ALSTOM’S LIMESTONE-BASED (LCL™) CHEMICAL LOOPING PROCESS

OCC3, Ponferrada, September 12th 2013

John Marion

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a-ALSTOM
b – US-DOE/NETL
Chemical Looping
Fossil fuel Power with CCS at lower cost than alternates

“Breakthrough CCS Technology”

“Transformational Coal Power Technology”

➢ Alstom targets:
  ✓ Coal power generation for electricity
  ✓ Coal/Petcoke to liquid fuels and chemicals

CO₂ capture process in oxy-combustion using solid oxygen carriers rather than an ASU (cryogenic O₂ production), avoiding related cost & energy penalty
Chemical Looping Process: Options and Applications

Applications

- CO₂ Capture – PC Retrofit
- CO₂ Capture – CFB Retrofit
- CO₂ Capture-Ready Power Plant
- Advanced Steam Cycles with CO₂ capture

- IGCC with Down-Stream CO₂ Capture
- Industrial Syngas production
- Coal-to-Liquid Fuels

- CO₂ Capture – PC Retrofit
- CO₂ Capture – CFB Retrofit
- CO₂ Capture-Ready PC/CFB Power Plant
- Advanced Steam Cycles with CO₂ capture
- IGCC with CO₂ Capture
- Fuel Cell Cycles with CO₂ Capture
- Industrial Hydrogen with CO₂

Flexible technology with low cost
Limestone Based Chemical Looping
CaS - CaSO4 Loop in CFB Reactors

Fuel Reactor (Endothermic - Reducer)

\[ 2 \text{C}_{\text{fuel}} + \text{CaSO}_4 + \text{Heat} \rightarrow \text{CaS} + 2 \text{CO}_2 \]

\[ 8 \text{H}_{\text{fuel}} + \text{CaSO}_4 + \text{Heat} \rightarrow \text{CaS} + 4\text{H}_2\text{O} \]

Air Reactor (Exothermic - Oxidizer)

\[ \text{CaS} + 2\text{O}_2 \rightarrow \text{CaSO}_4 + \text{Heat} \]

CaS - CaSO4 Combustion Loop in CFB Reactors
Calcium-based oxygen carrier process is suited to coal
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Alstom Targets – CLC for Coal Power with CCS

- **LCoE <30% penalty** vs. Plant without CCS *(stretch target < 20%)*

- **CO2 Capture Cost < 25 €/ton** *(stretch target < 15 €/ton)*

Targets appear to be achievable
Reference Plant Studies

<table>
<thead>
<tr>
<th>Date</th>
<th>Plant Size</th>
<th>STUDY</th>
</tr>
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<tbody>
<tr>
<td>2013</td>
<td>550 MWe</td>
<td>Phase 1 FOA (4 Cases Just Completed) (DOE)</td>
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<tr>
<td>2012</td>
<td>550 MWe</td>
<td>Update of 2003 Study (DOE)</td>
</tr>
<tr>
<td>2006</td>
<td>400 MWe</td>
<td>CO₂ Product Gas (Alstom)</td>
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<tr>
<td>2005</td>
<td>455 MWe</td>
<td>ENCAPco₂ (EU-FP6)</td>
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<tr>
<td>2003</td>
<td>220 MWe</td>
<td>Green House Gas Control (DOE)</td>
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Latest analysis is consistent with prior studies, that CLC has potential to be lowest LCoE for coal-based power with CCS
Alstom Chemical Looping Reference Studies
latest analysis – completed June 2013

- **Case 1** [base]  Atm. pressure LCL-C™ system using “fast CFB” transport reactors
- **Case 2**  Atm. pressure LCL-C™ system with the Reducer reactor in the CFB mode,
- **Case 3**  Atm. pressure LCL-C™ system of Case 1 with an AUSC steam cycle,
- **Case 4**  3 – 7 bar pressurized LCL-C™ system with an AUSC steam cycle

Latest analysis is consistent with prior studies, that CLC has potential to be lowest LCoE for coal-based power with CCS
Comparison of Nominal USC-660MWe gross Boiler Plants: Oxy-PC, Oxy-CFB, and LCL™ (1 atm and 7 atm)
### Performance and Economic Comparison

