Development and scale-up of an advanced aqueous amine-based post-combustion CO_2 capture utilizing BASF's OASE® blue technology

CARBON CAPTURE, UTILIZATION & STORAGE CONFERENCE

JUNE 14-16, 2016 | SHERATON TYSONS CORNER | TYSONS, VA

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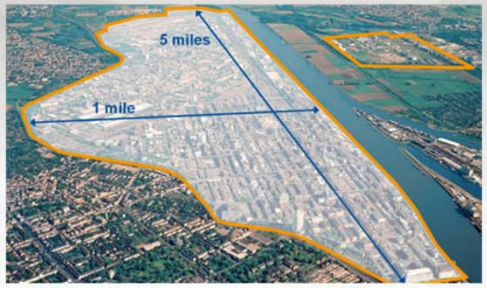
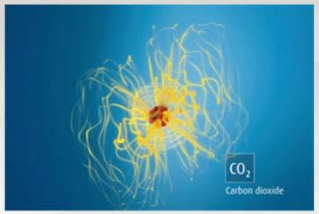
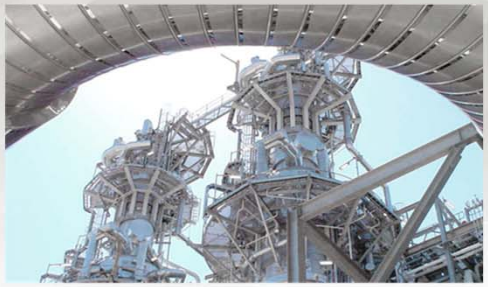
BASF / Linde partnership

Delivers total solutions with confidence







BASF Solvent/Process Expertise
- Basic Design Package
- Process performance
- Emissions performance

Linde Engineering Expertise
- Process optimization
- Basic/Detailed Engineering
- Package/EPC wrap

PCC capture

	BASF	Linde
Founded	1865	1879
Sales (2014)	€70.5 billion	€17.9 billion
Employees	~ 112,000	~ 64,000

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BASF OASE® blue Technology Development

Adapted and optimized for PCC applications

BASF We create chemistry

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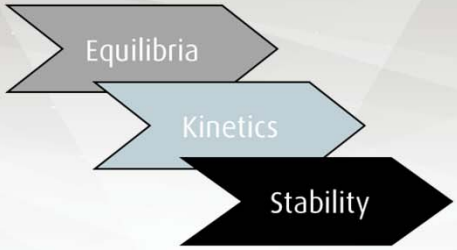
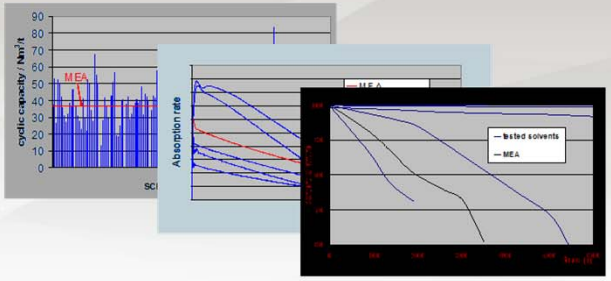
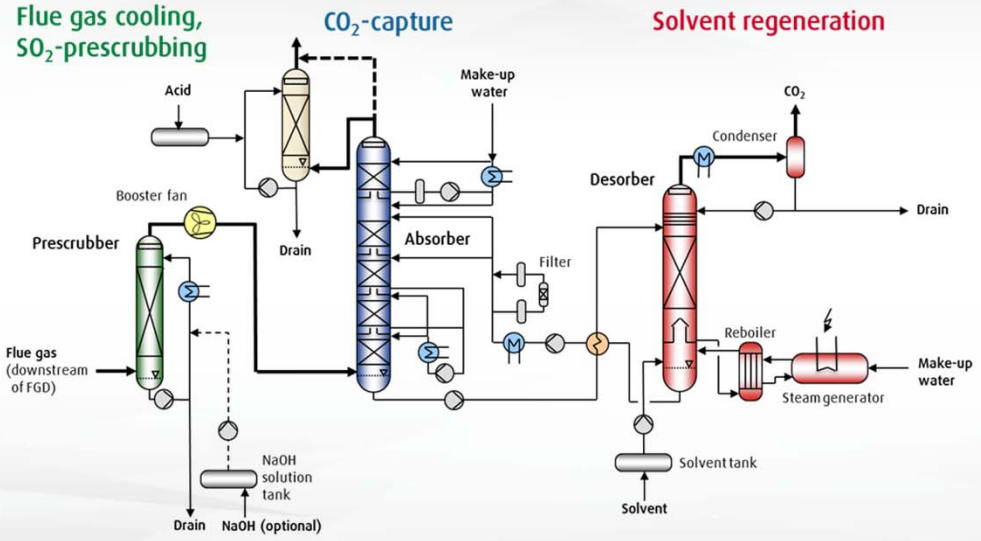




