Outline

- **Background**
  - Project Participants
  - Process Concept
  - Commercialization Path

- **250 KWth Pilot Facility**
  - Update on 250 kWth pilot testing
  - CFM Testing & Particle Synthesis

- **10 MWe Pilot Plant pre-FEED**
  - H&M Balances
  - Steam Cycle Integration
  - 10 Mwe Pre-FEED Study
  - Schedule

- **Acknowledgements**
Project Participants

- **Federal Agencies**
  - DOE/NETL

- **State Agency**
  - Ohio Development Services Agency

- **Project Participants**
  - Babcock & Wilcox (B&W)
  - Ohio State University (OSU)
  - Clear Skies Consulting
  - Dover Light & Power (DPL)
    - Trinity Consultants
    - Worley Parsons
  - Electric Power Research Institute (EPRI)
  - Johnson Matthey (JM)

- **Industrial Review Committee**
  - American Electric Power
  - Duke Energy
  - FirstEnergy
  - CONSOL Energy
CDCL Reducer Concept

**Section 1**

\[ C_x H_y + Fe_2O_3 \rightarrow CO_2 + H_2O + FeO \]

**Devolatilization**

Coal \( \rightarrow \) C + \( C_x H_y \)

**Section 2**

\[ C + CO_2 \rightarrow 2 \ CO \]
CDCL Reducer Concept

Section 1

\[ C_{x}H_{y} + Fe_{2}O_{3} \rightarrow CO_{2} + H_{2}O + FeO \]

Devolatilization

Coal \( \rightarrow C + C_{x}H_{y} \)

Section 2

\[ C + CO_{2} \rightarrow 2CO \]

\[ CO + Fe_{2}O_{3} \rightarrow CO_{2} + FeO/Fe \]
CDCL Reducer Concept

Section 1
\[ C_x H_y + Fe_2O_3 \rightarrow CO_2 + H_2O + FeO \]

Devolatilization
Coal \( \rightarrow \) C + C_x H_y

Section 2
\[ C + CO_2 \rightarrow 2CO \]
\[ CO + Fe_2O_3 \rightarrow (CO_2) + FeO/Fe \]
CDCL Process

Coal

H₂O+CO₂
(Ash, Hg, Se, As)

>96 % Purity

Top Section
Volatile

Char
Bottom Section

Fe₂O₃

FeO

Two-stage Counter-current Moving Bed

AIR

HEAT
CDCL Commercialization Path

- OSU’s Laboratory Scale
- OSU’s Sub-Pilot 25 kW_{th}
- CDCL Phase I
- CDCL Phase II 250 kW_{th}
- HEN and Dynamic Model
- 10 MWe Feasibility Study: Ph1
- 10 MWe Pre-FeED
- Phase II&III: Large Pilot Testing 10 MW_{e}
- Demo 70 MW_{e}
- Commercial 100 - 550 MW_{e}

Timeline:
- 2004
- 2008
- 2011
- 2014
- 2017
- 2020
- 2023
- 2026
- 2030
- 2035
## CDCL Technology Development

<table>
<thead>
<tr>
<th>Laboratory 2.5 kWth</th>
<th>25 kWth</th>
<th>250 kWth</th>
<th>4 x 2.5 MWe</th>
<th>1 x 70 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Particle recyclability and reactivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Individual reactions in the reducer and combustor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Integrated operation reducer and combustor for more than 200 hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Coal conversions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• CO₂ Purity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Adiabatic reducer operation for more than 250 hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Process efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Evaluate emissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Large scale particle manufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Particle attrition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Long Term operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Coal distribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Modular integration and operation - Start up, turn down, shutdown cycles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Steam generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Economics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Commercial Operation of a single module</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Fabrication</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scale Up Plan

Laboratory 2.5 kWth

25 kWth

250 kWth

4 x 2.5 MWe

1 x 70 MWe

Critical Dimension Scale up Factor:
- x1
- x4
- x6
- x2.3
- x2.8

Reducer reactor

Coal distribution

Distance:
- 1.5”
- 6”
- 3’
- 7’
- 20’
250 kW$_{th}$ Pilot Plant - Design

Specifications

- Materials: Refractory lined Carbon Steel
- Max Operating Temperature: 2012 °F
- Reducer: Counter-current moving bed
- Combustor: Bubbling bed
- Overall Height: 32 ft
- Footprint = 10’ x 10’
- Thermal Rating: 250 kWth
- Coal Feed Rate: 10 to 70 lb/hr
- Coal Size: Pulverized coal
- Particle Transport: Pneumatic
- Oxygen Carrier: Iron based
- Oxygen Carrier Size: 1.5 mm
# 250 kW<sub>th</sub> Test Campaign Summary

