Coal Direct Chemical Looping Retrofit for Pulverized Coal-fired Power Plants with In-Situ CO₂ Capture

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Hyung Ray Kim
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William G. Lowrie Chemical and Biomolecular Engineering
The Ohio State University

March. 25th, 2008
Clean Coal Conversion Program at The Ohio State University

A. HPHT Slurry Bubble Column Reactor

B. 120 kW_th CCR Demonstration Unit

C. Lab Scale Calcium Looping Unit

D. 2.5 kWth Chemical Looping Unit

E. 25 kW_th Syngas Chemical Looping Demonstration Unit
Project Overview
# Project Funding

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<th>Participant</th>
<th>Cash</th>
<th>In-Kind</th>
<th>Total</th>
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<td>OCDO</td>
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<td><strong>Total</strong></td>
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*DOE $2.86 million, Participants Cost Share $1.12 million*
# Project Timeline

## Task 1.0: Project Management Planning
- Subtask 1.1: Testing Procedure for measuring Reactivity
- Subtask 1.2: Testing procedure for Sulfur Tolerance
- Subtask 1.3: Oxygen Transfer and Sulfur Fouling Mechanism
- Subtask 1.4: Sample Development and Selection of candidates
- Subtask 1.5: Prellatization of selected candidates
- Milestone - selection of 5 candidates

## Task 2.0: Particle Improvement
- Subtask 2.1: Direct Gasification of Char
- Subtask 2.2: Indirect Gasification of Char
- Subtask 2.3: Determination of Fuel Reactor operating condition range
- Milestone - selection of the gas enhancer

## Task 3.0: Identification of Optimal Fuel Reactor Operating Condition
- Subtask 3.1: Size of the Reactor and Better Solid sampling design
- Subtask 3.2: Char size to be used and contacting pattern
- Milestone - Constructed New Bench Scale Reactor

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- Subtask 4.1: Moving Bad Testing
- Subtask 4.2: The Large Scale Production of Finalized Looping Medium
- Milestone - 700 kgs of finalized particle pellets

## Task 5.0: Particle Finalization
- Subtask 5.1: Fuel Reactor with Char
- Subtask 5.2: Regeneration with Air and Steam
- Milestone - continuous operation of Bench Scale reactor for 15 hours

## Task 6.0: Ash Separation and Particle Attrition
- Subtask 6.1: Effect of Temperature
- Subtask 6.2: Ash Separation using Cyclone and Particle Attrition test

## Task 7.0: Bench Scale Demonstrations and Fate of Sulfur and Nox
- Subtask 7.1: Design and Construction of Coal Inlet
- Subtask 7.2: Sub-pilot scale CDCL system Assembly and Shakedown
- Milestone - Modified Proof-of-concept Scale Reactor

## Task 8.0: Modification and Construction of sub-pilot scale CDCL system
- Subtask 8.1: Design and Construction of Coal Inlet
- Subtask 8.2: Sub-pilot scale CDCL system Assembly and Shakedown
- Milestone - Modified Proof-of-concept Scale Reactor

## Task 9.0: Integrated System Performance
- Subtask 9.1: Continuous in-situ CO₂ Capture
- Milestone - continuous operation of Unit

## Task 10.0: Techno-Economic Analysis performed by CONSOL
- Milestone - Techno-economic Analysis Report
Project Participants

• Project Manager: Timothy Fout

• Lead Applicant
  – The Ohio State University
    • Prof. Liang-Shih Fan (PI) & Research Associates
    • Planning, Experiments, and Demonstrations

• Partners
  – Clear Skies Consulting
    • Organization and Coordination
  – Shell/CRI Inc.
    • Particle Synthesis Procedure Scale up and Economics
  – CONSOL Energy Inc.
    • Techno-Economic Study of the Overall CDCL System
  – The Bobcock and Wilcox Company
    • Engineering Consultation and Support on PC Plant Retrofit
  – Air Products and Chemicals Inc.
    • Gas Handling
Process Review
Overall CDCL Scheme

Step I: Coal + Fe$_2$O$_3$ (Hot) $\rightarrow$ Fe/FeO + H$_2$O + CO$_2$

Step II: Air + Fe/FeO $\rightarrow$ Fe$_2$O$_3$ (Hot) + Spent Air (To boiler)

Overall reaction

Coal + Air $\rightarrow$ CO$_2$ + H$_2$O + Spent Air (Heat)
**Key Challenge: Particle Selection and Development**