Lab scale	Mini plant	Pilot: 0.45 MWe	Pilot: 1.5 MWe
— Ludwigshafen, Germany — Advanced solvent screening, development, optimization	— Ludwigshafen, Germany — Solvent performance verification	— 2009, Niederaussem — Process opt., materials & emissions testing	— 2014, Wilsonville, AL — Design improvements, emissions confirmation

Niederaussem PCC pilot plant
Fact sheet

- Flue gas: 1,550 Nm^3/h; CO_2 product: 7.2 t CO_2/day; capture rate 90%
- Commissioning and start-up 2009, availability of 97%
- BASF's OASE® blue was tested over 26,000 hours (> 3 years)
- nearly 7,000 t CO_2 were captured with OASE® blue



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Niederaussem PCC Pilot

Test campaigns

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Solvent testing

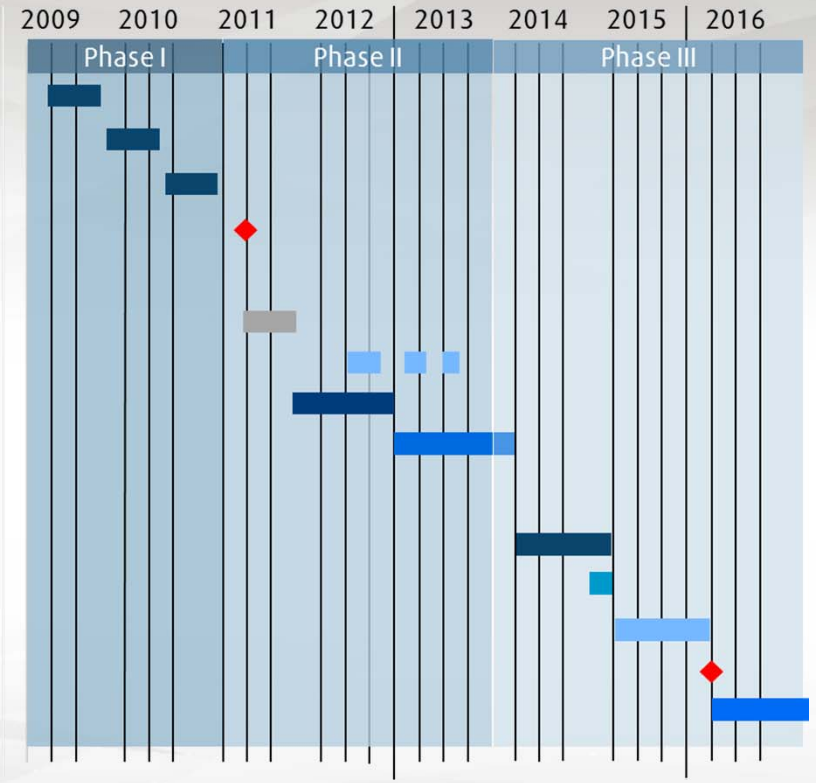
- MEA & Process
- GUSTAV200
- LUDWIG540
- ⇨ Selection optimal solvent: OASE® blue

Long-term testing, optimisation

- Modification of plant components
- Intermediate testing
- Long-term testing (FGD)
- Long-term testing (FGDplus)

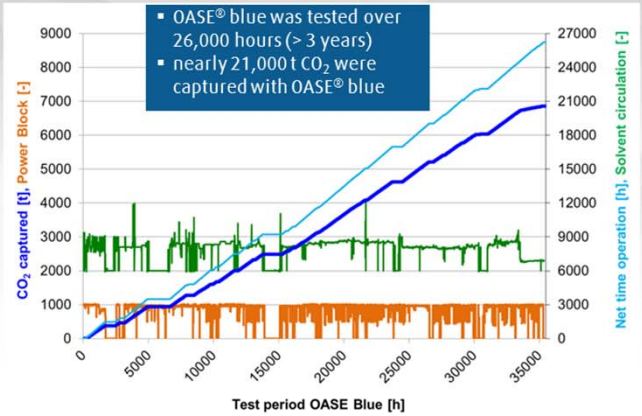
Optimisation, Long-term testing

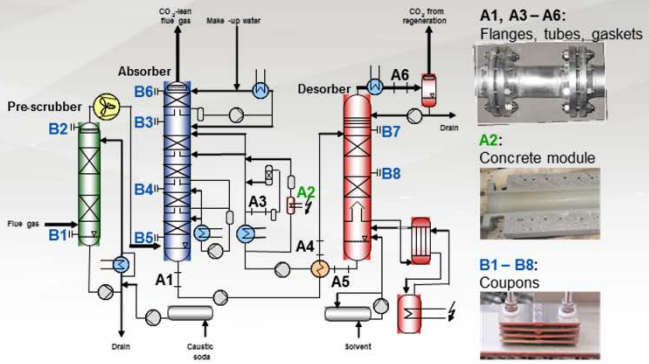
- Overall optimum emission mitigation
- Increase of O_2-content flue gas
- Variation OASE® blue
- ⇨ Optimum OASE® blue
- Long-term testing (FGD/FGDplus)



