



Slipstream pilot plant demonstration of an amine-based post-combustion capture technology for CO₂ capture from coal-fired power plant flue gas

DOE funding award DE-FE0007453

2016 NETL CO₂ Capture Technology Meeting

Krish R.
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Linde LLC
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Pittsburgh, PA

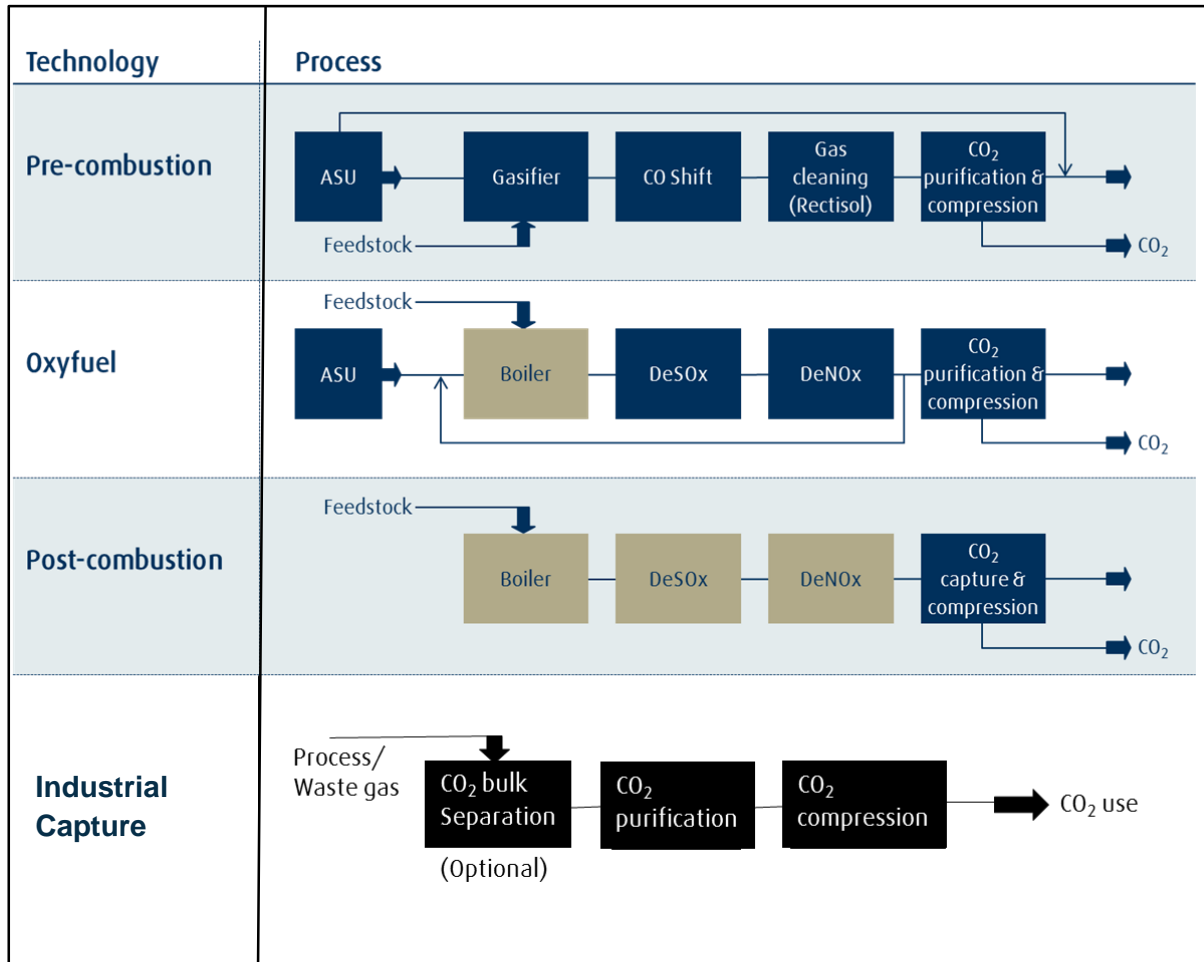
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Linde

