Atmospheric Iron-Based Coal Direct Chemical Looping Process for Power Production

Pittsburgh, PA. Jun 26. 2015
Project Objectives

Phase I Project objectives: 2012 -2013

- Evaluate commercial viability of OSU’s coal-direct chemical looping process for power production with CO₂ capture.
- Perform a techno-economic evaluation of the commercial design.

Phase II Project Objectives: 2013-2016

- Reduce technology gaps identified in Phase I by conducting laboratory testing and small pilot-scale testing.
- Update design and cost performance of the commercial 550 MWe CDCL power plant
- Re-evaluate the CDCL technology and identify development pathway for commercialization in year 2025.
Project Participants

Federal Agencies:
• DOE/NETL

Project participants:
• The Babcock & Wilcox, PGG
• The Ohio State University
• Clear Skies Consulting

Industrial Review Committee:
• American Electric Power
• Consol Energy
• Dayton Power & Light
• Duke Energy
• First Energy
• Ohio Development Service Agency
Outline

- Commercialization Path
  - Phase I: CDCL Concept and Techno-Economic Analysis
  - Phase I: Technology Gaps
  - Phase II: Pilot Design
  - Phase II: Laboratory Testing and Studies
  - Project Schedule
  - Conclusions and Acknowledgments
Commercialization Path

Work performed under this award

Phase II
B&W's 250 kWth

B&W's Phase I

OSU's Laboratory Scale

OSU's Sub-Pilot 25 kWth

B&W's Pilot 3 MWth

Demo 50 MWth

Commercial 100 - 550 MWth

Time

Scale
Outline

➢ Commercialization Path

➢ Phase I: CDCL Concept and Techno-Economic Analysis

➢ Phase I: Technology Gaps

➢ Phase II: Pilot Design

➢ Phase II: Laboratory Testing and Studies

➢ Project Schedule

➢ Conclusions and Acknowledgments
Chemical Looping Concept

Coal → Reducer → CO₂ + H₂O → Fe₂O₃ → Combustor → Heat out

Fe + FeO
**CDCL Moving Bed Reactor Concept**

**Top Section**
- \( C_xH_y + Fe_2O_3 \rightarrow Fe + FeO + CO_2 + H_2O \)
- \( CO + Fe_2O_3 \rightarrow Fe + FeO + CO_2 \)
- \( H_2 + Fe_2O_3 \rightarrow Fe + FeO + H_2O \)

**Coal Volatilization**
- \( Coal \rightarrow C + C_xH_y \) (Volatiles)

**Bottom Section**
- \( C + CO_2 \rightarrow 2 CO \)
- \( 2 CO + Fe_2O_3 \rightarrow Fe + FeO + 2 CO_2 \)

* Reactions not balanced
Outline

➢ Commercialization Path

➢ Phase I: CDCL Concept and Techno-Economic Analysis

➢ Phase I: Technology Gaps

➢ Phase II: Pilot Design

➢ Phase II: Laboratory Testing and Studies

➢ Project Schedule

➢ Conclusions and Acknowledgments
OSU’s experimental data was converted into a commercial 550 MWe CDCL power plant.

- Material and Energy Balance
- Process Flow Diagrams
- Equipment Drawings
- Arrangement Drawings
- Plant layout Drawings
- 3-D Models
Modular Loop Design

- Distributor
- Riser
- Reducer
- Combustor
# CDCL Technology Comparison

<table>
<thead>
<tr>
<th></th>
<th>Base Plant</th>
<th>MEA Plant</th>
<th>CDCL Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Feed, kg/h</td>
<td>185,759</td>
<td>256,652</td>
<td>205,358</td>
</tr>
<tr>
<td>CO₂ Emissions, kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>801</td>
<td>111</td>
<td>31</td>
</tr>
<tr>
<td>CO₂ Capture Efficiency, %</td>
<td>0</td>
<td>90</td>
<td>96.5</td>
</tr>
<tr>
<td>Net Power Output, MW&lt;sub&gt;e&lt;/sub&gt;</td>
<td>550</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Net Plant HHV Heat Rate, kJ/kWh (Btu/kWh)</td>
<td>9,165 (8,687)</td>
<td>12,663 (12,002)</td>
<td>10,084 (9,558)</td>
</tr>
<tr>
<td>Net Plant HHV Efficiency, %</td>
<td>39.3</td>
<td>28.5</td>
<td>35.6</td>
</tr>
<tr>
<td>Cost of Electricity, $/MWh</td>
<td>80.96</td>
<td>132.56</td>
<td>102.67</td>
</tr>
<tr>
<td>Increase in Cost of Electricity, %</td>
<td>-</td>
<td>63.7</td>
<td>26.8</td>
</tr>
</tbody>
</table>
Outline

