Oxy-Combustion
Pressurized Fluidized Bed
with Carbon Dioxide Purification

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Agenda

- Project Overview
- Background
- Technical Approach / Project Scope
- Progress and Current Status
- Future Plans
- Summary
Phase II Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC) Overview

Description and Impact

**Phase II Description**
- Advance Oxy-PFBC technology to TRL 6 through pilot testing
- Budget: $19.1M ($12M DOE funding)
- Period of Performance: 33 months (7/1/2014 - 3/31/2017)
- Impact: Exceed DOE Goals of >90% CO2 capture with no more than 35% increase in cost of electricity

**Team Members and Roles**
- Gas Technology Institute (GTI) – Lead, PFBC technology
- Linde, LLC – Gas supply, CPU technology, HEX design
- CanmetENERGY – Pilot plant test facility and test support
- Alstom – PFBC design support and commercialization partner
- Pennsylvania State University (PSU) – Fuel & limestone testing, agglomeration model development
- Electric Power Research Institute (EPRI) – End user insight, review of process and cost modeling
- Utility End User - TBD – End user insight, demo plant site and demo plant design support

**Project Objectives**
- Assess the components of the system designed in Phase I to confirm scalability, performance, and cost
- Test the system at subscale pilot facility to evaluate system performance and operability
- Develop algorithms to model the components and system for scale-up
- Use the validated models to predict commercial scale cost of electricity
- Develop Phase III project plan, risk mitigation status and TRL advancement, and identify partners and sites for 30-50 MWth plant

**Schedule**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program Management</td>
<td>Cold Flow Test</td>
<td>Component Tests</td>
<td>Final Report</td>
</tr>
<tr>
<td>Component testing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Design</td>
<td>Pilot Design</td>
<td>Demo Plant Pre-FEED Design</td>
<td>Material &amp; TRL Evaluation</td>
</tr>
<tr>
<td>Analysis</td>
<td>Go/No Go Decision for Testing</td>
<td>MFIX Modeling</td>
<td></td>
</tr>
<tr>
<td>Pilot Test</td>
<td>Pilot Fab</td>
<td>Pilot Testing</td>
<td>Permit Risk Assessment</td>
</tr>
<tr>
<td>Commercialization Plan</td>
<td>Demo and Commercial Plant Economics</td>
<td>TRL 6 Demonstrated</td>
<td></td>
</tr>
</tbody>
</table>
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Oxy-PFBC Technology Overview

INNOVATION
- High power density reactor for coal-fired plants with CO2 capture
  - In-bed heat exchanger for ultra-compact combustor
  - Elutriated flow removes ash and sulfur prior to CO2 recycle
  - 1/3 the size and half the cost of traditional boiler

BENEFITS
- Produces affordable electric power with near zero emissions
- Produces steam for heavy oil recovery using low value feedstock (petcoke, coal, biomass)
- Produces pure CO2 for Enhanced Oil Recovery (EOR)

MARKETS
- Electric power generation with CO2 capture, including CHP
- Heavy oil production (once-through steam)
- Light oil production (CO2 floods)

STATUS
- Long-life, in-bed heat exchangers demonstrated in 1980s
- Two active DOE contracts
- Next step: TRL 6 by Spring 2017 with Pilot scale (1 MWth) testing
Phase 1 Economic Analysis Results

• PFBC system provides affordable COE with additional upgrade paths
• No net increase in COE for CO2 prices/credit > $30/ton, or $18/ton with SCO2
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**Technical Approach**

- **Success Criteria:** Provide knowledge for target operating conditions and design features for the demonstration and commercial scale units. Examples:
  - Use test data to calibrate models for combustion, bed stability and heat removal, enabling a trade of bed height and staging strategy for commercial plants
  - Pressurized staged oxy-combustion system operation is characterized to develop operability criteria and scaled-up system requirements
Risks for Commercial System Development

**Risks/mitigation**

1) Reaction chemistry is too fast/slow
   - **Mitigation:** Coal and sulfation reaction testing, Pilot plant testing

2) Bubbling bed fluidizing velocity inappropriate or unstable
   - **Mitigation:** Cold flow fluidized bed testing, Pilot plant testing

3) In-bed HEX erosion/corrosion shortens life
   - **Mitigation:** Cold flow fluidized bed testing & CFD analysis, Pilot plant testing

