Slipstream pilot plant demonstration of an amine-based post-combustion capture technology for CO$_2$ capture from coal-fired power plant flue gas

DOE funding award DE-FE0007453

2014 NETL CO$_2$ Capture Technology Meeting
Krish R. Krishnamurthy, Linde LLC
July 30, 2014
Pittsburgh, PA
The Linde Group Overview
Fully integrated gases and engineering company

Founded | 1879
Sales | ~$20 billion
Employees | ~62,000
Countries | >100

Linde Engineering
Technology-focused

Air Separation
Global #1

Hydrogen/Syn Gas
Global #2

Olefins
Global #2

Natural Gas
Global #3

Leveraging Synergies

Linde Gas - Tonnage
World-class operations

HyCO Tonnage Plants
>70 plants

ASU Tonnage Plants
>300 plants

CO2 Plants
>100 plants

Packaged Std Plants
>1,000 plants
# Project Budget: DOE funding and cost share (Amended Feb 2014)

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<tr>
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<tr>
<td>DOE Funding</td>
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<td>$10,441,507</td>
<td>$3,107,167</td>
<td>$16,218,847</td>
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<td>Cost Share</td>
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<td>$3,237,450</td>
<td>$776,792</td>
<td>$4,681,785</td>
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<td>Total Project</td>
<td>$3,337,716</td>
<td>$13,678,957</td>
<td>$3,883,959</td>
<td>$20,900,633</td>
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Cost share commitments:
- Linde: $4,091,046
- BASF: $493,360
- EPRI: $97,379

Note: * BP3 continuation proposal sets the BP3 performance dates as from Dec 1, 2014 to Aug 31, 2016
<table>
<thead>
<tr>
<th>Partner/Organization</th>
<th>Lead contact(s)</th>
<th>Key Role(s)</th>
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</thead>
<tbody>
<tr>
<td>DOE-NETL</td>
<td>Andrew P. Jones, Project Manager</td>
<td>-Funding &amp; Sponsorship</td>
</tr>
<tr>
<td>Linde LLC</td>
<td>Krish Krishnamurthy, PI Stevan Jovanovic, Technical Lead</td>
<td>-Prime contract -Overall program management -Operations and testing</td>
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<tr>
<td>BASF</td>
<td>Sean Rigby (BASF Corp) Gerald Vorberg (BASF SE)</td>
<td>-OASE® blue technology owner -Basic design -Solvent supply and analysis</td>
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<tr>
<td>EPRI</td>
<td>Richard Rhudy</td>
<td>-Techno-economics review -Independent validation of test analysis and results</td>
</tr>
<tr>
<td>Southern Co./NCCC</td>
<td>Frank Morton Michael England</td>
<td>-NCCC Host site (Wilsonville, AL) -Infrastructure and utilities for pilot plant build and operations</td>
</tr>
<tr>
<td>Linde Engineering, Dresden</td>
<td>Torsten Stoffregen</td>
<td>-Basic engineering -Support for commissioning -Operations and testing</td>
</tr>
<tr>
<td>SFPC (LENA)</td>
<td>Keith Christian</td>
<td>-Detailed engineering -Procurement and installation</td>
</tr>
</tbody>
</table>
Project Objectives

Overall Objective

— Demonstrate Linde-BASF post combustion capture technology by incorporating BASF’s amine-based solvent process in a 1 MWel slipstream pilot plant and achieving at least 90% capture from a coal-derived flue gas while demonstrating significant progress toward achievement of DOE target of less than 35% increase in levelized cost of electricity (LCOE)

Specific Objectives

— Complete a techno-economic assessment of a 550 MWel power plant incorporating the Linde-BASF post-combustion CO₂ capture technology to illustrate the benefits
— Design, build and operate the 1MWel pilot plant at a coal-fired power plant host site providing the flue gas as a slipstream
— Implement parametric tests to demonstrate the achievement of target performance using data analysis
— Implement long duration tests to demonstrate solvent stability and obtain critical data for scale-up and commercial application
Project Overview: Key Drivers

— Post-combustion CO$_2$ capture technology is flexible and can be applied to both new and existing power plants

— Solvent based technologies are today the leading option as they have been commercially applied at large scale in other applications (e.g. natural gas processing, syngas purification)