- Commercialization Path
- Phase I: CDCL Concept and Techno-Economic Analysis
- Phase I: Technology Gaps
- Phase II: Pilot Design
- Phase II: Laboratory Testing and Studies
- Project Schedule
- Conclusions and Discussion
Technology Gap Analysis

Reducer
- Coal Injection and distribution
- Char residence time
- Ash Separation/Enhancer Gas
- Fate of alkali
- Fate of S, Hg, and N

Particles
- Max. op. temp.
- Attrition
- Reactivity
- Deactivation

Operation
- Start up
- Shut down
- Turn down – Idle
- Hazardous Op

To Convection
pass

Coal

Distributor

Reducer

Combustor
- In-bed Heat exchanger
- Auto-thermal Operation

Riser

Air

Air
## CDCL Technology Gaps

<table>
<thead>
<tr>
<th>Design/Technology Issues</th>
<th>Ongoing/Past Mitigation</th>
<th>Planned Mitigation</th>
<th>Future Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing Cost</td>
<td>Under OSU’s SOW</td>
<td>Particle Manufacturer</td>
<td></td>
</tr>
<tr>
<td>Attrition</td>
<td>NCCC</td>
<td>Lab 2” BFB / Envergex</td>
<td></td>
</tr>
<tr>
<td>High Temperature Resistance</td>
<td>TGA</td>
<td>TGA</td>
<td></td>
</tr>
<tr>
<td><strong>Reducer Design</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal Injection &amp; Distribution</td>
<td>OSU’s Sub-Pilot</td>
<td>Small-pilot Unit</td>
<td>3 MWth-Pilot</td>
</tr>
<tr>
<td>Char Residence Time</td>
<td>OSU’s Sub-Pilot</td>
<td>TGA, Small-pilot Unit</td>
<td></td>
</tr>
<tr>
<td>Ash Separation / Enhancer Gas</td>
<td>OSU’s Sub-Pilot</td>
<td>Small-pilot Unit</td>
<td></td>
</tr>
<tr>
<td>Pressure Drop</td>
<td>Phase I (Calculation)</td>
<td>Small-pilot Unit</td>
<td></td>
</tr>
<tr>
<td>CO₂ Purity</td>
<td>Phase I (Calculation)</td>
<td>Small-pilot Unit</td>
<td></td>
</tr>
<tr>
<td>Sulfur, NOx, Hg Emissions</td>
<td>OSU’s Sub-Pilot</td>
<td>Small-pilot Unit</td>
<td>3 MWth-Pilot</td>
</tr>
<tr>
<td>Alkaline Management</td>
<td>2” BFB (Preliminary)</td>
<td>2” BFB</td>
<td>3 MWth-Pilot</td>
</tr>
<tr>
<td><strong>Combustor Design</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger surface</td>
<td>B&amp;W’s CFB Technology</td>
<td></td>
<td>3 MWth-Pilot</td>
</tr>
<tr>
<td>Auto-thermal Operation</td>
<td>Phase I (Calculation)</td>
<td>Small-pilot Unit</td>
<td>3 MWth-Pilot</td>
</tr>
<tr>
<td><strong>System</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>NCCC</td>
<td>Small-pilot Unit</td>
<td>3 MWth-Pilot</td>
</tr>
<tr>
<td>Start up/ Shut down</td>
<td>NCCC</td>
<td>Small-pilot Unit</td>
<td>3 MWth-Pilot</td>
</tr>
<tr>
<td>Safety</td>
<td>NCCC</td>
<td>Small-pilot Unit</td>
<td>3 MWth-Pilot</td>
</tr>
</tbody>
</table>
Outline

- Commercialization Path
- Phase I: CDCL Concept and Techno-Economic Analysis
- Phase I: Technology Gaps
- Phase II: Pilot Design
- Phase II: Laboratory Testing and Studies
- Project Schedule
- Conclusions and Acknowledgments
Pilot Unit Design

**Physical Specifications**
- Materials: Refractory lined Carbon Steel
- Overall Height: 32 ft
- Footprint = 20’ x 20’

**Process Specifications**
- Thermal rating: 250 kWth
- Coal Feed Rate: 70 lb/hr
- Coal size: Pulverized coal
- Max Operating Temperature: 2012 °F
- Oxygen Carrier: Iron based
- Reducer: Counter-current moving bed
- Combustor: Bubbling bed
- Particle transport: Pneumatic

**Oxygen Carrier Specifications**
- Active metal: Iron based
- Size: 1.5 mm
CDCL 250 kW<sub>th</sub> Pilot

- **Coal residence time**
  Controlling coal and particle flow rate

- **Ash separation**
  Controlling enhancer gas flow rate; Material (ash) balance.