#### Oxy-Combustion vs. Chemical Looping

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<th>Atm Pressure Oxy-Combustion</th>
<th>Case 1 LCL™ SC 1 atm</th>
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<tr>
<td>Net Plant Efficiency Change Relative to Atm. Air-Fired SCPC w/o CCS</td>
<td>-26%</td>
<td>-9%</td>
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<tr>
<td>Capital Cost Change Relative to Atm Air-Fired SCPC w/o CCS</td>
<td>+62%</td>
<td>+14%</td>
</tr>
<tr>
<td>Levelized COE Increase Relative to Atm. Air-Fired SCPC w/o CCS</td>
<td>53.5%</td>
<td>19.5%</td>
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<tr>
<td>CO₂ Capture ($/ton CO₂) [€/ton]</td>
<td>79.3</td>
<td>27.0 [20]</td>
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**SCPC w/o CCS – 550 MWe net Reference Plant Basis:**

- Net Plant Efficiency: 39.3% HHV
- Total Overnight Capital Cost: 2452 $/kW [1816 €/kW]
- Cost of Electricity: 81.0 $/MWhr [60 €/MWhr]
- Fuel: Illinois #6 bituminous coal

**LCL-C™ has potential to be lowest LCoE for coal-based power with CCS**

Pre-, Post-, or known “transformational technologies” such as POx, SCO2
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Alstom - Chemical Looping Process
Managed Development and Scale-up Steps

We are here, Significant progress made

1st Worldwide to achieve “Auto Thermal Operation”
Limestone Based (LCL™) CLC Process
3 MWth Prototype – Windsor, CT, USA

Chemical looping – 3 MWth CaOx Prototype - Coal

Main objectives:
- Design, engineering, construction, commissioning and operation of a 3 MWth CaS prototype
- Autothermal operation of CaOx prototype
- Proof of concept – deliver data required to scale up to Demo and commercial size

50 month program
- First coal fire completed 2Q 2011
- Autothermal Operation Achieved – July 2012
- 40+ Hr. Autothermal Operation Achieved – May 2013
- Over 350+ hours of prototype operation

Total budget: 15 M$, cost share by US-DOE and Alstom
Partners: US-DOE/NETL & Alstom
Limestone Based (LCL™) CLC Process
3 MWth Prototype – Windsor, CT, USA

Main SPCV and Reducer Cactus

Reducer Primary Cyclones

Main SPCV Control Valve (SPCV)

Reducer

Oxidizer

Pressurizing Column (RPC)

Main Dip Leg

Dip Leg

N2

CO2

top of oxidizer

65 ft

RBO

Oxidizer, Startup Burner & RBO

Alstom Limestone CLC (LCL™) IEA 0CC3_13 Sept’13 Ponferrada, Spain_J.Marion, I. Abdally P 15

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Achievements to date:

1. 3 MWt prototype achieved sustained reactions or so called “auto-thermal” operation in July 2012. First in the World for chemical looping technology.

2. Total of 52 hours of autothermal operation and over 350 hrs of cumulative facility operation as of June 2013.

LCL™ process optimization at prototype scale (3 MWt) is on-going.
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Limestone Chemical Looping (LCL™) Development

Advanced Oxy Combustion – Next Steps proposed

- **Continued testing on the 3MWth prototype**
  - Modify Prototype based on lessons learned
  - Parametric process optimization tests

- **Pre-FEED and FEED Study of a small scale demonstration plant**
  - Develop project with host and partners
  - Develop project & product specifications
  - Develop LCL™ island design
  - Complete pro-forma of the demonstration unit

Paving the road to a commercial product
Next Steps: Development & Commercialization - Timeline

Small Demo Scale > 25 MWe

Pre- FEED
FEED
Prototype Tests Campaigns
- Optimization tests
- Demo specific tests

Testing Phase
Pre- FEED FEED Engineering, Procurement & Construction Phase Demo Testing Phase


Commercial Scale Demo > 100MWe

Proposal made for DOE-FOA 636 Phase II Funding

Secure Demo Funding

DOE-FOA 636 Phase I Funding 1MUSD Awarded

* pre-FEED + partial FEED Demo related Studies

Resume testing at 3 MWt pilot
Summary

• CLC is a break-through technology in terms of efficiency and economics, and has the potential of being the lowest cost CO₂ capture option

• CLC is a flexible technology that can be configured in a new or retrofit application to produce Syngas, hydrogen or power

• DOE, ÉCLAIR & ACCLAIM programs are validating Limestone based (LCL™) and MeOx Chemical Looping Combustion at 1-3 MWth prototype scale

• Next step before a large commercial unit will be a demonstration steam generator unit ~10-50 MWe scale
Thank you for your attention!

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