the same steam cycle parameters and carry out performance and economic analyses.

- Performance and economic analyses of IGCC cases for comparison (with and without CO₂ capture). These cases will be based upon prior DOE and Parsons study, but will be modified to allow comparison with the Base Case including similar thermal fuel input

- Bench and Pilot Testing of Promising Case(s)
Cases Studied: All ~ 210 MWe Gross

**Case 1: Base Case Circulating Fluid Bed (CFB) Boiler**
Conventional Air-Fired CFB without CO₂ Capture.
Provides Reference Point for Performance & Economic Analyses of Cases 2-7

**Case 2: New Compact O₂-Fired CFB with CO₂ Capture, Purification, Compression and Liquefaction**
Same Thermal Input But Smaller Boiler Island than Case 1. Oxygen Is from a Cryogenic ASU Plant. CFB Plant Provides Concentrated CO₂ Flue Gas.
**Implication:** Cost Savings on Boiler Island and On CO₂ Processing Equipment

**Case 3: New Compact O₂-Fired CFB with Flue Gas Compression and Liquefaction**
Same as Case 2, But Without CO₂ Purification. Flue Gas Compression and Liquefaction for Sequestration Only.
**Implication:** Gas Processing System Cost Reduction from Case 2
Case 4: **O₂-Fired Circulating Moving Bed (CMB) with CO₂ Purification, Compression and Liquefaction**
Same as Case 2, But Uses Advanced Boiler Design Concepts.
**Implication:** Further Boiler Cost Savings Compared to Case 2

Case 5: **Air-Fired CMB with High Temperature Regenerative Carbonate Process**
Air-Firing and Carbonate Regeneration at Higher Temperatures Than Steam Cycle Temperatures:
**Implication:** Advanced Novel Concept Eliminates Energy Penalty for CO₂ Capture

Case 6: **Case 2 or 4, Integrated with Oxygen Transport Membrane (OTM)**
OTM is a More Efficient Method for O₂ Production Than Conventional Cryogenic ASU
As Was the Case with Cases 2 & 4.
**Implication:** Potential Reduction of Energy Penalty by About One-third.

Case 7: **Indirect Combustion of Coal via Chemical Looping**
Utilizes a Solid Oxygen-Carrier (e.g., Fe₂O₃), Which Oxidizes the Fuel Into H₂O and CO₂,
Condensing H₂O Then Yields a Virtually Pure CO₂ Stream

Cases Studied: All ~ 210 MWe Gross
Cases Studied - these 250 MW gross

**Case 8: Present Day Integrated Gasification Combined Cycle (IGCC)**
Conventional Operating IGCC (Single Train F-Class Gas Turbine) Without CO₂ Capture. Provides a Reference Point for Performance and Economic analyses of Cases 9 and 10

**Case 9: Present Day IGCC With Shift Reaction and CO₂ Capture, Compression, and Liquefaction**
Same as Case 8, But With Scrubbing Equipment for CO₂ Capture, Compression, and Liquefaction

**Case 10: Future (2015) IGCC With Shift Reaction and CO₂ Capture, Compression, and Liquefaction**
Same as Case 9, But Applying the Most Advanced Thinking of Technology Breakthroughs (e.g., OTM for O₂ Production and H-Class Gas Turbine)

**Implication** Potential Reduction in Cost and Improvement in Performance of an IGCC Power Plant
Basic Work Steps for each Case

1) Develop Process Design
   Material & Energy Balance (Gas side, Steam side)
   Overall plant performance & CO2 emission summary

2) Develop System / Component Specifications and Designs

3) Develop Equipment Costs
   Capital Costs
   O&M Costs

4) Develop Boiler and Plant Drawings

5) Economic Evaluation
   Cost of Electricity (COE)
   CO2 Mitigation Cost
Case 1: Air-Fired CFB -- Boiler Island Equipment Scope Definition