Niederaussem PCC Pilot

Operational experiences and main results

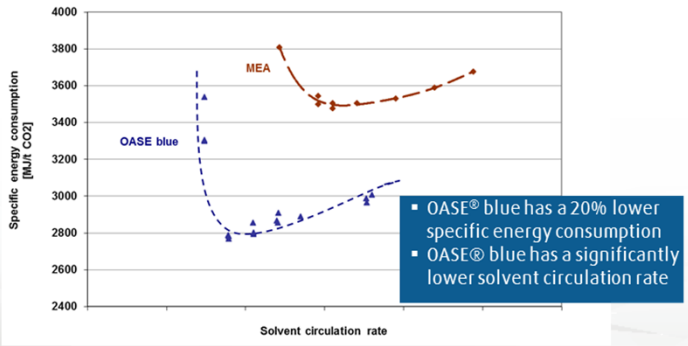


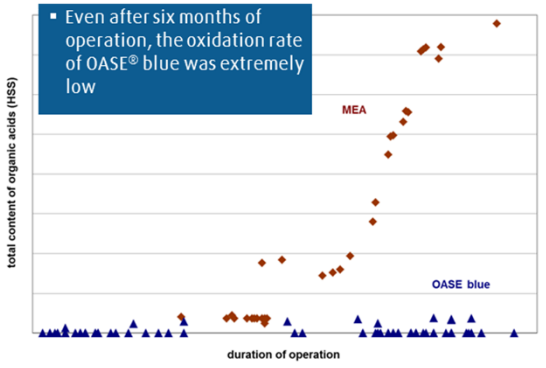


A1, A3 – A6:
Flanges, tubes, gaskets

A2:
Concrete module

B1 – B8:
Coupons





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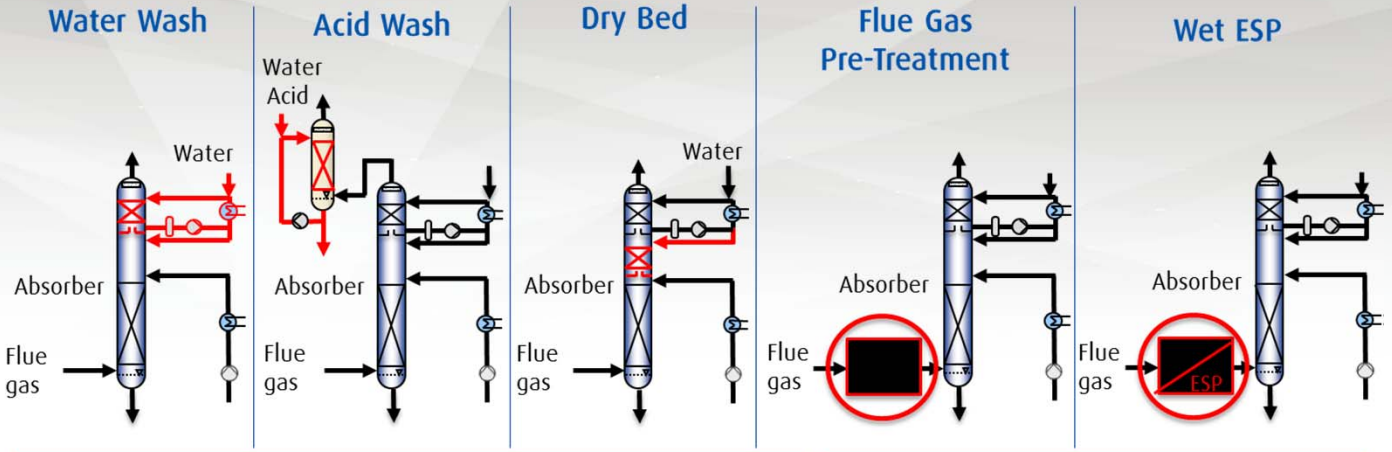
Niederaussem PCC Pilot

Emissions reduction measures



Variation of Process Configurations:

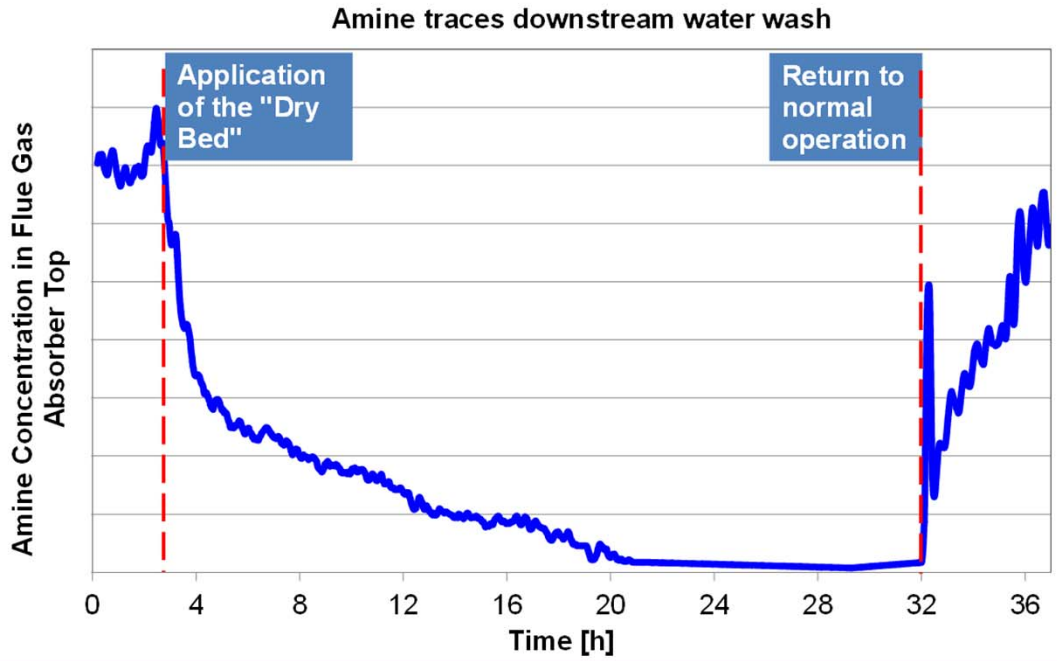
- FGDplus/pre-scrubbing (w/wo addition of NaOH)
- Number of water wash steps (1 or 2)
- Water wash with double height
- Combination water wash and dry bed
- Combination acid wash and dry bed
- Combination with wet electric precipitator

Variation of Parameters:

- Water wash temperature (40° - 60°C)
- Intercooler temperature
- pH-value acid wash
- Voltage of wet electric precipitator

Niederaussem PCC Pilot

Emissions reduction measures: “Dry Bed”



Reduction of amine emissions by an order of magnitude:
→ Proprietary process configuration “Dry Bed“

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Wilsonville PCC Pilot

Fact sheet

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Project essentials

- DOE-NETL funded project ($16.2 million funding)
- Total project cost $22.7 million
- Location: 880 MWe Gaston Power plant (operated by Southern Co.) in Wilsonville, AL
- Site of the National Carbon Capture Center
- Capacity: Up to 6,250 Nm^3/h flue gas from coal fired power plant (30 t/d CO_2); Up to 1.5 MWe
- CO_2 purity 99+ vol % (Dry basis)
- Project start: November 2011
- Start-up: January 2015
- Project Duration: 4.5 years
- Partners: Linde LLC, Linde Engineering North America, Linde Engineering Dresden, BASF, DOE-NETL, EPRI, Southern Company (Host site)

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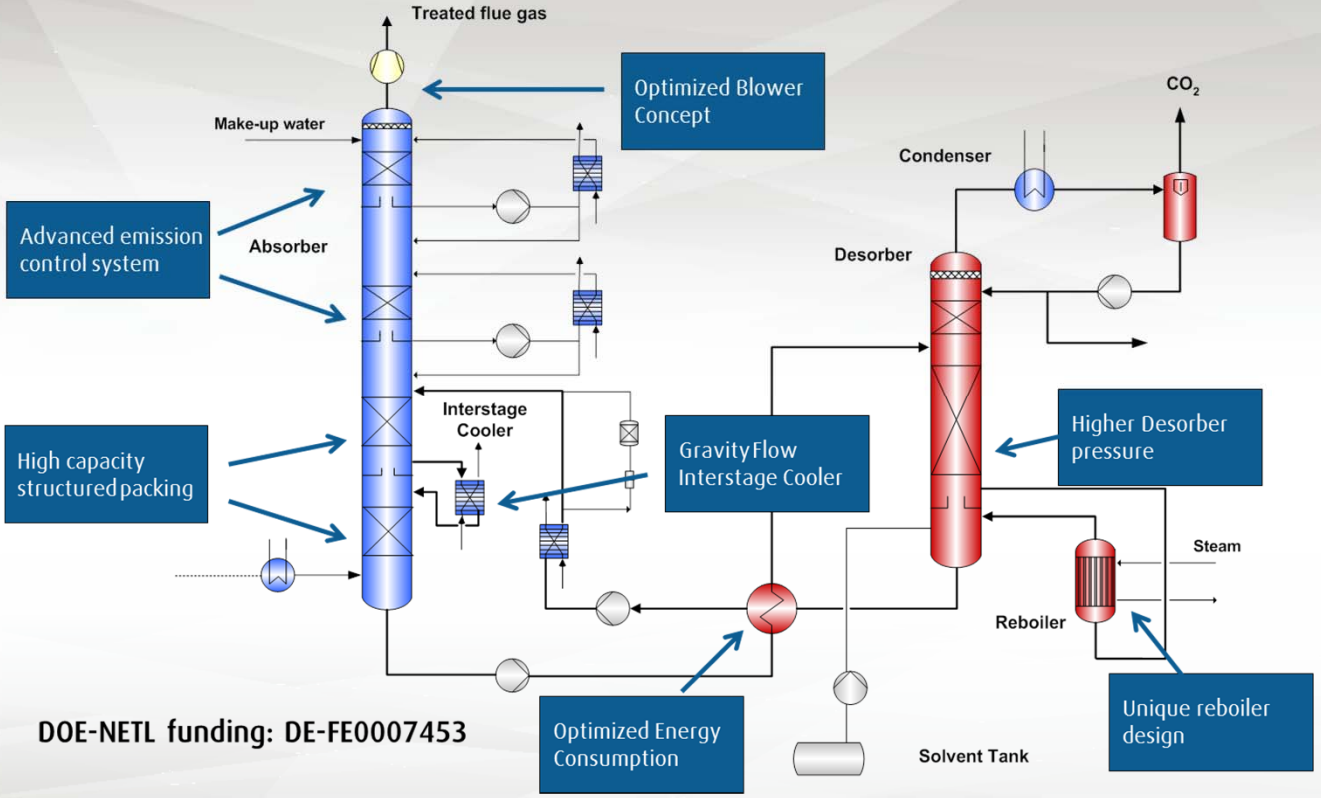
Wilsonville PCC Pilot