4) Flue Gas does not meet emissions or pipeline specs
   - **Mitigation:** Pilot plant testing

5) Pulverization and drying of coal lowers efficiency by using too much CO2 or heat
   - **Mitigation:** Use waste heat for drying

6) Inert particles change size over time leading to inoperable conditions
   - **Mitigation:** Pilot plant testing and analysis

7) Corrosion in convective HEX or recycle gas due to exceeding acid dewpoint limits
   - **Mitigation:** Pilot plant testing and analysis
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Significant Accomplishments

- Completed coal reactivity tests
  - Kinetics model validated, supports performance predictions

- Agglomeration model developed and validated
  - Predictions indicate minimal risk of agglomeration

- Completed pressurized elutriation testing
  - Quantified impact of elevated pressure on residence time; Sufficient time for complete carbon burnout

- Completed pre-FEED design

- 1 MWth pilot construction underway at CanmetENERGY
  - Major equipment installed
  - Gas cleanup skids design complete, fabrication underway
  - Component commissioning started

Testing and analysis results support performance predictions
Coal Kinetics Testing Approach

- Pressurized fluidized bed oxy-combustion coal reactions with gas evolution data
  - CO, CO₂, temperature
  - Flow CO₂ and O₂ in specified ratio
  - Measure time for gas to return to initial concentration

- Reaction rate determined from exit gas composition versus time

### PSU Test Rig Schematic

- **CO₂**
- 90% CO₂ / 10% SO₂
- **O₂**
- Steam

- **Solids feed**
- **Solid feed port**
- **Porous frit**
- **Reactor tube**
- **Reactor shell**
- **Bed Temp**
- **20 µm Metal filter**
- **0.01 µm Ceramic filter**
- **Mixer**
GTI coal reactivity models anchored with PSU test results

- Test results validate GTI coal kinetics models at expected pilot test operating conditions; Reasonable prediction of burnout time

Reduced the risk of reaction kinetics driving combustor temperatures outside of operational limits, and validated residence time requirements
Agglomeration Model Results

Validation Results - Model based on FactSage/MFIX

<table>
<thead>
<tr>
<th>Bed temperature (°C)</th>
<th>Superficial gas velocity (m/s)</th>
<th>Particle diameter (µm)</th>
<th>Defluidization time (h)</th>
<th>Defluidization time obtained from model (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>0.25</td>
<td>425–500</td>
<td>15.36</td>
<td>13.9</td>
</tr>
<tr>
<td>850</td>
<td>0.25</td>
<td>425–500</td>
<td>7.23</td>
<td>8.0</td>
</tr>
<tr>
<td>900</td>
<td>0.25</td>
<td>330–355</td>
<td>7.22</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Predictions indicate low risk of agglomeration at planned operating conditions
Pressurized Elutriation Testing

- **Objective:** Determine effect of pressurization on fine particle elutriation rates and residence time
- **Approach**
  - Continuous injection and capture of fine particles (fuel)
  - For operations at $P > 1$ bar, the fluidization gas is recycled via a centrifugal compressor with a variable speed drive
  - Each filter contains interchangeable filter bags to measure entrainment rate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column Diameter</td>
<td>0.15 m (6 inch)</td>
</tr>
<tr>
<td>Fluidization Section Height</td>
<td>2.95 m</td>
</tr>
<tr>
<td>Column Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Gas Type</td>
<td>Air</td>
</tr>
<tr>
<td>Gas Velocity Tested</td>
<td>1.5-2.5 $U_{mf}$</td>
</tr>
<tr>
<td>Gas Pressure Tested</td>
<td>1, 6, 9, 12 bar</td>
</tr>
<tr>
<td>Gas Temperature Tested</td>
<td>24 ± 1°C</td>
</tr>
<tr>
<td>Inert bed material surrogate</td>
<td>Glass beads ($\rho = 2500 \text{ kg/m}^3$)</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>0.8-1.2 mm</td>
</tr>
<tr>
<td>Coal surrogate (fines)</td>
<td>Glass beads ($\rho = 2500 \text{ kg/m}^3$)</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>30-158 µm</td>
</tr>
<tr>
<td>Fines feeding rate</td>
<td>5.9 kg/h</td>
</tr>
<tr>
<td>Inert Bed Static Height</td>
<td>0.50 m</td>
</tr>
<tr>
<td>L/D</td>
<td>3.3</td>
</tr>
<tr>
<td>Fluidization Time</td>
<td>28 minutes</td>
</tr>
</tbody>
</table>