CFB Steam Generator Unit

Alstom Scope

Coal & Limestone Receiving, Handling & Prep System

1

2

Combustor

External Heat Exchanger

3

Fluidizing Air Blower

16

Ash Handling System

Ash Cooler

17

Induced Draft Fan

8

Particulate Removal System

13

Secondary Air Fan

14

Primary Air Fan

9

Secondary Air Fan

14

Particulate Removal System

13

Induced Draft Fan

8

Air Heater

11

Backpass Heat Exchangers

4

Stack

12

Induced Draft Fan

7

External Heat Exchanger

5

Stack

12

Induced Draft Fan

7

Parsons Scope

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Case 2/3: Oxygen-Fired CFB -- Boiler
Island Equipment Scope Definition

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- CFB Steam Generator Unit
- Combustor
- Cyclone
- Backpass Heat Exchangers
- External Heat Exchanger
- Ash Cooler
- Fluidizing Gas Blower
- Oxygen Heater
- Oxygen
- Air
- PFWH
- Particulate Removal System
- Gas Cooler
- Induced Draft Fan
- Gas Recirculation Fan
- Nitrogen
- CO₂-rich Product to Gas Processing System

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Air Fired CFB

Plan View

220'

110'
Oxygen Fired CFB

Plan View

ALSTOM
Case 6: CMB Boiler Integrated with Oxygen Membrane System

**ABB LGI Scope**
- Sweep Gas Fan
- Induced Draft Fan
- Condensate
- CO₂ rich product to Gas Processing System

**Praxair Scope**
- Oxygen Transport Membrane

**ALSTOM Scope**
- Particulate Removal System
- PFWH
- Limestone
- Cooled Solids
- Coal & Limestone Receiving, Handling & Prep System
- Ash Handling System

**Parsons Scope**
- LT Sweep Gas as Heater
- HT Sweep Gas Heater
- Heat Recovery Steam Generator
- Transport Air Heater
- Transport Air Blower
- Air

**Coal & Limestone**
- Falling Solids Combustor
- Coal
- Limestone

**Ash Cooler**
- Ash

**Moving Bed Heat Exchangers**
- Induced Draft Fan
- LT Air Heater
- LT Air Blower
- Air Comp
- Transport Air Heater
- Vent

**CMB Steam Generator Unit**
- Cyclone
- Cyclone
- Winter Sweep Gas Heater
- Winter Sweep Gas as Heater
- Heat Exchanger
- Heat Exchanger
- Ash Cooler
- Cooled Solids
- Fluidizing Gas Blower
- Optional Gas Burner

**Transport Air**
- Heat Recuperation Steam Generator
- Stack
- Generator
## Performance Comparison - Air (base case) to Oxy-fuel firing

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
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<tbody>
<tr>
<td>Air</td>
<td>O2</td>
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<tr>
<td><strong>Boiler Efficiency</strong> (fraction)</td>
<td>0.8948</td>
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<tr>
<td><strong>Steam Turbine Heat Rate</strong> (Btu/kwhr)</td>
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<tr>
<td><strong>Power Plant Auxiliary Power</strong> (kw)</td>
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<td>10071</td>
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<tr>
<td><strong>Air Separation Unit Power</strong> (kw)</td>
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<td>37505</td>
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<tr>
<td><strong>CO₂ Purification &amp; Compression</strong> (kw)</td>
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<td><strong>Total Plant Auxiliary Power</strong> (kw)</td>
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<td><strong>Generator Output</strong> (kw)</td>
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<td><strong>Net Plant Output</strong> (kw)</td>
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<td>133335</td>
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<tr>
<td><strong>Coal Heat Input (HHV)</strong> (10⁶ Btu/hr)</td>
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<td>1806</td>
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<tr>
<td><strong>Net Plant Heat Rate (HHV)</strong> (Btu/kwhr)</td>
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<td><strong>Net Plant Thermal Efficiency (HHV)</strong> (fraction)</td>
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<tr>
<td><strong>Carbon Dioxide Emissions</strong> (lbm/kwhr)</td>
<td>2.000</td>
<td>0.170</td>
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</table>
Performance Comparisons - Air to All Oxy-fuel firing Cases