Flowsheet: Novel features evaluated



DOE-NETL funding: DE-FE0007453

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Wilsonville PCC Pilot

Construction

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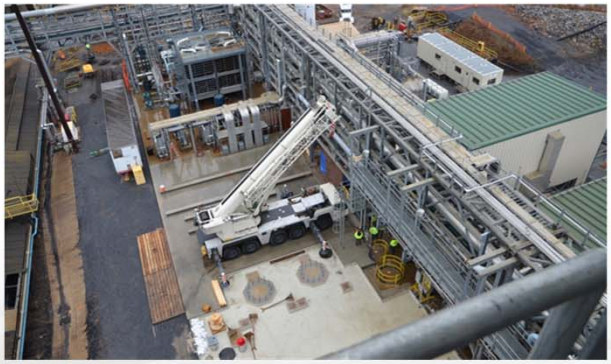
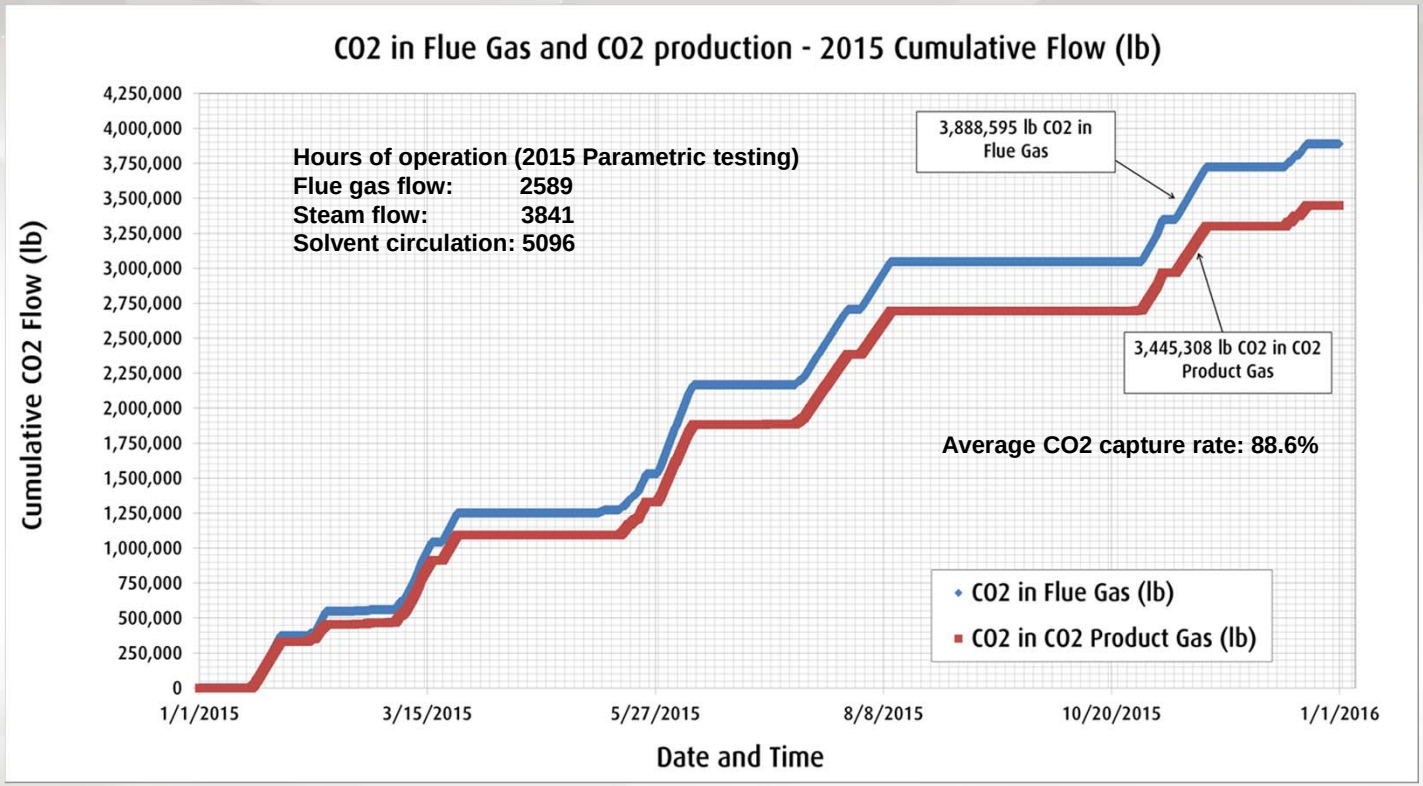