— Advanced amine based technologies with properly selected solvent can overcome performance and stability issues with the current state-of-the-art reference MEA solvent

— The specific advanced amine based solvent (BASF OASE® blue ) offers key performance benefits (increased CO$_2$ loading, reduced regeneration steam requirements, stable in the presence of oxygen and significant potential for lower capital costs)
BASF OASE® blue Technology Development
Designed for PCC Applications

Equilibrium Kinetics Stability

Fundamental Lab Scale R&D:
Advanced Solvents Screening, Development,

BASF Miniplant,
Ludwigshafen, Germany:
Solvent Performance

0.45 MWe PCC Pilot,
Niederaussem, Germany:
Preliminary Process Optimization
Niederaussem Pilot Plant: Main results of Phase I

- OASE blue has a 20% lower specific energy consumption
- OASE blue has a significant lower solvent circulation rate

Even after six months of operation, the oxidation rate of OASE blue was extremely low.
Pilot Plant Niederaussem Test run history
Phase 2 focus: Long term testing evaluating materials, solvent degradation and emissions reduction

Status: Phase I and II (Dec 2013)
- > 26,000 hours operation
- > 7200 t CO₂ captured
- availability: 97%
Linde-BASF advanced PCC plant design

- Optimized Blower Concept
- Advanced emission control system
- High capacity structured packing
- Advanced Column Material & Design
- Optimized Energy Consumption

Diagram:
- FLUE GAS FEED downstream of DCC & Blower
- CO₂-Lean stream
- Gravity Flow Interstage Cooler
- Absorber
- Interstage cooler
- Filter
- Condenser
- Reboiler
- LP Steam
- Condensate
- Make-up Water
- Higher Desorption Pressure
- Optional Interstage Heater
- El. Power Supply
- Cooling Water In
- Cooling Water Out

- Advanced emission control system
- High capacity structured packing
- Advanced Column Material & Design
- Optimized Energy Consumption
Linde-BASF PCC Plant Design for 550 MWe PC Power Plant

- Single train PCC design for ~ 13,000 TPD CO₂ capture
- 40-50% reduced plot area to 180m x 120 m
Comparative PCC Performance Results
Linde-BASF vs Reference DOE/NETL Case*

Effect of PCC technology improvements on incremental energy requirement for power plant with CO2 capture and compression

Energy demand for different PCC plants
- NETL-MEA
- Linde-BASF PCC (LB-1)
- Linde-BASF PCC (LB-2)

Specific energy demand elements
- Reboiler Duty
- Cooling Duty
- Electrical Power

Incremental fuel requirement for CO2 capture and compression
- NETL-MEA
- Linde-BASF PCC (LB-1)
- Linde-BASF PCC (LB-2)

* Reference Case # 10 of DOE-NETL 2007/1281 Report
Power plant efficiency improvements and LCOE reductions with Linde-BASF PCC technology

Incremental improvements in power plant efficiency from MEA based PCC to LINDE-BASF LB-2 Option

- NETL - MEA: 24.9%
- Advanced Solvent: 1.76%
- PCC Optimization (LB-1): 1.39%
- Heat and Power Integration (LB-2): 1.35%
- LINDE-BASF (LB-2): 29.4%

Incremental Reductions in Levelized Cost Of Electricity from MEA based PCC to LINDE-BASF LB-2 Option

- NETL - MEA: $95
- Advanced Solvent: $101.6
- Process Enhancements: $107
- PCC Optimization (LB-1): $103.5
- Heat and Power Integration (LB-2): $101.2
- LINDE-BASF: $95

Key Budget Period 1 Project Milestones


— Submit project management plan (03/09/2012) √
— Conduct kick-off meeting with DOE-NETL (11/15/2011) √
— Complete initial techno-economic analysis on a 550 MWel power plant (05/04/2012) √
— Complete basic design and engineering of a 1 MWe pilot plant to be tested at NCCC (06/20/2012) √
— Execute host site agreement (10/31/2012) – completed 01/09/2013 √
— Complete initial EH&S assessment (10/31/2012) – Completed 12/14/2012 √
— Complete detailed pilot plant engineering and cost analysis for the 1 MWe pilot plant to be tested at NCCC (01/31/2013) – Completed 02/15/2013 √
### Project progress and accomplishments by task
(BP2 initiated in March 2013 and in progress)