Linde has options in all carbon capture pathways through commercial products or technology/solution development



Solvent based post-combustion CO₂ capture is currently a leading option:

- Applicable to new or retrofit plants
- Capture all or part of flue gas
- Applied at large scale in other applications
- Novel solvents (e.g. OASE[®] blue) are stable in presence of flue gas contaminants & oxygen
- Significant progress made toward the capture cost goal

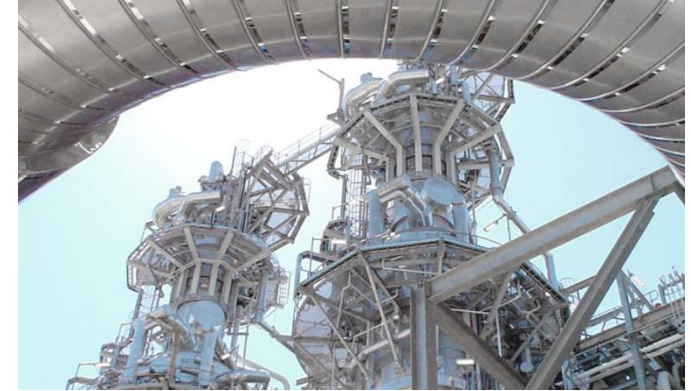
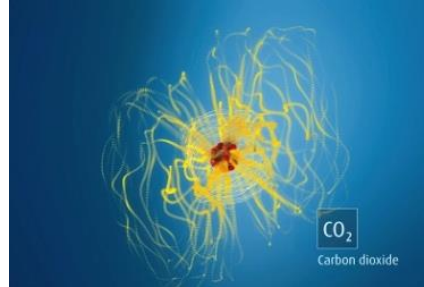
BASF / Linde partnership

Delivering total solutions with confidence

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BASF Solvent/Process Expertise

Basic Design Package

Process performance

Emissions performance

Founded 1865

Sales (2015) €70.5 billion

Employees ~112,000



PCC capture



Linde Engineering Expertise

Process optimization

Basic/Detailed Engineering

Package/EPC wrap

Founded 1879

Sales (2015) €17.9 billion

Employees ~64,000

Project Budget : DOE funding and cost share (Amended Aug 2014)



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Source	Budget Period 1 Dec 2011 – Feb 2013 Design & Engineer	Budget Period 2 Mar 2013 – Aug 2014 Procure & Build	Budget Period 3 Sep 2014 – Nov 2016 Operate & Test	Total
DOE Funding	\$2,670,173	\$11,188,501	\$2,360,173	\$16,218,847
Cost Share	\$667,543	\$4,335,102	\$1,472,506	\$6,475,151
Total Project	\$3,337,716	\$15,523,602	\$3,832,679	\$22,673,998

June 2016	Budget	Actual
Total	\$21.40m	\$20.87m
DOE	\$15.89m	\$15.37m
Cost share	\$ 5.51m	\$ 5.50 m

Cost share commitments:

Linde: \$5,884,411

BASF: \$ 493,360

EPRI: \$ 97,379

Project participant(s) competency and contribution critical to successful outcome



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Project sponsorship and funding



National Carbon Capture Center

Host site; Infrastructure & utilities for pilot plant build and op's



Independent analysis of test results & TEA review



Technology owner, basic Design & solvent supply

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Overall program management, EPC, Operations & Testing