<table>
<thead>
<tr>
<th></th>
<th>Fe$_2$O$_3$</th>
<th>NiO</th>
<th>CuO</th>
<th>CoO</th>
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<tr>
<td>Cost</td>
<td>+</td>
<td>–</td>
<td>~</td>
<td>–</td>
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<tr>
<td>Oxygen Capacity$^2$ (wt %)</td>
<td>30</td>
<td>21</td>
<td>20</td>
<td>21</td>
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<tr>
<td>Thermodynamics</td>
<td>+ (+)</td>
<td>+ (–)</td>
<td>+ (–)</td>
<td>+ (+)</td>
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<tr>
<td>Kinetics/Reactivity</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>–</td>
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<tr>
<td>Melting Points</td>
<td>+</td>
<td>~</td>
<td>–</td>
<td>+</td>
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<tr>
<td>Strength</td>
<td>+</td>
<td>–</td>
<td>~</td>
<td>~</td>
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<td>Environmental&amp; Health</td>
<td>~</td>
<td>–</td>
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</tbody>
</table>
Recyclability of Commercial Fe$_2$O$_3$
Recyclability of Composite Fe$_2$O$_3$ Particles

Iron Based Composite particles are completely recyclable for more than 100 cycles
Pelletization
Pellet Strength: Compression Strength Test and Dropping Test (ASTM D4179)

Pellets have Good Strength
Pellet Strength: Attrition Test

0.57% fresh pellet makeup is sufficient
Key Challenge: Reducer

- 2-Stage Moving Bed
  - Counter-current flows
  - Gaseous volatiles
  - Coal char

- Reaction Enhancer
  - Initiates the solid-solid reaction
  - Direct enhancer: $\text{CO}_2, \text{H}_2\text{O}, \text{O}_2$
    - $\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$
  - Indirect enhancer: $\text{H}_2$
    - $3\text{H}_2 + \text{Fe}_2\text{O}_3 \rightarrow 2\text{Fe} + 3\text{H}_2\text{O}$
Key Challenge: Solid Fuel Conversion Enhancement

“Chain Reaction” Effect

CO₂ + H₂O  →  CO₂ + C → 2CO
Coal + Fe₂O₃  →  2CO + 2FeOₓ → 2FeOₓ₋₁ + 2CO₂
Fe/FeO  →  2CO₂ + 2C → 4CO

Contacting Pattern

1CO₂  →  2CO₂  →  4CO₂

THE OHIO STATE UNIVERSITY
Reducer Bench Scale Demonstrations

Motor

Light In → Light Out

Gas Out

Gas / solid
Sample Out

Gas In

Motor

Temperature Measurement
Reducer Tests with Various Fuels

<table>
<thead>
<tr>
<th>Type of Fuel</th>
<th>Coal Volatile (CH₄)</th>
<th>Lignite Char</th>
<th>Ohio Char</th>
<th>Coal</th>
<th>Anthracite Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Conversion (%)</td>
<td>99.8</td>
<td>94.9</td>
<td>90.5</td>
<td>95.5</td>
<td></td>
</tr>
<tr>
<td>CO₂ Concentration in Exhaust (% Dry Basis)</td>
<td>98.8</td>
<td>99.23</td>
<td>99.8</td>
<td>97.3</td>
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</tr>
</tbody>
</table>

High Conversions of various types of fuels are achieved.
Combustor Tests

- Particle Temperature - 933°C → 1166°C
- Gas Temperature - 924°C → 971°C
- Particle Recyclable After Three Cycles
System Performance