<table>
<thead>
<tr>
<th>Case 1 (Air)</th>
<th>Case 2 (O2)</th>
<th>Case 3 (dirty CO2)</th>
<th>Case 4 (CMB)</th>
<th>Case 6 (OTM)</th>
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<td><strong>Boiler Efficiency</strong> (fraction)</td>
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<td><strong>Steam Turbine Heat Rate</strong> (Btu/kwhr)</td>
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<td><strong>Air Separation Unit Power</strong> (kw)</td>
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<td>210056</td>
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<td><strong>Coal Heat Input (HHV) (10⁶ Btu/hr)</strong></td>
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<td><strong>Net Plant Heat Rate (HHV) (Btu/kw/hr)</strong></td>
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<td>13576</td>
<td>13492</td>
<td>13518</td>
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<td><strong>Net Plant Thermal Efficiency (HHV) (fraction)</strong></td>
<td>0.3554</td>
<td>0.2514</td>
<td>0.2530</td>
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<tr>
<td><strong>Carbon Dioxide Emissions (lbm/kwhr)</strong></td>
<td>2.000</td>
<td>0.170</td>
<td>0.035</td>
<td>0.180</td>
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Relative Net Plant Thermal Eff, %(HHV)
to base case

Base Case: Air-Fired CFB w/o CO2 Capture
O2-Fired CFB w/CO2 Capture
O2-Fired CFB w/ASU & Flue Gas Sequestration
O2-Fired CMB w/ASU & CO2 Capture
O2-Fired CMB w/OTM & CO2 Capture
Relative Investment Costs ($/KW)

- Base Case: Air-Fired CFB w/o CO2 Capture
- O2-Fired CFB w/CO2 Capture
- O2-Fired CFB w/ASU & Flue Gas Sequestration
- O2-Fired CMB w/ASU & CO2 Capture
- O2-Fired CMB w/OTM & CO2 Capture
Relative Cost of Electricity (Cents/KW-hr)

- Base Case: Air-Fired CFB w/o CO2 Capture
- O2-Fired CFB w/CO2 Capture
- O2-Fired CFB w/ASU & Flue Gas Sequestration
- O2-Fired CMB w/ASU & CO2 Capture
- O2-Fired CMB w/OTM & CO2 Capture
Estimated Economics for an O2-Fired CFB Plant with CO₂ & N₂ Capture

Assumptions:

• Fuel Costs
  - Coal: $1.32/MMBtu
  - Pet. Coke: $0.65/MMBtu

• CO₂ & N₂ & CaCO₃ Costs
  - CO₂: $17/Ton
  - N₂: $11/Ton
  - CaCO₃: $10/Ton

• Grid Electricity Cost: $0.04/kWh

• Plant Capacity Factor: 80% (7000 hrs./yr.)

Analysis:

• Economics are viable expenses = revenues
### Preliminary Economics of Oxy-Fuel CFB for EOR Application

#### Plant Without CO₂ Capture
- **Gross Output**: 210 MWe
- **Aux Power, Fractional**: 0.076
- **Net Output**: 194 MWe

#### Plant With CO₂ Capture
- **Gross Output**: 210 MWe
- **Net Output, Fractional**: 0.613 Fraction of gross
- **Net Output**: 128.6 Mw
- **Net Plant Heat Rate**: 14079 Btu/kwhr
- **Fuel Heat Input**: 1811 $10^6$ Btu/hr
- **Limestone Usage**: 0.13 lbm/kW-gross 14.1 Tons/hr

#### Plant Cost With CO₂ Capture
- **Power Plant Cost**: 1100 $/kW-net w/o capture
- **Oxygen Plant Cost**: 148 $/lbm/hr CO₂ captured
- **Gas Processing System Cost**: 149 $/lbm/hr CO₂ captured
- **Total Installed Plant Cost**: 2475 $/kW-net