<table>
<thead>
<tr>
<th>Test Campaigns</th>
<th>Main Achievements</th>
<th>Lessons Learned</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Initial Heat up (DE-FE-0009761)</td>
<td>Heated up to 1600 °F for more than 24 hrs</td>
<td>○ Quench system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>○ Need extra NG injection</td>
</tr>
</tbody>
</table>
| #2 Unit shake down, start up and      | • Reached 1800 °F  
• Achieved expected solid circulation  
• Characterization of temperature/pressure distributions, gas sampling and analysis | ○ Coal injection pressure unbalance                  |
| operation (DE-FE-0009761)            |                                                                                    | ○ Blower capacity low at startup                      |
| #3 Coal injection test (DE-FE-0037654)| • Reached 1950 °F  
• Injected coal successfully  
• High volatile conversion           | ○ Air infiltration                                    |
|                                       |                                                                                    | ○ Flame temperature startup sensitivity               |
250 kW_th Pilot – Test Results
250 kW<sub>th</sub> Pilot – Test Results

![Graph showing CO<sub>2</sub> and CO levels over time.]

- **CO<sub>2</sub>, Reducer**
- **CO, Reducer**
- **CO<sub>2</sub>, Combustor**

**High coal volatile conversion**
Modifications to the Pilot Facility

Hardware
1. Air Compressor
2. Electric air pre-heaters
3. Natural gas distributor for direct injection
4. Modified gas sampling system to prevent leaks
5. Modified access port to the reducer to allow hot gas injection
6. Forced-air fan to quench system
7. Insulate reactor shell to reduce heat losses

Operation
1. pre-heating reducer
2. Positive pressure operation
3. Using quench air instead of water

NEXT TEST RUN SCHEDULED ON AUGUST 20th
CFM Testing

Reducer Reactor
• PSRI: adapting existing CFM units
• Coal distribution in reducer reactor

Combustor Reactor
• Particle mixing and distribution
• In-bed Heat Exchanger

Oxygen Carrier Manufacturing

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 OSU OC production cost
Pre-FEED Study

- Heat & Material Balances
- Functional Specifications
  - Mechanical
  - Electrical, Instrumentation & Controls
  - System specifications (CDCL Operation & Steam Cycle)
- Piping & Instrumentation Diagrams
- General Arrangement Drawings
- Foundation and Steel Structural Supports
- Balance of Plant Equipment
  - Coal Handling System
  - Oxygen Carrier Handling System
  - Ash and Fines Handling System
  - Environmental Control Equipment
  - $\text{CO}_2$ Compression System
Heat & Material Balance

CDCL ISLAND

Primary Loop Cycle

Steam Cycle
10 MWe Modular Pilot Design

- 4 Modules of 2.5 MWe
- 1st module will be built and operated to validate the design.
- Following modules will be constructed
- Integration of the modules operation and controls
Advantage of Modular Design and Sparing Philosophy

- **Startup**
  - Sequential module startup with sharing resources

- **High Reliability**
  - Independent steam generation
  - Easier for scheduling maintenance
  - 4-33% modules provide full load capacity with module-out of service

- **Flexible Operation**
  - Fast response
  - Turn down/up
  - Particle exchange among modules
Host Site: Dover Light & Power

