Alstom’s [GE] Chemical Looping Combustion Technology with CO2 Capture for New and Existing Coal-fired Power Plants (FE0009484)

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*Imagination at work*
Chemical Looping Combustion
Advanced oxy-combustion without air separation losses

- Avoids CAPEX and high energy consumption of cryogenic air separation unit (ASU)
- No large gas recirculation
- Two interconnected boilers
- Low cost coal-based power generation with CO₂ Capture
GE Limestone Chemical Looping Combustion

**Product Attributes:**
- Lowest cost option for coal Power Generation with CCS
- Lowest energy penalty
- Fuel flexible
- Near zero emissions
- Useful solid ash by-product
- Application flexible:
  - Coal-based power, syngas, hydrogen
- Builds on CFB experience
- Uses conventional construction and materials

**Targets:**
- LCoE <20% increase vs. Plant without CCS
- CO₂ Capture Cost < $25/ton
- Efficiency <10% CCS penalty vs Plant w/o CCS
Chemical Looping Combustion Process

Combustion Products \((\text{CO}_2+\text{H}_2\text{O})\)

O\(_2\) Depleted air

Steam to cycle

Fuel reactor

Hot carrier with \(\text{O}_2\)

Cold Carrier Without \(\text{O}_2\)

Air reactor

\(\text{O}_2\)

\(\text{Coal}\)

Air \((\text{O}_2+\text{N}_2)\)
Limestone Chemical Looping–Combustion Process

Oxygen carrier:
- CaS-CaSO$_4$ from limestone
- Low cost; availability
- No ash/carrier separation (solids soup like CFB)

Chemistry:

**Reducer:**
- CaO + H$_2$S => CaS + H$_2$O
- C + CO$_2$ => 2 CO
- CaSO$_4$ + 4 CO => CaS + 4 CO$_2$
- H$_2$O + CO <=> H$_2$ + CO$_2$
- CaO + CO$_2$ <=> CaCO$_3$

Carbon/carrier separation

**Purpose**
- Sulfur capture
- Carbon gasification
- CO$_2$/CaS formation
- Water Gas shift for H$_2$
- CO$_2$ capture for H$_2$
- Cold flow tests

**Oxidizer:**
- CaS + 2 O$_2$ => CaSO$_4$

- CaS combustion
Possible Unfavorable Side Reactions

**Oxidizer**

Sulfur Loss side-reaction:
- \( \text{CaS} + 1.5 \text{O}_2 \rightarrow \text{CaO} + \text{SO}_2 \)

Carbon Carryover side-reaction:
- \( \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \)

**Reducer**

Sub-Stoichiometric Reactions:
- Low CO concentration
  - \( \text{CaSO}_4 + \text{CO} \rightarrow \text{CaO} + \text{CO}_2 + \text{SO}_2 \)
- Low H\(_2\) concentration
  - \( \text{CaSO}_4 + \text{H}_2 \rightarrow \text{CaO} + \text{H}_2\text{O} + \text{SO}_2 \)

**Universal**

Sulfur Loss by CaS-CaSO\(_4\) direct reaction:
- \( 3\text{CaSO}_4 + \text{CaS} \rightarrow 4\text{CaO} + 4\text{SO}_2 \)

CaSO\(_4\) thermal decomposition:
- \( \text{CaSO}_4 \rightarrow \text{CaO} + \text{SO}_2 + \frac{1}{2} \text{O}_2 \)

Control process conditions to minimize side reactions and optimize performance
GE - Chemical Looping Development
Managed Scale-up Steps

Reference Design Studies

Scale-Up

1996-2000

Bench Tests
TRL 3 to 5

2000-2016

Pilot Plant
65 & 100 kWth
TRL 3 to 5

2012-2016

CFD Modeling, Controls and Tool Development

2017-2025

Demonstration
10 - 50 MWe
TRL 7 or 8

Commercial Scale
>100 MWe
TRL 9

Prototype
TRL 5 to 6

Progressive development – US & EU – MeOx & CaOx Carriers

Cold Flow Models
GE – Limestone Chemical Looping Development

Technology Development

LCL-C™ Combustion FE0009484
LCL-G™ Syngas FE0023497
LCL-C™ Reducer Gas FE0025073

US DOE collaborations
NDIC to verify application to ND Lignite


Product Demo

Secure Host
Dedicated prototype test with project fuel(s)

today
Pre- FEED
Engineering, Procurement and Construction Phase
Demo Phase

10 - 25 MWe steam demo
150 MWe steam demo

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Limestone-based Chemical Looping Combustion Project FE0009484

Goal
To develop a chemical looping combustion process with 90% CO$_2$ capture at 20% or less increase in cost of electricity compared to new coal power plants without capture.