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

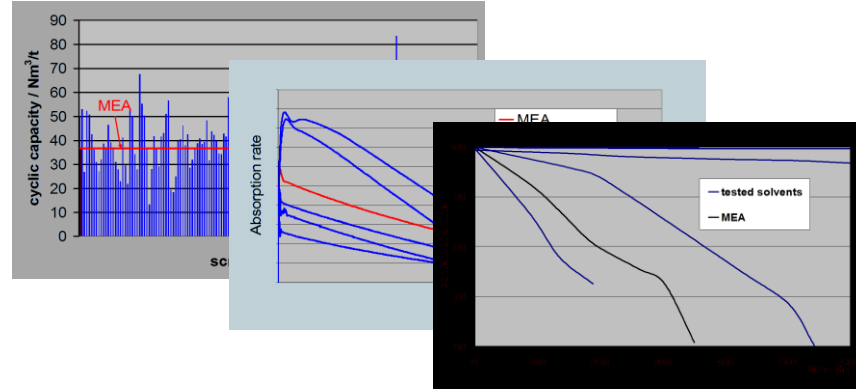
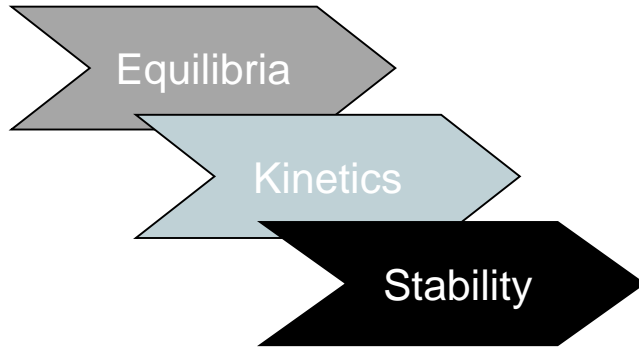
BASF OASE[®] blue technology roadmap

Adopted and optimized for PCC applications

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Lab. & Mini plant (2004)

Pilot: 0.45 MWe (2009)

Pilot: 1.5 MWe (2014)

Large Pilot (proposed): 15 MWe (2016-2020)

- Ludwigshafen, Germany
- Solvent selection & performance verification

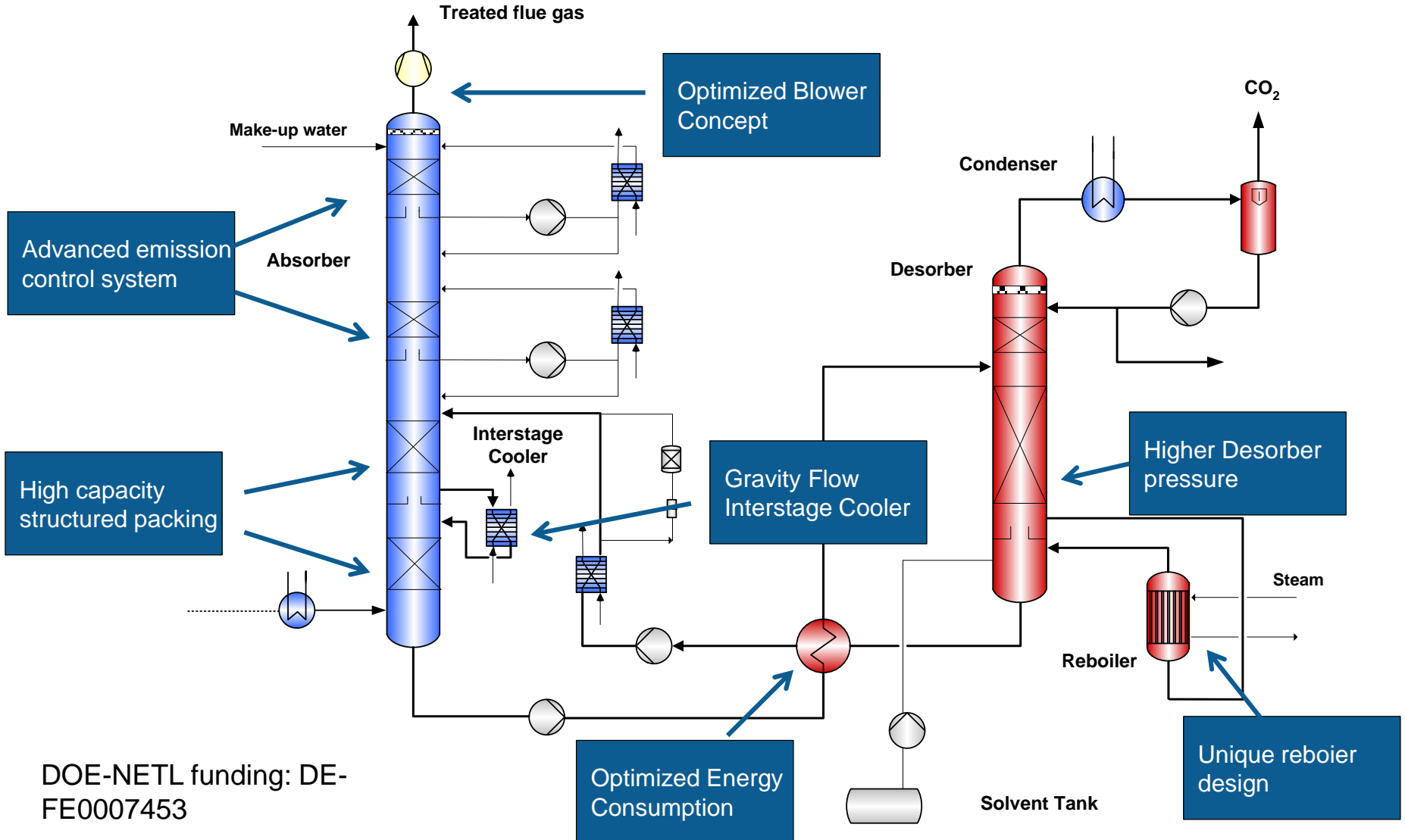
- Niederaussem, Germany
- Process opt., materials & emissions testing