<table>
<thead>
<tr>
<th>Task #</th>
<th>Task Description</th>
<th>Key Objectives</th>
<th>Accomplishments</th>
</tr>
</thead>
</table>
| 6      | Supply of plant equipment            | - Complete the equipment and modules purchases (including fabrication shop installation) and have them transported to the NCCC site  
         |                                                     | - Prepare the site (civils and utilities) for pilot plant installation                                | - Completed purchase orders and fabrication contracts (June 2013)                                     
         |                                                     |                                                                                                      | - Completed site preparation and foundations installation to receive pilot plant at NCCC (Jan. 2014)  
         |                                                     |                                                                                                      | - Completed shop fabrication of equipment and modules and associated engineering checks (Dec 2013)    
         |                                                     |                                                                                                      | - Shop fabrication of absorber/stripper columns completed and shipped to NCCC site in March 2014    |
| 7      | Plant construction and commissioning | - Complete the installation of the pilot plant at site                                               | - All modules, columns and equipment (analytical container, solution storage tank) have been installed at site |
         |                                                     | - Enable mechanical completion of the pilot plant                                                    | - All piping, electrical, instrumentation and control installation complete (except for punch list from pre-start up safety review and Hazop actions update) |
         |                                                     |                                                                                                      | - Flushing of the sub-systems, pressure testing, I&C loop checking completed (except punch list items) |
BP2 project schedule: Key dates

- Construction process safety review (PSR4) completed Dec. 9, 2013
- NCCC site orientation and training for construction personnel: Dec 2013-Jan 2014
- Linde HSE site for project: Initiated Jan 2014/ongoing reporting
- Pre-start up safety review (PSSR) completed July 17, 2014 with follow on actions ongoing
Key BP2 Project Milestones and Status


— Complete purchase orders and fabrication contracts for the 1 MWe pilot plant (06/30/2013) √

— Complete shop fabrication of equipment and modules and associated engineering checks (12/15/2013) – Completed 12/20/2013 √

— Complete site preparation and foundation installations at NCCC to receive pilot plant (11/15/2013) – Completed 1/3/2014 √

— Complete installation of the 1 MWe pilot plant at NCCC (02/28/2014) – Completed 3/28/2014 √

— Mechanical completion of 1 MWe pilot plant at NCCC (05/28/2014) – Completed 7/18/2014 √ (punch list developed and work in progress)
Key Process Equipment for the Pilot Plant

**Heat Exchangers (Plate and Frame)**
- Tested & inspected at vendor site
- Installed on modules
- Provision to add plates for additional heat transfer area

**Process and Cooling Water Pumps**
- All pumps except reflux pump are centrifugal
- Tested & inspected at vendor site
- Installed on modules
- Spares: 3 spare internals for use in all pumps + one spare reflux pump

Plate frame Heat Exchangers

Process Pumps
Module design:
1. Six equipment modules (approximately 30 ft x 13 ft x 9 ft).
2. Arranged in three levels, two side by side at each level.
3. Design was to maximize shop fabrication. Off module piping produced by module fabricator.
4. Steel structure above the top module to support absorber (prevent swaying, 90 miles/hr wind design basis)
Columns fabrication in the shop in Decatur, Alabama

- Stripper column fabrication and internals assembly completed. Shipment to site as one piece: March 9, 2014
- Absorber columns section fabrication and internals assembly completed. Shipment to site in three sections: March 17-26, 2014.
- Absorber column packing and internals for the bottom two sections installed at site. Completed March 28, 2014.
SCS/ NCCC scope and accomplishments:

1. Civil design completed. Micro-pile installation, form and pouring foundation completed.
2. FRP flue gas header designed & installed.
3. Sump pump, flue gas blower, pre-scrubber packing and internals purchased and installed.
4. Pre-scrubber modifications completed for increased flue gas capacity.
5. Pure solvent storage system modifications completed. Demin. water pump impeller replacement.
Site prepared and ready to install equipment and modules (Jan 10, 2014)
First of 6 modules set in position
Module 5 lifted into place
Steel structure for wind load protection (absorber) lifted into position
Analytical container set in place (left) and module installation completed (right)
Solution storage tank set in place in front of modules
Analytical container fabricated in shop and installed at site