- **Pressure drop**
  Pressure balance on the system

- **CO<sub>2</sub> Purity; Sulfur, NOx emissions**
  Gas analysis throughout the reactor

- **Autothermal operation**
  Steady-state operation without primary burner

- **System Operation**
  Start up and shutdown, HazOp, JSA and other operation protocols
Outline

- Commercialization Path
- Phase I: CDCL Concept and Techno-Economic Analysis
- Phase I: Technology Gaps
- Phase II: Pilot Design
- Phase II: Laboratory Testing and Studies
- Project Schedule
- Conclusions and Acknowledgments
Coal Flow Model Tests: Fines entrainment
Fines Residence Time in Moving Bed

5CFM, 160g flint clay

Pressure drop (in of water) vs. Time (s)
Ash and Fines residence time ($T_r$)

- Iron 100, mass ratio = 0.01
- Iron 100, mass ratio = 0.02
- Iron 100, mass ratio = 0.04
- Iron 325, mass ratio = 0.01
- Iron 325, mass ratio = 0.02
- Iron 325, mass ratio = 0.04
- Clay 300, mass ratio = 0.04
- Clay 300, mass ratio = 0.01
- Clay 300, mass ratio = 0.02
Particle Characterization

Time to reach 50% conversion as a function of gas flow rate

![Photograph of TGA Analyzer](image1)

![Gas Delivery System](image2)
Particle Reduction Studies

Degree of oxidation (0 = Fe, 1=Fe2O3) vs. Time during 3rd cycle (min)

- 850 C
- 1000 C
- 1150 C

Gas and fines

Particles

Top Moving Bed

Bottom Moving Bed

Combustor

Coal + CO₂

CO₂

Air
Particle Oxidation Studies

Gas and fines → Particles → Top Moving Bed → Combustor
Coal + CO₂ → Bottom Moving Bed → Risers
CO₂ → Air

850°C, 850°C, 1000°C, 1000°C, 1150°C

Degree of oxidation (0 = Fe, 1 = Fe₂O₃)

Time during 3rd cycle (min)

© 2015 Babcock & Wilcox Power Generation Group, Inc. All rights reserved.
Particle Integrity Studies: Carbon formation

Above 900 °C there is no carbon formation
Alkaline injection test in BFB

Particles agglomerate at very high alkaline content: ~9.1wt.%
Agglomerated particle caused by alkaline can be regenerated in the combustor.
Outline

- Commercialization Path
- Phase I: CDCL Concept and Techno-Economic Analysis
- Phase I: Technology Gaps
- Phase II: Pilot Design
- Phase II: Laboratory Testing and Studies
- Project Schedule
- Conclusions and Acknowledgments
## Project Schedule

<table>
<thead>
<tr>
<th>Phase II</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 5 6 7 8 9 10 11 12</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
</tr>
<tr>
<td>Task 1. Project Management and Planning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 2. Laboratory Testing and Oxygen Carrier Characterization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot Plant Design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot Plant Cost Estimate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot Plant Construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot Plant Testing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 4. Data Analysis and Update of Commercial Plant Economic Analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 5. Phase II Final Report</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Outline

- Commercialization Path
- Phase I: CDCL Concept and Techno-Economic Analysis
- Phase I: Technology Gaps
- Phase II: Pilot Design
- Phase II: Laboratory Testing and Studies
- Project Schedule
- Conclusions and Acknowledgments
Conclusions

• CDCL offers a cost-effective alternative for coal-based power generation with carbon capture

• The commercial CDCL modular design is ideal for commercial deployment of the technology

• Cold flow model and laboratory testing is confirming assumptions and design features of the 250 kWth pilot unit and the commercial design

• The design of 250 kWth pilot plant has been completed and we are moving soon towards the construction and testing
Acknowledgments

This material is based upon work supported by the Department of Energy under Award Number DE-FE0009761