Specific Project Objectives

- Address technology development gaps
  - Solids Transport
  - Carbon Loss / CO$_2$ Capture
  - Sulfur Retention

  using
  - CFD and Cold Flow modeling
  - Bench-scale testing
  - 100 kWt Pilot-scale Test Facility (PSTF) testing
  - 3 MWt Prototype testing

- Generate information needed for 10-25 MWe Demonstration
- Update techno-economic analysis based on test results
Limestone-based Chemical Looping Combustion
FE0009484

Project Start: Oct 2013  End: June 2017

Major Milestones Achieved

• Techno-economic studies on four LCL-Combustion cases  Completed June 2013

• Two 3 MWt test programs with auto-thermal operation assessing technical gaps
  Completed  Oct 2014 and July 2015

• Relocated 3 MWt Prototype to new GE Clean Energy Laboratory location (Bloomfield, CT)
  Completed  Aug  2015

• Installed new 100 kWt Chemical Looping Facility  Completed Oct 2015

• Six 100 kWt test programs addressing technical gaps  Completed Nov 2015 – June 2016
100 kWt PSTF Testing

Allows testing under highly controlled conditions with detailed solids and gas mapping to better understand behavior.

Configuration flexible to run single and double loop tests, vary Reactor volumes/residences time, etc.

Testing conducted to assess technical gaps and impacts key parameters on performance:

- Solids flow and circulation behavior
- Carbon conversion and residence time requirements
- Coal volatile cracking and conversion
- Oxidizer CaS oxidization behavior
- Oxidizer/Reducer sulfur capture and release mechanisms
- Behavior of different fuel types
### PSTF Results* - June 2016 Campaign

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam location</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>1,2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Limestone pph</td>
<td>17.3</td>
<td>17.7</td>
<td>17.8</td>
<td>18.0</td>
<td>17.0</td>
<td>17.5</td>
<td>17.4</td>
<td>17.5</td>
</tr>
<tr>
<td>BFB % CO</td>
<td>2.0</td>
<td>3.0</td>
<td>4.5</td>
<td>4.4</td>
<td>5.6</td>
<td>5.3</td>
<td>6.3</td>
<td>8.0</td>
</tr>
</tbody>
</table>

| Ox SO2, ppm | 371 | 99  | 34  | 0   | 4   | 0   | 26  | 0   |
| BFB SO2, ppm | 3100 | 2300 | 2200 | 1500 | 1100 | 1500 | 1600 | 200 |
| BFB Total Red S, ppm | -   | -   | -   | -   | 520 | 600 | -   | 280 |
| Sulfur Retained, % | 2.9 | 37.4 | 24.1 | 62.5 | 62.4 | 52.5 | 61.5 | 94.0 |

| % C gasified | 83  | 84  | 80  | 86  | 82  | 79  | 81  | 70  |
| % C carryover | 15.5 | 14.4 | 15.4 | 12.5 | 15.2 | 14.5 | 13.6 | 20.7 |
| % Ox demand | 7.9 | 10.3 | 13.3 | 14.3 | 17.3 | 15.9 | 18.3 | 18.7 |

