FE0027654: 10MW<sub>e</sub> Coal Direct Chemical Looping Large Pilot Plant: Pre-Front End Engineering and Design Study

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NETL CO<sub>2</sub> Capture Technology Project Review Meeting | 25 August 2017
OSU Chemical Looping Evolution

Laboratory Studies
- Reduction Kinetics and Mechanism
  - Oxygen Carrier Reactivity (TGA)
  - Fixed Bed
  - TGA

Bench Testing
- Moving Bed Model and Results
  - 2.5 kW\textsubscript{th} Reducer

Sub-Pilot Testing
- Integrated Design
- Reduce Gas Profile
- Sulfur Balance
  - 25 kW\textsubscript{th} CDCL Unit

Pilot Plant Demonstration
- 250 kW\textsubscript{th} CDCL Unit

1993 to 2013 to present
Oxygen Carrier Development

4Fe (s) + 3O₂ (g) → 2Fe₂O₃ (s)  
Fe₂O₃ (s) + 3H₂ (g) → 2Fe (s) + 3H₂O (g)

If the cyclic reactions proceed through Fe cation diffusion, core-shell structure forms, e.g. Fe₂O₃ + Al₂O₃.

If the cyclic reactions proceed through O anion diffusion, core-shell structure does not forms, e.g. Fe₂O₃ + TiO₂.

*Al₂O₃ is only a physical support, while TiO₂ alters the solid-phase ionic diffusion mechanism.
Main reactions:
Reducer: Coal + Fe$_2$O$_3$ $\rightarrow$ Fe/FeO + CO$_2$ + H$_2$O
Oxidizer: Air + Fe/FeO $\rightarrow$ Fe$_2$O$_3$ + Spent Air
Overall: Coal + Air $\rightarrow$ CO$_2$ + H$_2$O + Spent Air

Reducer Reactor Design

OSU Coal Direct Chemical Looping Process

**Fixed solid molar flowrate** $n_{Fe}$

**Oxygen content for solid** $y = \frac{3n_{H_2O} + 4n_{H_2O} + n_{FeO}}{n_{Fe}}$

**Fixed gas molar flowrate** $n_{H_2} + n_{H_2O}$

**Oxygen content for gas** $x = \frac{n_{H_2O}}{n_{H_2} + n_{H_2O}}$

**Oxygen Balance**

$n_{Fe}(y_{2+\Delta z} - y_2) = (n_{H_2} + n_{H_2O})(x_{2+\Delta z} - x_2)$

$\Delta z \rightarrow 0 \Rightarrow \frac{dy}{dx} = \frac{(n_{H_2} + n_{H_2O})}{n_{Fe}}$

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**Top Section**

- C$_x$H$_y$ + Fe$_2$O$_3$ $\rightarrow$ Fe/FeO + CO$_2$/H$_2$O
- CO + Fe$_2$O$_3$ $\rightarrow$ Fe/FeO + CO$_2$
- H$_2$ + Fe$_2$O$_3$ $\rightarrow$ Fe/FeO + H$_2$O

**Coal Volatilization**

- Coal $\rightarrow$ C + C$_x$H$_y$ (Volatiles)

**Bottom Section**

- C + CO$_2$ $\rightarrow$ 2 CO
- 2 CO + Fe$_2$O$_3$ $\rightarrow$ Fe + FeO + 2 CO

* Reactions not balanced
CDCL Process Analysis

Process Flow Diagram

550 MWₑ CDCL Plant Conceptual Design

Construct 250 kWₑ Test Unit

<table>
<thead>
<tr>
<th></th>
<th>Base Plant</th>
<th>MEA Plant</th>
<th>CDCL Plant</th>
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<tbody>
<tr>
<td>Coal Feed, kg/h</td>
<td>185,759</td>
<td>256,652</td>
<td>205,358</td>
</tr>
<tr>
<td>CO₂ Capture Efficiency, %</td>
<td>0</td>
<td>90</td>
<td>96.5</td>
</tr>
<tr>
<td>Net Power Output, MWₑ</td>
<td>550</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Net Plant HHV Efficiency, %</td>
<td>39.3</td>
<td>28.5</td>
<td>35.6</td>
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<tr>
<td>Cost of Electricity, $/MWh</td>
<td>80.96</td>
<td>132.56</td>
<td>102.67</td>
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<tr>
<td>Increase in Cost of Electricity, %</td>
<td>-</td>
<td>63.7</td>
<td>26.8</td>
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</table>
250 kW\textsubscript{th} CDCL Pilot Test Unit