- Wilsonville, AL (NCCC)
- Design improvements, emissions confirmation

- Abbott power plant, UIUC, Champaign, IL
- Full value chain demo.



Linde-BASF novel amine-based PCC technology features: NCCC 1 MWe pilot



DOE-NETL funding: DE-FE0007453

Budget Period 3 is in progress with a target project completion date of Nov. 30, 2016

- Task 8: Pilot plant start-up (Jan-Mar 2015)
 - Stable operations achieved within one week
 - Excellent mass & energy balance closures
- Task 9: Parametric Testing
 - Two campaigns (May 1-Aug 15, 2015) and (Oct 1-Dec 22, 2015)
 - Range of parametric testing completed. Validated higher pressure regeneration. Addressed aerosol-based amine carry-over.
- Task 10: Long Duration Testing
 - Pilot plant restart: May 16, 2016;
 - Long duration test campaign: May 20-Jul 29, 2016
 - Continuous operation for 1520 hours
 - Flue gas flow: 10,500 lbs/hr (~1 MWe); 3.4 bar(a) Regen. Pressure
 - EPRI analysis performed: week of June 13, 2016
- Task 11: Final TEA & Commercialization Plan
 - Complete updated TEA and EH&S report
 - Pilot plant to be dismantled and removed

Linde-BASF 1 MW_e pilot plant at the NCCC



Wilsonville PCC Pilot Plant

Parametric Testing Performed



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S.No.	Key variable	Status
1	Flue gas flow rate	7,500 to 15,750 lbs/hr
2	Flue gas temperature to absorber	86°F to 104°F
3	Treated gas temperature exit absorber	86°F to 115°F
4	Lean solution temperature to absorber	104°F to 140°F
5	Inter-stage cooler	On (104°F) /Off
6	Regeneration pressure	1.6 to 3.4 bars
7	Solvent circulation rate	Varied from 80 to 120%
8	CO ₂ capture rate	90% typical Varied from 85% to >95%