#### Annual Operating Time
- **7000 Hrs/yr**

#### Annual Revenues & Outputs

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<th>Item</th>
<th>(10^6 $/yr)</th>
<th>$/kwhr</th>
<th>Ton</th>
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<tr>
<td>Electricity</td>
<td>36.0</td>
<td>0.04</td>
<td>901</td>
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<tr>
<td>Carbon Dioxide</td>
<td>21.0</td>
<td>17</td>
<td>176</td>
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<tr>
<td>Nitrogen</td>
<td>41.0</td>
<td>11</td>
<td>532</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>98.0</strong></td>
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#### Annual Expenses

<table>
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<th>Item</th>
<th>(10^6 $/yr)</th>
<th>$/10^6 Btu</th>
<th>$/Ton</th>
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<tr>
<td>Capital Investment</td>
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<tr>
<td>Fuel</td>
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<td>1.3</td>
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<tr>
<td>Limestone</td>
<td>1.0</td>
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<td>Operating &amp; Maintenance</td>
<td>16.8</td>
<td>0.0187</td>
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<td><strong>TOTAL</strong></td>
<td><strong>98.0</strong></td>
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- **Coal**: $1.32/MMBtu
- **ALSTOM**

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### Preliminary Economics of Oxy-Fuel CFB for EOR Application

**Petcoke:** $0.65/MMBtu

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<td>0.04 $/kwhr</td>
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<td>17 $/Ton</td>
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<td><strong>Fuel</strong></td>
<td>8.2</td>
<td>0.65 $/10^6 Btu</td>
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<td><strong>Limestone</strong></td>
<td>1.0</td>
<td>10 $/Ton</td>
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<tr>
<td><strong>Operating &amp; Maintenance</strong></td>
<td>16.8</td>
<td>0.0187 $/kwhr</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>89.7</strong></td>
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</table>
Oxygen Fired CFB Recommended for further testing:

- It Is the Most Near-Term Solution, As it Uses Readily Available Commercial Technologies:
  - Oxygen Production by Cryogenic Air Separation
  - CO$_2$ Capture, Compression, and Liquefaction

- Preliminary Economic Analysis Looks Viable for Commercial EOR Application:
  - CO$_2$ Sale for Oil Field Stimulation
  - N$_2$ Sale for Oil Field Pressurization

- Is A Required Intermediate Step Leading to the More Advanced Combustion Processes, e.g.:
  - Case 5 (Carbonate Regeneration)
  - Case 7 (Chemical Looping)
Bench-Scale Testing

Four-Inch FBC Facility
Oxy-fuel FBC Bench-Scale Testing:

- NOx Emissions Roughly Equal to or Less Than from Air Firing
- SO\textsubscript{2} Emissions Roughly Equal to Air Firing
- CO Emissions significantly Higher Than for Air Firing, Most Likely Due to High CO\textsubscript{2} in the Flue Gas, Which Hinders CO Oxidation to CO\textsubscript{2}
- Burning the Base Case Coal in Up to 50%O\textsubscript{2}/50%CO\textsubscript{2} Presented No Bed Agglomeration Problems, Provided That The Bed Was Fully Fluidized.
To Generate Detailed Technical Data Needed to Establish Advanced CFB Design Requirements and Performance When Firing Coals and Delayed Petroleum Coke at \( \sim 10 \text{ MMBtu/h} \) in \( \text{O}_2/\text{CO}_2 \) Atmospheres.

- Flue Gas Quality
- Bed Dynamics
- Heat Transfer to the Waterwalls
- Flue Gas Desulfurization
- NOx Emissions Reduction
- Other Pollutants’ Emissions (\( \text{N}_2\text{O} \) and \( \text{CO} \))
- Bed and Ash Characteristics (e.g., Potential Bed Agglomeration)

ALSTOM MTF - Windsor, CT
O\textsubscript{2} & CO\textsubscript{2} Infrastructures Shown-

\begin{itemize}
  \item \textbf{O\textsubscript{2} / CO\textsubscript{2} INJECTION POINTS}
    \begin{itemize}
      \item HIGH PRESS
      \item LOW PRESS
    \end{itemize}
\end{itemize}