Wilsonville PCC Pilot

Start up, operations & parametric testing



Operations & Parametric testing

Overall (dry basis) mass balances

Overall Mass Balance (dry basis)			
Time/Date Interval	Average Mass Flow In (lb/hr)	Average Mass Flow Out (lb/hr)	% Difference
10/30/15 14:00:00 to 10/30/15 16:00:00	10094.06	10102.77	0.086%

CO2 Mass Balance			
Time/Date Interval	Average CO2 Mass Flow In (lb/hr)	Average CO2 Mass Flow Out (lb/hr)	% Difference
10/30/15 14:00:00 to 10/30/15 16:00:00	1628.82	1614.46	0.889%

CO2 Production Mass Flowrate vs. CO2 Content Solvent Analysis			
Time/Date Interval	CO2 Product (lb/hr) (calc. from solvent analysis)	CO2 Product (lb/hr) (measured)	% Difference
10/30/15 14:00:00 to 10/30/15 16:00:00	1432.13	1497.82	4.39%

Parametric testing performed

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%

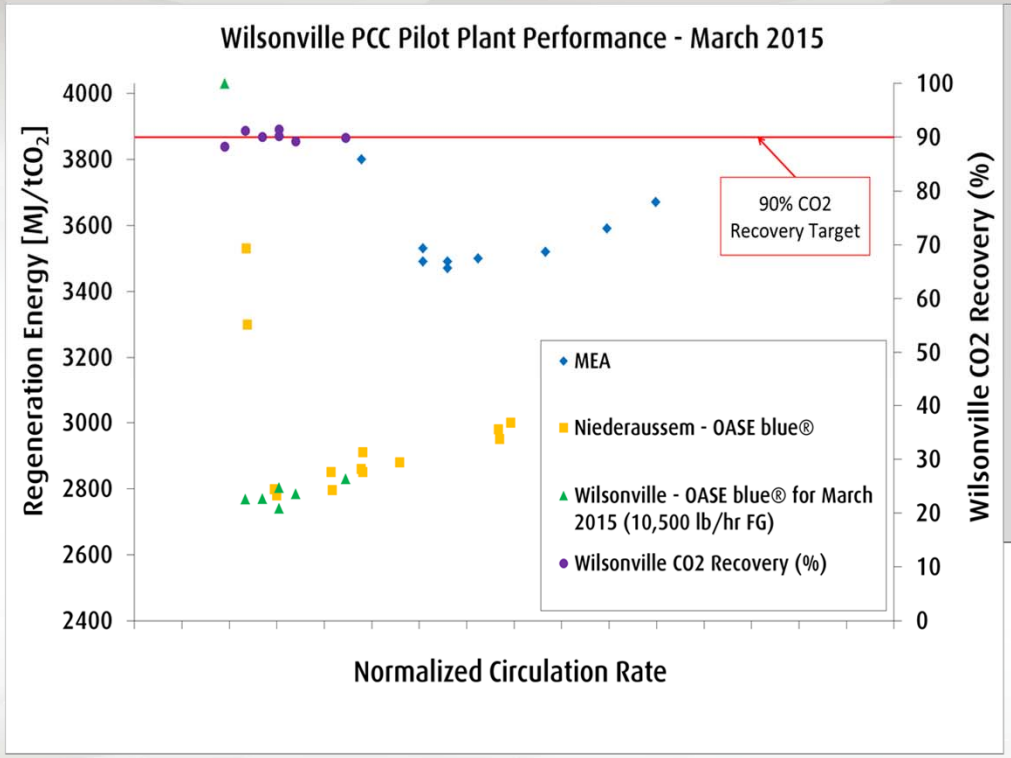
Parametric testing

Performance against targets

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.

Parametric testing: Key result

Specific energy vs solvent circulation rate



Test conditions:

- Flue gas flow Rate = 10,500 lb/hr
- Flue gas CO2 Concentration = 11.6%
- Regenerator Pressure = 2 bar a
- Flue gas to absorber Temperature = 35°C
- CO_2 Capture rate = 90% (target)