Pilot plant performance against targets: Accomplishments and next steps



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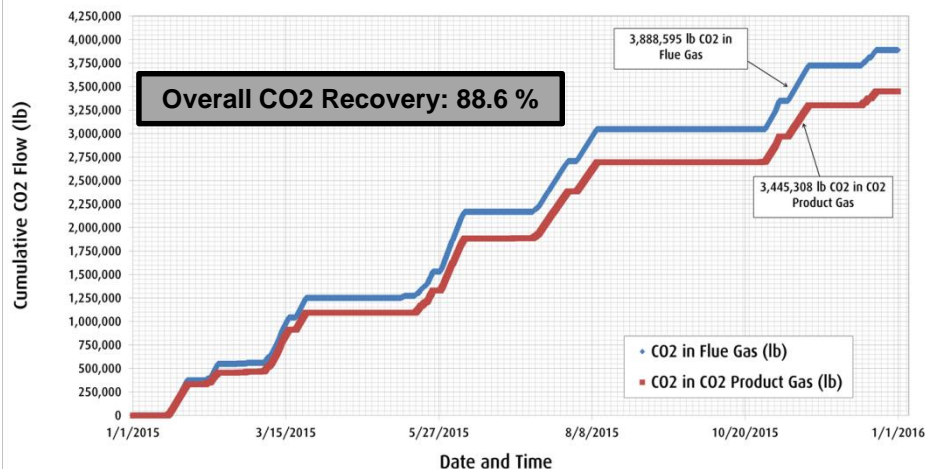


Performance Attribute	Current achievement against target	Remarks
1. CO ₂ capture rate	>90% per target	Achieved. Capture rate can be optimized for specific energy.
2. CO ₂ purity	99.9% dry basis per target	Achieved. Low O ₂ impurity level for EOR applications
3. Plant capacity	> 1.5 MWe per design target (>15,500 lbs/hr flue gas)	Achieved. Higher capacity testing performed ~10 days in May-June. Further testing in Nov 2015.
4. Regenerator steam consumption	~ 2.8 GJ/tonne CO ₂ (same as Niederaussem consumption)	Energy as low as 2.7 GJ/tonne CO ₂ observed.
5. Emissions control validation	Validation of dry bed (BASF patented) operation per design	Detailed isokinetic measurements (flue gas & treated gas) performed.
6. Regenerator operating pressure	- Testing performed up to 3.4 bars	Pressure parametric testing completed in Nov 2015
7. Validation of unique features	(i) high capacity packing, (ii) gravity driven intercooler, (iii) blower downstream of abs. (iv) unique reboiler design.	Design options for regenerator heat reduction through heat integration identified. Stripper interstage heater designs can result in ~ 2.3 GJ/tonne.

Note: Regenerator steam consumption above is intrinsic and does not include process and heat integration

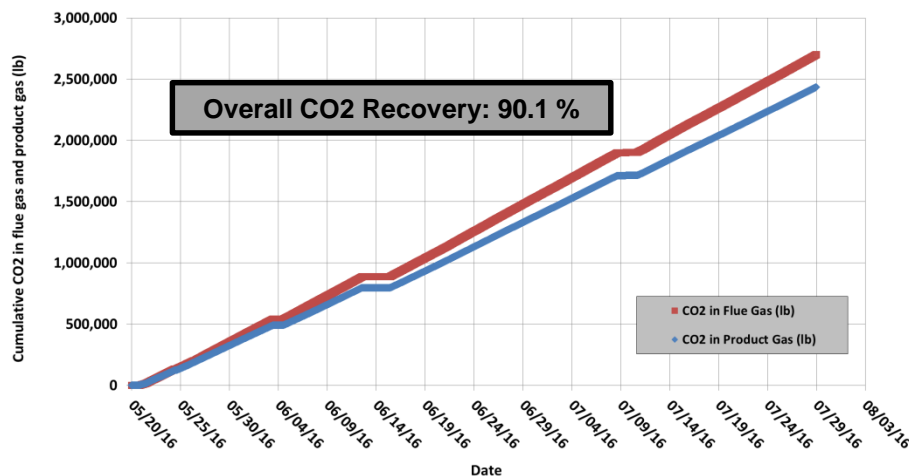
Linde Wilsonville PCC pilot plant - Cumulative CO₂ in Flue Gas and CO₂ Product Gas Flowrates (lb)

CO₂ in Flue Gas and CO₂ production - 2015 Cumulative Flow (lb)