- \textbf{Furnace}
  - T = 600 \textdegree F
  - P = 5 psig
  - \textbf{Over Fire Gas}

- \textbf{Fluid Bed Heat Exch}
  - \textbf{Moving Bed Heat Exch}
  - T < 1000 \textdegree F
  - P = 10 psig

- \textbf{Seal Pot}
  - T = Ambient
  - P = 80 psig

- \textbf{Gas Mixers}
  \begin{itemize}
    \item \textbf{Gas Mixer 1}
      - \textbf{Electric Heaters}
        - T = 600 \textdegree F
        - P = 5 psig
        - \textbf{CH4}\n        - \textbf{Air}
      - \textbf{Bed Drain}
    \item \textbf{Gas Mixer 2}
      - \textbf{CO2}
  \end{itemize}
MTF Pilot-Scale Facility

- **Cyclone & Inlet Dut Mods.**
- **New 24” ID Cooled Upper Combustor**
- **Add’n 8” Thick Refractory to Reduce to 24” ID**
- **New Lower Combustor Refractory Sections**
- **New Grid**
Conclusions

- Oxy-fuel Firing is a viable strategy for CO2 capture

- Capital Costs are high and Efficiencies are low
  - breakthrough needed in oxygen production
  - CFB offers reduced cost and application to low quality fuels.

- In the long run more cost effective options for CO2 capture and sequestration need development and verification.
  - IGCC
  - Chemical Looping
Conclusions - OCDO/AEP Study of CO2 Capture Retrofit to Existing Coal Plant

- No Major Technical Barriers
- Energy Requirements and Power Consumption are High,
- High Investment Costs (about 1000 to 2000 $/kW)
- Cost of Electricity increased by nearly 4 to 8 cents/kW-hr
- CO2 capture cost from 40 to 100 $/Ton CO2 avoided
- Oxygen fired boiler was more economic vs. amines

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Case</th>
<th>Concept 3A CO2 Capture w/ MEA</th>
<th>Concept 3B Oxy-fired Boiler</th>
<th>Concept 3C CO2 Capture w/ MEA/MDEA</th>
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</thead>
<tbody>
<tr>
<td>Plant Eff., % HHV</td>
<td>35</td>
<td>20</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>Net Power Output, MWe</td>
<td>434</td>
<td>250</td>
<td>291</td>
<td>313</td>
</tr>
<tr>
<td>CO2 Emissions, Ibm/kWh</td>
<td>1.997</td>
<td>0.202</td>
<td>0.175</td>
<td>0.185</td>
</tr>
<tr>
<td>CO2 Liquid Purity, %</td>
<td>N/A</td>
<td>99.95</td>
<td>97.80</td>
<td>99.97</td>
</tr>
</tbody>
</table>
Indirect Combustion via chemical Looping for CO2 Capture

- Atmospheric Pressure
- Oxygen carriers (Cu, Cd, Ni, Mn, Fe, Co)
- Potential combustion process with interconnected FBC’s

Another innovative technology option
**Work Breakdown Structure**

**TASK 1**
Preliminary Performance & Economic Analysis -- 10 Cases: Baseline, High O\textsubscript{2} Firing, Chemical Looping & IGCC

**TASK 2**
Bench-Scale Fluidized Bed Combustion (FBC) Experiments -- Bed Agglomeration and SO\textsubscript{2} Capture

**TASK 3**
Project Period I final Report -- Results/Recommendations

Decision Point (Define the Most Promising Concept)

Stop Project

Implement Budget Project Period II
Work Breakdown Structure -- Period II

TASK 4
Pilot-Scale Testing (MTF) of Most Promising Concept(s)
-- Detailed Combustion/Bed Dynamics Evaluation

TASK 5
Refined Performance & Economic Analysis of Most Promising Concept(s)

TASK 6
Period II Final Report -- Systems Performance & Economics