**Parameters and Values:**

- **Column Diameter:** 0.15 m (6 inch)
- **Fluidization Section Height:** 2.95 m
- **Column Material:** Stainless Steel
- **Gas Type:** Air
- **Gas Velocity Tested:** 1.5-2.5 $U_{mf}$
- **Gas Pressure Tested:** 1, 6, 9, 12 bar
- **Gas Temperature Tested:** 24 ± 1°C
- **Inert bed material surrogate:** Glass beads ($\rho = 2500 \text{ kg/m}^3$)
  - Particle size distribution: 0.8-1.2 mm
- **Coal surrogate (fines):** Glass beads ($\rho = 2500 \text{ kg/m}^3$)
  - Particle size distribution: 30-158 µm
  - Fines feeding rate: 5.9 kg/h
- **Inert Bed Static Height:** 0.50 m
- **L/D:** 3.3
- **Fluidization Time:** 28 minutes
Steady state entrainment is reached by approximately 8 min
3 entrainment rate measurements are done at 8, 18 & 28 min
Mass of fines in the bed \(m_{FB}\) is measured by capturing the entrained fines for 5 min after shutting off the feeder
Fines residence time in the bed: \(\theta = \frac{m_{FB}}{\dot{E}}\)  \((\dot{E} \text{ is the entrainment rate at steady state})\)

Conclusions
Effect of gas velocity, operating pressure, and presence of a tube bank on the fines residence time in the bed was determined

- **Increase in pressure decreased the fines residence time with tube bank present**
- The presence of tube bundle only augmented residence time of the larger particle while that of smaller particles on average remained similar.
- An increase in gas velocity decreased the fines residence time
- Presently collecting data where effect of pressure is determined by keeping the \(U-U_{mf}\) constant.
CO2 Purification Unit (CPU) and Heat Recovery System

- Detailed engineering & procurement of CO2 purification unit for pilot completed
  - Process Description and PFD
  - P&IDs and equipment layout
  - 3-D model of CPU
  - Piping and structural design
  - Factory testing of distributed control system, control logic and display graphics
- Fabrication of skid sub-assemblies are in progress in Linde’s Port of Catoosa facility
- DCC and LICONOX columns and other equipment shipped to Canmet in Ottawa. All skids expected to be shipped by Oct. 2016.

**CPU equipment enables reduced cost relative to traditional cryogenic units**

Engineering and procurement of CPU completed; Skid assembly is in progress
### CPU Sub-systems

**Process simulation for pilot confirms that all critical systems can achieve target performance**

<table>
<thead>
<tr>
<th>System</th>
<th>TRL</th>
<th>Target Performance</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC</td>
<td>6</td>
<td>Complete Removal HCl</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature &lt;60deg C</td>
<td></td>
</tr>
<tr>
<td>LiCONOX</td>
<td>5</td>
<td>&gt; 90% Nox removal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;95% SOx removal</td>
<td></td>
</tr>
<tr>
<td>De-OXO</td>
<td>5</td>
<td>&lt;100 ppm O2</td>
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</table>

**Flue Gas Feed**

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Temperature (deg C)</td>
<td>230</td>
</tr>
<tr>
<td>CO2 (mol%)</td>
<td>66</td>
</tr>
<tr>
<td>H2O (mol%)</td>
<td>31</td>
</tr>
<tr>
<td>O2 (ppm)</td>
<td>20,000</td>
</tr>
<tr>
<td>SOx (ppm)</td>
<td>482</td>
</tr>
<tr>
<td>NOx (ppm)</td>
<td>1000</td>
</tr>
<tr>
<td>HCl (ppm)</td>
<td>1025</td>
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</table>

**DCC Output**

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Temperature (deg C)</td>
<td>60</td>
</tr>
<tr>
<td>CO2 (mol%)</td>
<td>94</td>
</tr>
<tr>
<td>H2O (mol%)</td>
<td>1.8</td>
</tr>
<tr>
<td>O2 (ppm)</td>
<td>29,000</td>
</tr>
<tr>
<td>SOx (ppm)</td>
<td>683</td>
</tr>
<tr>
<td>NOx (ppm)</td>
<td>1505</td>
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<tr>
<td>HCl (ppm)</td>
<td>0</td>
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</table>