Parametric tests 2015: Operating hours

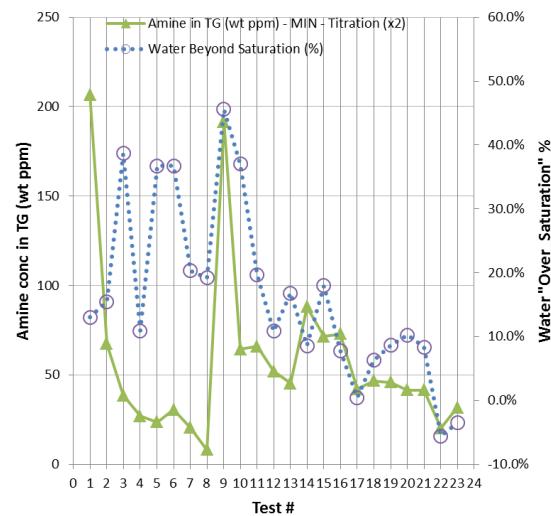
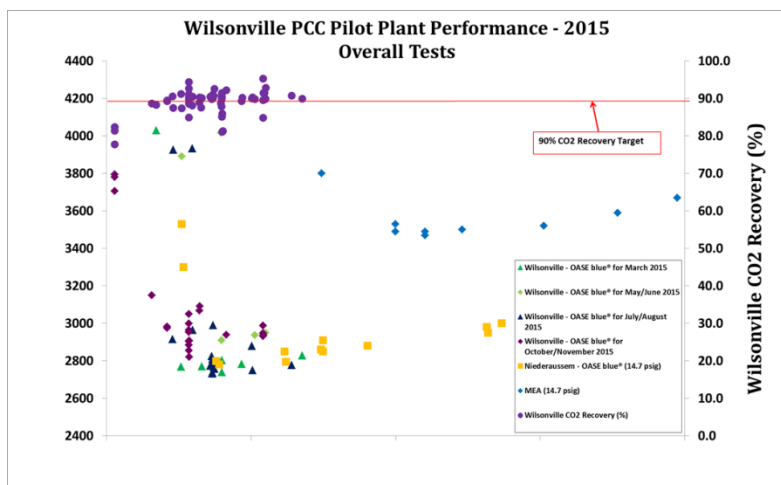
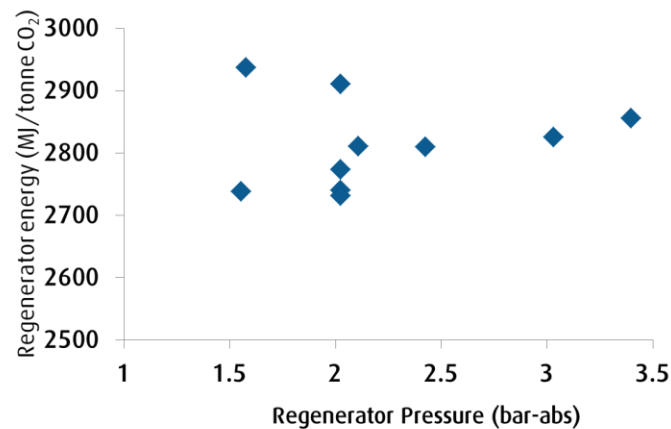
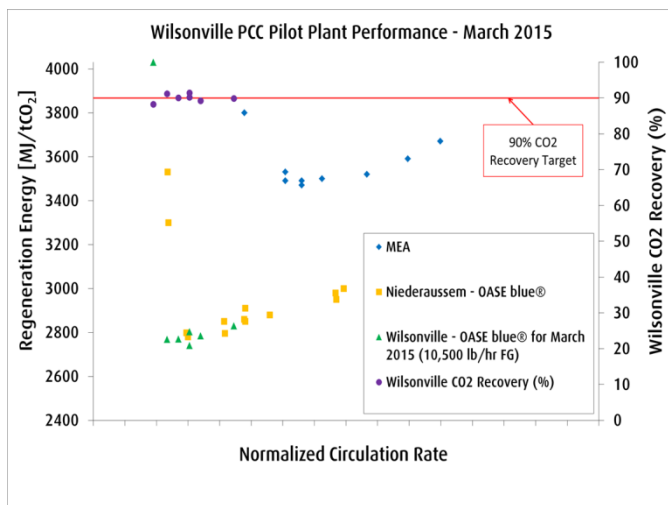
- Hours Flue gas testing: 2589
- Hours with steam on: 3841
- Hours of solvent circulation: 5096