- Pilot plant incorporates significant instrumentation and online analytical measurements

- Batch analysis in conjunction with online measurements allow redundancy checks for mass and energy balances

- Batch sampling and offsite analysis for solvent stability measurements

- Corrosion coupons incorporated to assess effect on materials over the testing duration

Analyzer and controls container

Analyzer and sampling panels
Stripper column delivery and installation at site
Absorber bottom section ready for installation
Absorber bottom section set in place (left); view of the installed solution storage tank
Absorber second section installation
Top section of the absorber lifted into position (left); Column installation complete (right)
Absorber and stripper column scaffolding to install piping, pipe supports, insulation and heat tracing.

Based on safety assessment, decision made by contractor to scaffold the columns for installation of piping, pipe supports, insulation, heat tracing, and insulation.
Challenges/Lessons learned in pilot plant build

- Critical to have early and firm scope definition and detailed engineering should be fully completed prior to procurement and contracts
- Due to their significant number and cost on a pilot plant, instrumentation and analysis specifications require careful attention
- Low bid on contracts is not always the best overall as scope changes or rework could introduce significant cost adders
- Need to have good alignment with and commitment of the site installation contractor
- Scope definition should minimize hand over as much as possible
- Changes in critical engineering resources can introduce errors and rework
BP3 Project Schedule (Continuous availability of site and utilities)

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project management and planning</td>
<td>11/30/15</td>
<td>12/31/15</td>
</tr>
<tr>
<td>2</td>
<td>8. Start-up and initial operation</td>
<td>12/31/15</td>
<td>2/27/16</td>
</tr>
<tr>
<td>3</td>
<td>8.1 Control system tuning and system checks</td>
<td>12/31/15</td>
<td>12/31/15</td>
</tr>
<tr>
<td>4</td>
<td>8.2 System calibrations at initial operation</td>
<td>1/1/16</td>
<td>2/27/16</td>
</tr>
<tr>
<td>5</td>
<td>Pilot plant operations validated and ready for testing</td>
<td>2/27/16</td>
<td>3/2/16</td>
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<tr>
<td>6</td>
<td>9. Parametric testing</td>
<td>3/2/16</td>
<td>8/28/16</td>
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<tr>
<td>7</td>
<td>9.1 Test plan development</td>
<td>3/2/16</td>
<td>3/31/16</td>
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<tr>
<td>8</td>
<td>9.2 Data collection and analysis</td>
<td>3/2/16</td>
<td>6/30/16</td>
</tr>
<tr>
<td>9</td>
<td>9.3 Data validation and process evaluation</td>
<td>9/1/16</td>
<td>9/28/16</td>
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<tr>
<td>10</td>
<td>Performance validated against targets</td>
<td>9/1/16</td>
<td>9/30/16</td>
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<td>11</td>
<td>10. Long duration continuous operation</td>
<td>9/1/16</td>
<td>5/31/16</td>
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<tr>
<td>12</td>
<td>10.1 Long term operation test plan development</td>
<td>9/1/16</td>
<td>9/30/16</td>
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<tr>
<td>13</td>
<td>10.2 Data collection and analysis</td>
<td>9/1/16</td>
<td>9/30/16</td>
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<tr>
<td>14</td>
<td>10.3 Assessment of long term performance</td>
<td>10/1/16</td>
<td>10/31/16</td>
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<tr>
<td>15</td>
<td>Long term operability and solvent stability</td>
<td>12/1/16</td>
<td>5/31/16</td>
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<tr>
<td>16</td>
<td>11. Final economic analysis and commercialization plan</td>
<td>6/1/16</td>
<td>8/31/16</td>
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<td>17</td>
<td>11.1 Updated economic assessments</td>
<td>6/1/16</td>
<td>7/23/16</td>
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<td>18</td>
<td>11.2 Commercialization plan development</td>
<td>6/1/16</td>
<td>8/31/16</td>
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<tr>
<td>19</td>
<td>Technology advantages demonstrated/Ready for commercial</td>
<td>8/31/16</td>
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<tr>
<td>20</td>
<td>Project Close</td>
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Acknowledgement: This presentation is based on work supported by the Department of Energy under Award Number DE-FE0007453.

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