<table>
<thead>
<tr>
<th></th>
<th>PC Plant</th>
<th>Retrofit with CDCL</th>
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</thead>
<tbody>
<tr>
<td><strong>CO₂ Captured, %</strong></td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>HP Steam Turbine Power</strong></td>
<td>103.48</td>
<td>113.25</td>
</tr>
<tr>
<td><strong>IP Steam Turbine Power</strong></td>
<td>90.75</td>
<td>97.76</td>
</tr>
<tr>
<td><strong>LP Steam Turbine Power</strong></td>
<td>192.15</td>
<td>202.97</td>
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<tr>
<td><strong>Gross Power Summary, MW</strong></td>
<td>386.38</td>
<td>413.98</td>
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<tr>
<td><strong>Pump + Fan</strong></td>
<td>13.03</td>
<td>35.13</td>
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<tr>
<td><strong>CO₂ Compressor</strong></td>
<td>0</td>
<td>31.41</td>
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<tr>
<td><strong>Auxiliary Load Summary, MW</strong></td>
<td>13.03</td>
<td>78.92</td>
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<tr>
<td><strong>Net Power, MW</strong></td>
<td>373.35</td>
<td>347.45</td>
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<tr>
<td><strong>Efficiency, HHV%</strong></td>
<td>36.43</td>
<td>33.93</td>
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<tr>
<td><strong>Retrofit System Cost (Estimated, Million Dollar)</strong></td>
<td>0</td>
<td>103</td>
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<tr>
<td><strong>Cost of Electricity ($/MWh)</strong></td>
<td>56.6</td>
<td>67.16</td>
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Very low CO₂ capture penalty in the retrofit scenario, much higher efficiency can be obtained in the case of a new CDCL plant (close to 50%)
Upcoming Project
Project Objectives

• Develop the CDCL Process for Retrofit to PC Plant
  – CDCL process Demonstration
    • Further Optimization of the Working Oxygen Carrier Particle
    • Lab, Bench (2.5kWt), Sub-pilot Scale (25kWt) Demonstrations
  – Sulfur, Mercury, and NO$_x$ control

• Demonstrate the Techno-Economic Performance
  – Low Energy Penalty
  – Low Carbon Capture Cost
Coal Direct Chemical Looping Retrofit to PC Plant

- Fixed Bed Tests
- Particle Optimization and TGA Tests
- Bench Scale Tests
- Sub-Pilot Tests after Modification to Current Chemical Looping Demonstration System
Technical Approach

Prior Data Analysis
- TGA, Fixed Bed & Moving bed experiments
- Decide on future path
- Describe the tasks to be accomplished
- Divide the work between members
- Discuss the Retrofit Scenario specifications
  - Preliminary Analysis and process economics

**Particle Improvement**
- Oxygen Transfer Mechanism
- Choice of Support
- Choice of Dopant
- Metal Oxide Loading
- Reactivity, Sulfur Tolerance
- Particle Pelletization

**PHASE I WORK**
- 5 candidates for Looping Medium
- Gas Enhancer selected
- New Bench Scale Reactor

**Particle Finalization**
- Moving Bed Experiments
- Large-scale Production of Ideal looping Medium

**Bench Scale Demonstrations**
- Char Tests
- Regeneration with Air and Steam

**PHASE II WORK**
- Design and construction of Coal Inlet
- Assembly and shake down

**Integrated System Performance**
- Continuous smooth operation
- Monitoring Conversion & Purity of Streams
- Conversion of Coal and looping Medium
- Temperature of Flue Gas

**Process Simulation**
- Done by CONSOL energy

**Process Economics**
- Done by CONSOL

**Milestones – Phase III**
- Continuous Operation of UNIT
- Techno-economic analysis Report

**CDCL CONCEPT INCEPTION**
- Thermodynamic Analysis
  - Oxygen Carrier Feasibility
- Particle Reactivity
- Particle Recyclability
- Particle Strength
- Fuel Reactor Demo I
  - Volatiles Conversion
- Fuel Reactor Demo II
  - Char Conversion
- Combustor Demonstration
- Ash Separation
- Fates of SOx, NOx
- Reactor Materials of Construction
- ASPEN® Simulations
  - Process Economics

**Milestones achieved**

**Modification of the Proof-of-Concept Scale CDCL unit**
- Temperature Window
- Ash separation using cyclone
- Particle attrition tests

**Bench Scale Construction**
- Solid Sampling Design
- Size Determination

**Milestones: PHASE I**
- Solid Sampling Design
- Size Determination
# Project Timeline

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<th>Task</th>
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<th>Year 2</th>
<th>Year 3</th>
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Current Status

- Particle Test Protocol Finalized
- Base Particle Tested with the Standard Protocol
- Multiple Particles are being Synthesized
- Fixed Bed Studies Performed
- A Cold Model for the CDCL Reducer is Designed and Fabricated

We are on Track ^_^
Current Status

We will be on Track ^_^
Future Demonstrations and Commercialization Plan

• Further Scale up to an Autothermal 1 – 5 MW$_{th}$ Scale CDCL System

• Detailed Updated Techno-Economic Analysis based on Scale Up Demonstrations

• Collaboration with Shell/CRI on Mass Production of Oxygen Carriers

• Commercialization with Industrial Partners
Questions?