**Combustor Temperature with Natural Gas Heating**

- **Combustor Temperature**
- **Total NG Flow into Combustor**
- **Burner NG Flow**
- **Windbox NG Flow**
- **Burner Natural Gas, lb/hr**
- **Combusor Natural Gas, lb/hr**
- **Total Natural Gas, lb/hr**

![Combustor image](image-url)
Project Objective

- Perform the (pre-) Front end Engineering Design (FEED) of a modular 10 MW$_e$ coal-direct chemical looping (CDCL) large pilot plant.
- Provide Functional specifications for integration with host site.
- Provide risk assessment, schedule and cost estimate for fabrication, construction and testing.
- Update design and commercial 550 MW$_e$ CDCL plant economic analysis
Project Objective and Schedule

- Objective: Completed a site specific design of a 10 MW_e large pilot CDCL test unit with >90% CO₂ capture
- 3 Major task to complete project
  - Task 2: Continued operation of 250 kW_th pilot test unit and 10 MW_e cold flow model studies
    - Coal/Fe ratio optimization, site specific coal studies, etc.
    - CFM studies on coal/reducing gas distribution and combustor fluidization performance
  - Task 3: 10 MW_e Unit Design and Costing
    - Host site selected
    - Oxygen carrier synthesis process costing
    - Detailed reactor sizing, HMB, HAZOP review, etc.
  - Task 4: Refine TEA models base on project results

Project Team

<table>
<thead>
<tr>
<th>OSU/B&amp;W</th>
<th>Lead and manage overall project activities Task 1 and conduct research, design and Engineering studies in Task 2, 3 and 4</th>
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<tbody>
<tr>
<td>Clear Skies Consulting</td>
<td>Task 3 &amp; 4: Coordinate IRC meetings \</td>
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<tr>
<td>EPRI</td>
<td>Task 4: TEA review and Balance of Plant Support</td>
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<tr>
<td>Johnson Matthey</td>
<td>Task 3: Develop OC manufacturing techniques</td>
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<tr>
<td>PSRI</td>
<td>Task 2: Perform cold flow model experiment</td>
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<tr>
<td>Dover</td>
<td>Task 3: Test site selection</td>
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<tr>
<td>Nexant</td>
<td>Task 4: TEA review</td>
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Task 3.6: Oxygen Carrier Commercial Manufacturing Development

**Phase I**
- Verification of reactivity with TGA
- Strength and attrition analysis with Jet-Cup

**Phase II**
- Incorporation of natural ilmenite
- Raw material size optimization
- Shape factor optimization

**Phase III**
- JM cost-model analysis
- First estimate of ITCMO production cost

**Johnson Matthey**
• First round of samples have been received and characterized
• One sample achieved target conversion (33%) with stable strength after 200 cycles (64 MPa)
• Next steps:
  • Optimize sphericity of oxygen carrier
  • Use of natural ore ilmenite as raw material
  • Attrition resistance measurement with Jet-cup

<table>
<thead>
<tr>
<th>Sample #160317/1&amp;2</th>
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<tr>
<td>Density</td>
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<tr>
<td>Average Diameter</td>
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<tr>
<td>Crushing Strength</td>
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<td>Conversion (%)</td>
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Concluding Remarks

• CDCL process represents an advanced, next generation oxy-combustion technology capable of high process efficiency for electricity production with >95% carbon capture

• Project objective is to complete a Preliminary FEED study of the CDCL 10MW_e large-pilot facility incorporating a modular reactor design

• Small pilot scale testing ongoing with promising initial results

• Oxygen carrier synthesis assessment initiated with initial sample production from Johnson Matthey showing good performance. OSU sample characterization studies ongoing.
Acknowledgements

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Project Participants
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- Nexant
- Industrial Review Committee
  - AEP
  - First Energy
  - Dayton Power & Light
  - Ohio EPA
  - CONSOL Energy
  - Public Utility Commission of Ohio

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