* Preliminary results analysis
## Performance Summary

<table>
<thead>
<tr>
<th>Carbon Conversion Performance</th>
<th>Commercial Goal</th>
<th>3 MW Prototype - Current Level</th>
<th>Project Success Criteria (3 MW Prototype)</th>
<th>100 kW PSTF - Current Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Gasified in Reducer (%)</td>
<td>&gt;95</td>
<td>40 - 50</td>
<td>&gt;80</td>
<td>70 - 85</td>
</tr>
<tr>
<td>Unburned Carbon Loss in Ash (%)</td>
<td>&lt;0.5</td>
<td>Up to 20</td>
<td>&lt;5</td>
<td>3 -5</td>
</tr>
<tr>
<td>Carbon Carryover to Oxidizer (%)</td>
<td>1</td>
<td>20 - 40</td>
<td>&lt;20</td>
<td>13 -21</td>
</tr>
<tr>
<td>Reducer Gas Oxygen Demand (% of Stoichiometry O₂)</td>
<td>&lt;5</td>
<td>25 - 15</td>
<td>&lt;10</td>
<td>8 -19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sulfur Retention by Reactors</th>
<th>Commercial Goal</th>
<th>3 MW Prototype - Current Level</th>
<th>Project Success Criteria (3 MW Prototype)</th>
<th>100 kW PSTF - Current Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur Capture (% of S input)</td>
<td>&gt;85</td>
<td>Net Sulfur Loss</td>
<td>&gt;70</td>
<td>0 - 94</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Solids Transport</th>
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</thead>
<tbody>
<tr>
<td>Solids Circulation Rate</td>
</tr>
<tr>
<td>Dipleg Flushing (Frequency)</td>
</tr>
<tr>
<td>Solids Loss Rate Thru Cyclones (lb/MBtu- Fired)</td>
</tr>
</tbody>
</table>

**Significant Progress Achieved to Targets**
GE Limestone Chemical Looping

Current status of development

1) Solids Transport
   • Need stable solids flow and low solids loss thru cyclone. Experienced solids flow instability during coal firing in 3 MWt tests
   • Mitigation with mechanical valves; reduced carbon in circulating solids. Have achieved good solids flow control and stable operation at 100 kWt.

2) Carbon Loss / Carbon Carryover
   • Need low loss thru cyclones and low carbon carryover to Oxidizer to achieve % carbon capture target. Carbon loss levels of 1-20% loss thru cyclones and 20-40% carbon carryover to oxidizer during 3 MWt tests
   • Mitigation with larger fuel reactor and improve solids management at 100 kWt.

3) Carrier stability and Sulfur Loss
   • For limestone carrier, need to control of sulfur
     Still challenge; have achieved acceptable sulfur retention at 100 kWt, further optimize with carbon conversion.
   • For all carriers, need acceptable attrition, agglomeration and reactivity life; achievement currently acceptable

4) Product Gas Quality (FE 0025073)
   • Need complete fuel conversion – unburned combustibles in gas from Fuel Reactor
   • Assessing mitigation by reaction enhancement (mixed carriers, increased temperatures, steam vs CO₂ gasification); on-going
   • Assessing mitigation by post processing (O₂, second stage CLC, special GPU with recycle of CO and CH₄)
Next Steps: Testing Plan

100 kWt PSTF Test 7: Continued Performance Improvements (Sept 2016)
   • Continued Parametric Testing (Temperatures, Circulation Rate, Fluidization Flows, CO2 and Steam Reaction Gas, etc.)
   • Addition of Ilmenite (10% and 20% Ilmenite blends)

100 kWt PSTF Test 8/9: LCL-C Optimization (Oct/Nov 2016)
   • Reconfigured System As Needed Based On Test 7 Results
   • Modify Reducer & Oxidizer Cyclone Systems to Improve Flyash Capture (Sulfur Retention and Carbon Loss Improvement)
   • Parametric Testing Over Selected Conditions

3 MWt Prototype Conformation Testing (Feb 2017)
   • Validation 100kWt PSTF results and solutions for technical gaps
   • Define Performance and key design information
GE Limestone Chemical Looping Combustion

Summary

• Techno-economic studies continue to indicate that Limestone Chemical Looping technology has the potential for lowest cost coal-based power generation with CO₂ capture

• Significant knowledge and understanding has been developed through comprehensive testing, modeling and engineering studies

• Autothermal operation has been achieved at the 3 MWₜₜ scale confirming chemical looping reactions and performance potential

• Development gaps have been identified and are being addressed

• The 100 kWt PSTF has been an excellent tool to develop chemical looping and address technical gaps

• Substantial progress has been achieved in addressing Limestone Chemical Looping technical gaps and GE is on track to validate the process for the next step of large pilot demonstration
Acknowledgements and Disclaimer

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