**LiCONOX® Output**

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Temperature (deg C)</td>
<td>38</td>
</tr>
<tr>
<td>CO2 (mol%)</td>
<td>95.4</td>
</tr>
<tr>
<td>H2O (mol%)</td>
<td>0.6</td>
</tr>
<tr>
<td>O2 (ppm)</td>
<td>29,000</td>
</tr>
<tr>
<td>SOx (ppm)</td>
<td>29</td>
</tr>
<tr>
<td>NOx (ppm)</td>
<td>128</td>
</tr>
<tr>
<td>HCl (ppm)</td>
<td>0</td>
</tr>
</tbody>
</table>

**CO2 Product**

<p>| | |</p>
<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Temperature (deg C)</td>
<td>118</td>
</tr>
<tr>
<td>CO2 (mol%)</td>
<td>98.4</td>
</tr>
<tr>
<td>H2O (mol%)</td>
<td>1.2</td>
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<tr>
<td>O2 (ppm)</td>
<td>100</td>
</tr>
<tr>
<td>SOx (ppm)</td>
<td>29</td>
</tr>
<tr>
<td>NOx (ppm)</td>
<td>128</td>
</tr>
<tr>
<td>HCl (ppm)</td>
<td>0</td>
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</tbody>
</table>

**De-OXO Reactor**

**Direct Contact Cooler (DCC)**

**Flue Gas Feed**

**LiCONOX**

**De-OXO Reactor**

**Direct Contact Cooler (DCC)**

**LiCONOX**

**CO2 Product**

**De-OXO Reactor**

**Direct Contact Cooler (DCC)**

**LiCONOX**

**CO2 Product**

**De-OXO Reactor**

**Direct Contact Cooler (DCC)**

**LiCONOX**

**CO2 Product**

**De-OXO Reactor**

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**De-OXO Reactor**

**Direct Contact Cooler (DCC)**

**LiCONOX**
Pilot Plant Construction

- Enhancement of building utilities (structural, water, electrical, compressed air) complete. Canadian Federal government funding used for all building enhancements.
- All contracts for major equipment awarded
- Pilot plant equipment installation in progress (40% complete) including:
  - Bulk gas supply systems for O₂, N₂, CO₂, and NG
  - Bulk fuel and sorbent handling systems
  - GTI equipment including combustor and pressure vessel, particulate filter, convective heat exchanger
  - Linde direct contact cooler and Liconox™ columns
Pilot Plant Layout & Hardware Progress

- Coal & limestone hoppers
- Fly ash filter
- DCC & Liconox bases
- CHX2 + pressure vessel
- Combustor spool
- PFBC Pressure Vessel
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Future Plans

Phase II plans

- Fabrication and testing of the pilot scale rig
  - Update performance and technoeconomic analysis
  - Material and TRL evaluation
  - Anchor analysis codes
- CFD modeling
- Complete commercialization activities
Oxy- PFBC Commercialization Plan

Phase I – 2012 – 2013

Cold Flow Testing & Bench Scale Kinetics (TRL 3)

Demonstrates:
- Coal & sulfation reaction rates at high CO2 and H2O partial pressure
- Heat transfer coefficients
- Bubble control
- Residence time

Duty ~1 MWth
Size ~1 foot scale

Phase II – 2014 – 2017

Pilot Plant (TRL 6)

Demonstrates:
- Pressurized system operation
- Elutriated bed operation and chemistry
- Flue gas clean-up
- Erosion risks

Duty ~30-50 MWth
Size ~3-4 foot scale

Phase III – 2017 – 2021

Large Pilot / Demo Plant

Demonstrates:
- Operation at scale
- Component life
- Operating parameters
- Maintenance approaches
- Erosion risks

Duty 275+ MWe
Size ~20+ foot scale

Phase IV – 2020 – 2025

Commercial Demonstration 5+ years

Validates:
- System efficiency
- Capital costs
- O&M costs

Plan for commercial scale demonstration by 2025
Summary

- Component testing completed and validates performance predictions
- Agglomeration model validated and indicates low agglomeration risk
- 1 MWth pilot plant construction well underway with major equipment installed
- Pilot testing expected to start late this year
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**NETL Program Manager:** Robin Ames