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Parametric testing

Energy and emissions optimization

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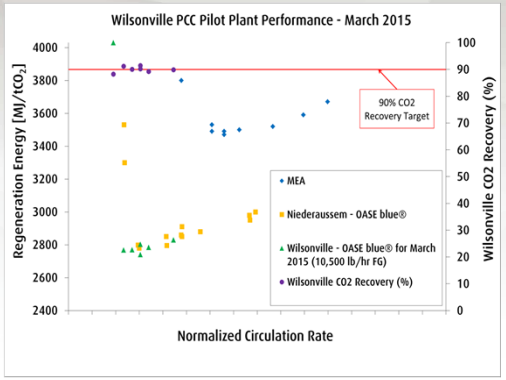
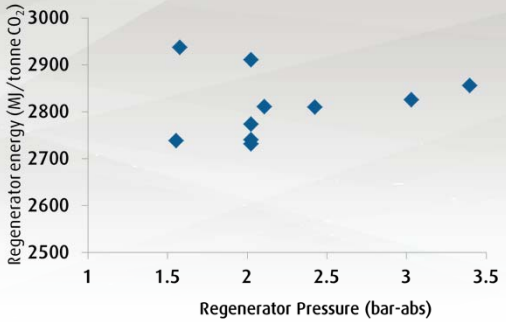
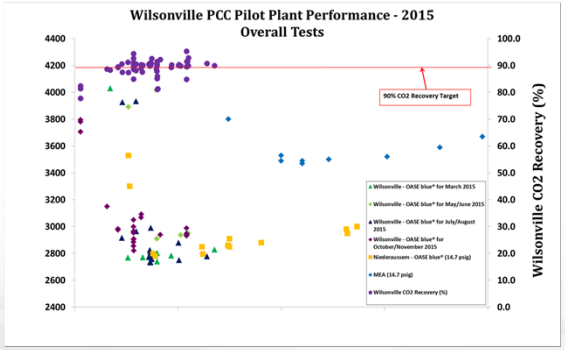
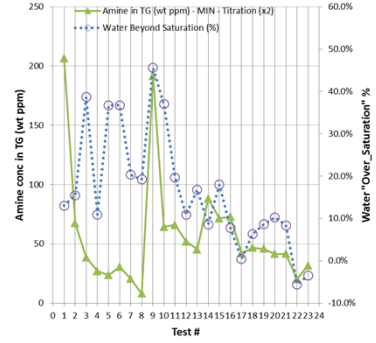








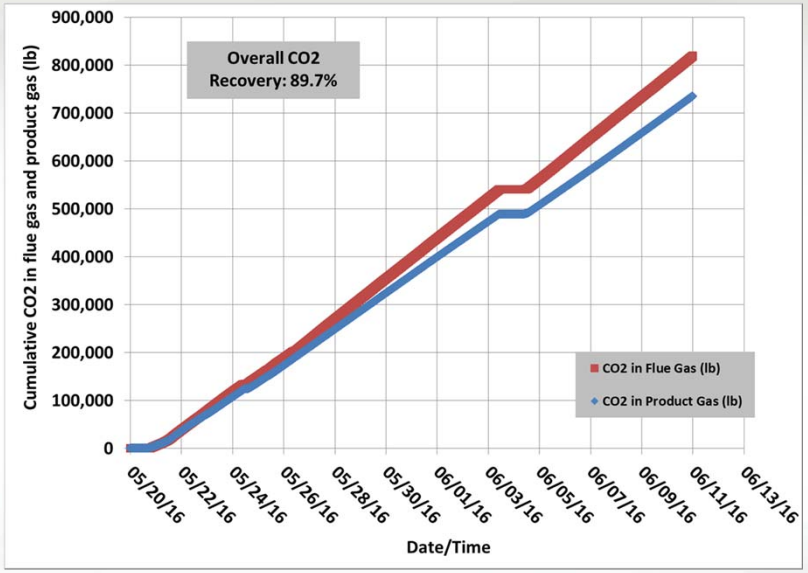
Long duration testing (in progress)

485 hrs of capture since May 20, 2016

Test Set-up

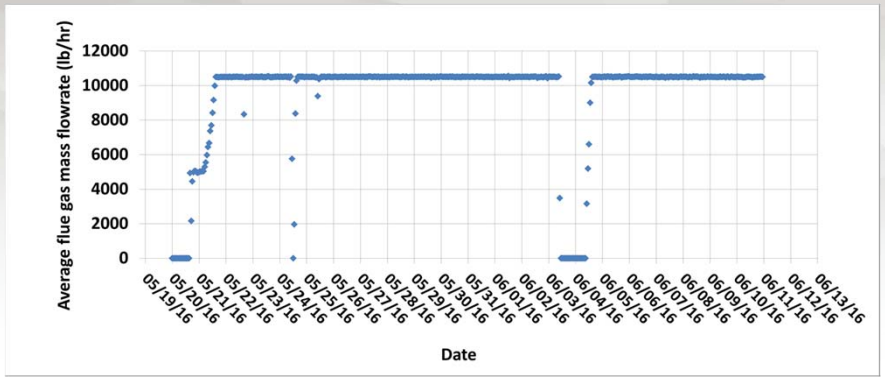
- FG flow rate: 10,500 lb/hr (~1 MWe)
- Flue gas CO_2 conc. : 12% target
- Regenerator pressure : 3.4 bar a
- Temp of FG to absorber : 35°C
- Absorber inter-stage cooling : 40°C
- Absorber exit treated gas temp: 40°C
- CO_2 Capture rate: 90% (target)