Long duration tests 2016: Operating hours

- Hours Flue gas testing: 1520
- Hours with steam on: 1532
- Hours of solvent circulation: 1668

Parametric testing (Jan-Dec 2015): Energy and emissions optimization

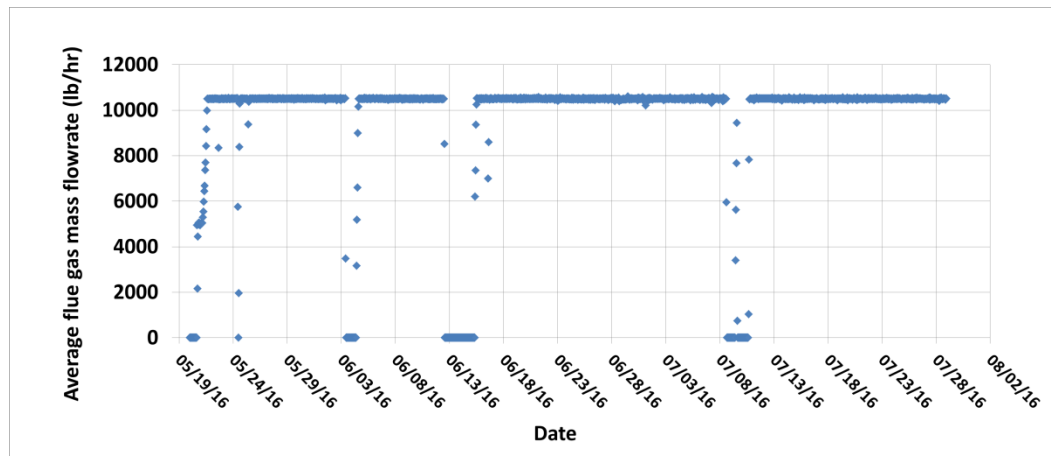


Long duration testing: 1520 hours continuous & steady operation from May 20 – July 29, 2016

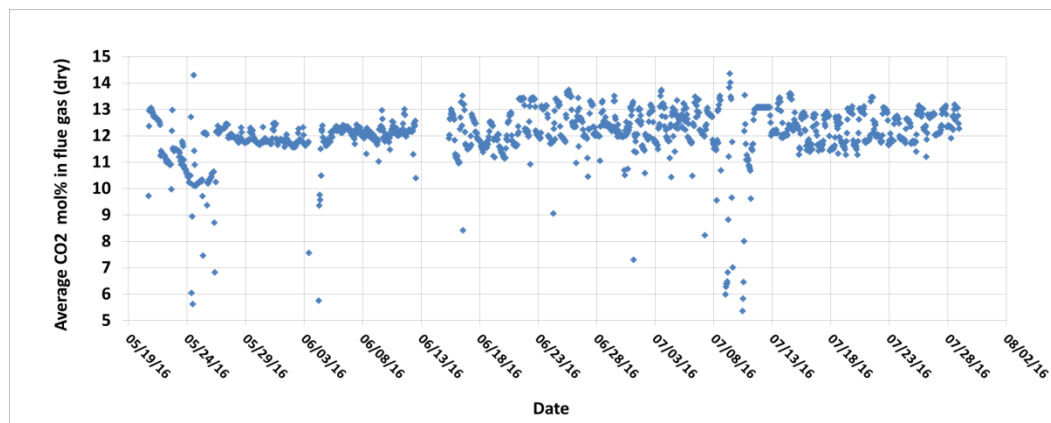
Test Set-up

- FG flow rate: 10,500 lb/hr (~1 MWe)
- Flue gas CO₂ conc. : 12% target
- Regenerator pressure : 3.4 bar a
- Temp of FG to absorber : 35°C
- Absorber inter-stage cooling : 40°C
- Absorber exit treated gas temp: 40°C
- CO₂ Capture rate: 90% (target)