Existing

- 20 MWe Stoker coal fired boiler
- 20 MWe Steam turbine

Planning

- 10 MWe natural gas package boiler
- 10 MWe CDCL unit
- 20 MWe Steam turbine
- Increase power capacity
- Preserve a balance between coal and natural gas
- Potential CO₂ market from local industries
CDCL Module Design
10 MWe Pilot Facility
<table>
<thead>
<tr>
<th>Task 1. Project Management and Planning</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Task 2. 250 kW, Pilot Facility &amp; CFM Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtask 2.1. 250 KW, Pilot Testing</td>
</tr>
<tr>
<td><em>Milestone: 250 kW, Pilot Testing Report</em></td>
</tr>
<tr>
<td>Subtask 2.2. Design, Construction and Testing of Modular CFM</td>
</tr>
<tr>
<td><em>Milestone: Cold Flow Model Testing Report</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10 MWe CDCL pre-FEED STUDY</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>FISCAL YEAR 1</td>
<td>FISCAL YEAR 2</td>
<td>FY3</td>
</tr>
<tr>
<td>4/1/17 - 9/30/17</td>
<td>10/1/2017-9/30/2018</td>
<td>10/1/18 - 3/31/19</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
</tbody>
</table>

- **Q4**
- **Q4**
- **Q1**
### Schedule

#### Task 3. 10 MW, Pilot Facility Design and Costing

- **Subtask 3.1. Host Site Selection and Agreement**
- **Subtask 3.2. Modular CDCL Reactor System Integration Design**
- **Subtask 3.3. Technology Engineering Design Specifications**
  * **Milestone: Design Basis Report**
- **Subtask 3.4. Technology Readiness and Risk Assessment**
- **Subtask 3.5. Oxygen Carrier Commercial Manufacturing Development**
  * **Milestone: Oxygen Carrier Commercial Manufacturing Report**
- **Subtask 3.6. CDCL Large Pilot Facility Design**
  - **Subtask 3.6.1 Detail Heat and Material Balances**
  - **Subtask 3.6.2. Development of Functional Equipment Specifications**
  - **Subtask 3.6.3. Development of a Performance Testing Plan**
  - **Subtask 3.6.4. Integration of Pilot Facility with Existing Equipment**
  - **Subtask 3.6.5. Piping & Instrumentation Diagrams (P&IDs) Drawings**
  - **Subtask 3.6.6. Mechanical, Electrical and Equipment Specifications**
  - **Subtask 3.6.7. System Control Specifications**
  * **Milestone: Design Functional Specifications**
  - **Subtask 3.6.8. Hazard Design and Hazard Operation Analysis**
  - **Subtask 3.6.9. General Arrangement Drawings**
  - **Subtask 3.6.10. Foundations and Steel Structural Support**
- **Subtask 3.7. Building and Utilities**
  - **Subtask 3.7.1. Balance of Plant Specifications and Modifications**
  - **Subtask 3.7.2. Environmental Control Equipment and CO2 Capture**
  - **Subtask 3.7.3. Waste Treatment and Disposal**
  * **Milestone: Emissions Performance and Environmental Control Report**
- **Subtask 3.8. Construction and Operation Cost Estimate**
  - **Subtask 3.8.1. Equipment Cost Estimate**
  - **Subtask 3.8.2. Construction and Operation Schedule**

<table>
<thead>
<tr>
<th>10 MWe CDCL pre-FEED STUDY</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FISCAL YEAR 1</td>
<td>FISCAL YEAR 2</td>
<td>FY3</td>
</tr>
<tr>
<td></td>
<td>4/1/17 - 9/30/17</td>
<td>10/1/2017-9/30/2018</td>
<td>10/1/18 - 3/31/19</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q4</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
</tbody>
</table>
## Schedule

### 10 MWe CDCL pre-FEED STUDY

<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FISCAL YEAR 1</td>
<td>FISCAL YEAR 2</td>
<td>FY3</td>
</tr>
<tr>
<td></td>
<td>4/1/17 - 9/30/17</td>
<td>10/1/2017-9/30/2018</td>
<td>10/1/18 - 3/31/19</td>
</tr>
<tr>
<td>Task 4. Commercial Design &amp; Economic Evaluation</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>Subtask 4.1. Update Commercial Plant Design and Evaluation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 4.2. Update Commercial Cost Analysis and Comparison</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 4.3. CDCL Commercialization Roadmap and Risk Assessment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 5. Final Report and Close Out Documents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subtask 5.1. Final Report and Close Out Documents</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Pilot Demonstration Decision Point Go/No-Go**
- **Phase II Final Report and Close Out Documents**
Acknowledgements

This presentation is based upon work supported by the Department of Energy under the Award: DE-FE-0037654 and the Ohio Development Services Agency under the Award: OER-CDO-D-17-03.