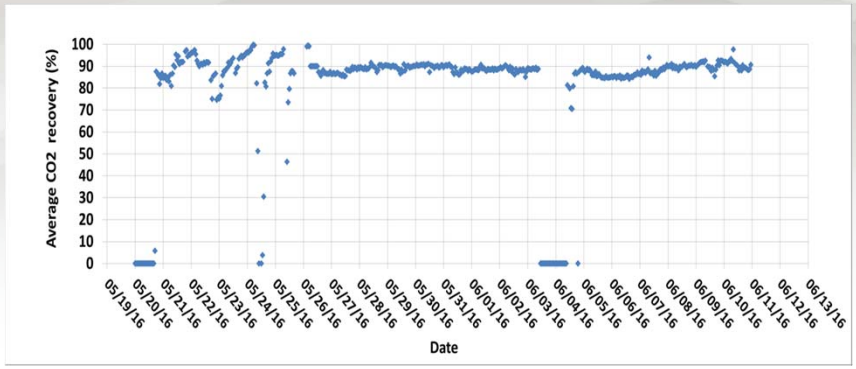
CO_2 in feed and product

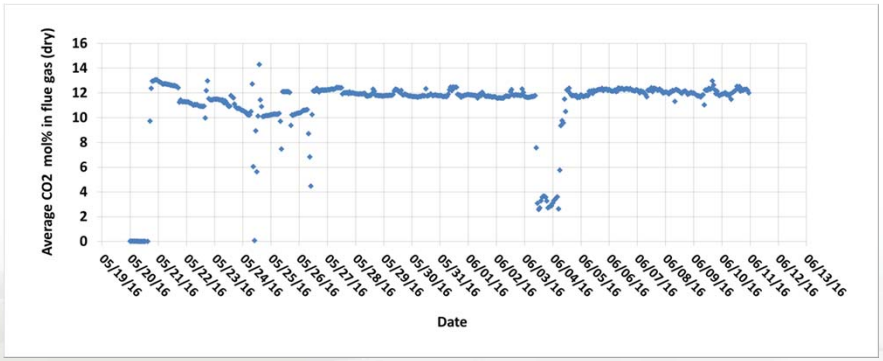


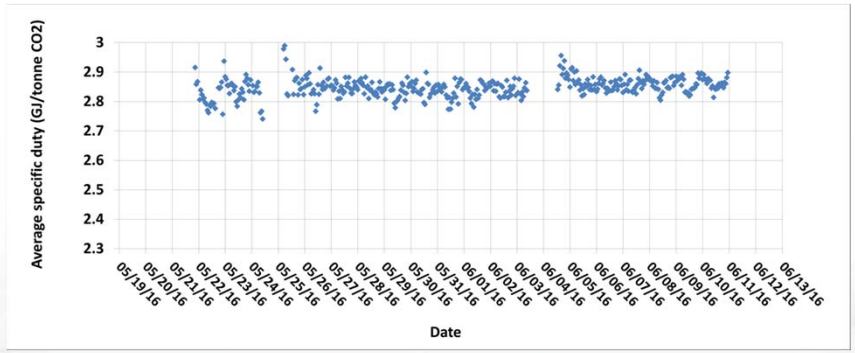
Long duration testing (in progress)

Steady operations & results on target









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Large pilot development

Abbott Power Plant, Univ. of Illinois

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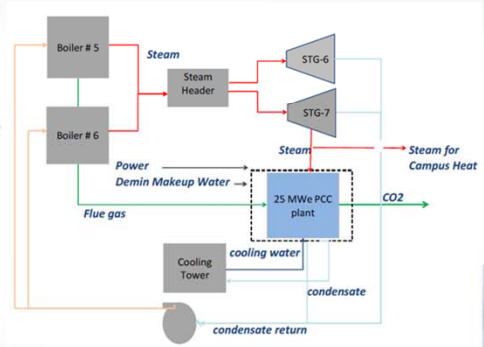
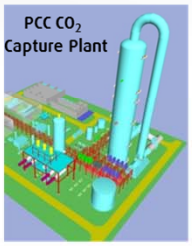
PILOT

- 1.5 MWe coal-fired flue gas (30 TPD CO2)
- Located at the National Carbon Capture Center, Wilsonville, AL; Host site: Southern Co.'s Alabama Power Gaston plant 880 MWe
- Project period: 2011-2016

LARGE PILOT

- 15 MWe coal-fired flue gas (300 TPD CO2)
- Located at Abbott Power Plant, Campaign, IL ; Host site: Univ. of Illinois 35 MWe cogen plant
- US DOE funding: $1 million; Phase 1 Project definition & Phase 2 proposal (by June 2016)
- Expected award selection & start: Oct. 1, 2016





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Summary and concluding remarks

- 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 built, commissioned; initial operations & parametric testing completed have demonstrated stable operation, validation of functional features and achievement of several key targets
- Long duration testing for min. 60 days and EPRI independent analysis are in progress in current campaign which started May 20, 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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Acknowledgements & Disclaimer

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Thank you for your attention!

Questions?

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