Flue gas flowrate

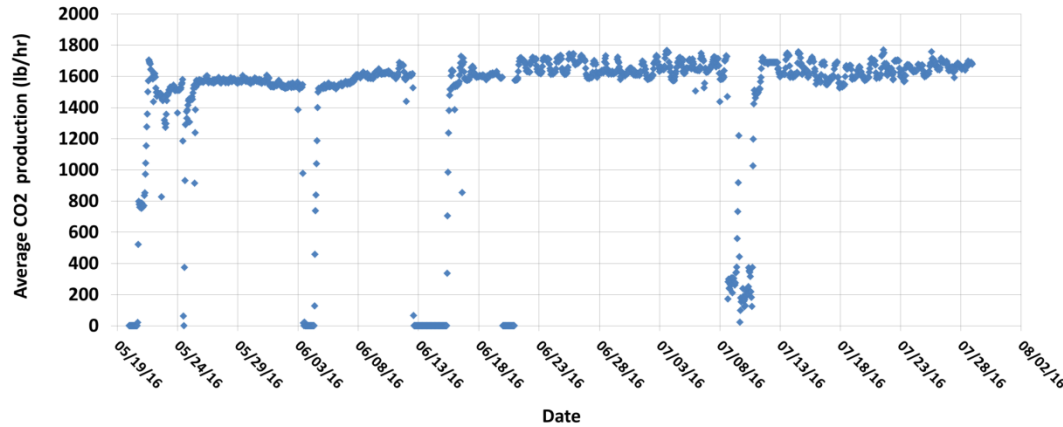


Flue gas CO₂ mole percent

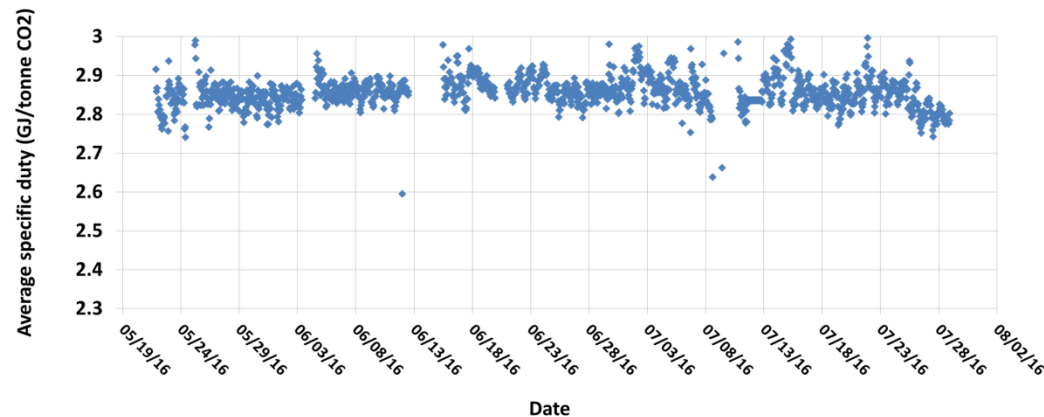


Long duration test performance

Average CO₂ capture rate over entire test duration: 90.1%



CO₂ production



Regenerator specific energy consumption

- Linde and BASF are partnering in the development of an advanced PCC technology incorporating BASF's novel amine-based process, OASE[®] blue, along with Linde's process and engineering innovations
- Performance demonstrated and long term stability validated on a 0.45 MWe lignite fired power plant flue gases (Niederaussem, Germany)
- Nominal 1 MWe pilot plant at the NCCC in Wilsonville, AL commissioned; parametric and long-duration testing completed have demonstrated stable operation, validation of functional features and achievement of key performance targets
- EPRI independent analysis performed during long-duration test campaign in June 2016.
- Technology has been selected by DOE for Phase 1 of the Large Pilot opportunity. Phase 2 proposal has been submitted with Univ. of Illinois as prime and the Abbott coal fired power plant as host site. This will mark the next stage of technology development and evolution.

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