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

2015 NETL CO_2 Capture Technology Meeting

Krish R. Krishnamurthy, Linde LLC

June 24, 2014

Pittsburgh, PA

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Linde, a fully integrated gases and engineering company with a long experience in the field of CO_2 handling

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CO_2 Capture and injection

LNG plant for Statoil in Snøhvit/Norway with CO_2 capture from natural gas using OASE® purple and CO_2 re-injection off-shore

CO_2 Wash Units

Experience in design and erection of different wash processes for CO_2 removal

- Linde-Rectisol®
- BASF OASE® technology
- Benfield

CO_2 Food Grade Plants

Removal of impurities like Hydrocarbons, Heavy metals, O_2, H_2O for food grade CO_2

CO_2 Transport and distribution

Long experience in operation of CO_2 plants, transport and distribution

- OCAP pipeline (Netherlands)
- Onsite business
- Bulk supply

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

Source	Budget Period 1 Dec 2011 – Feb 2013 Design & Engineer	Budget Period 2 Mar 2013 – Aug 2014 Procure & Build	Budget Period 3 Sep 2014 – Aug 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

March 2015	Budget	Actual
Total	$19.33m	$19.48m
DOE	$14.23m	$14.33m
Cost share	$ 5.10m	$ 5.15m

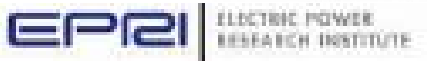
Cost share commitments:

Linde: $5,884,411

BASF: $ 493,360

EPRI: $ 97,379

Project Participants and Role



Partner/ Organization	Lead contact(s)	Key Role(s)
DOE-NETL	Andrew P. Jones, Project Manager	-Funding & Sponsorship
Linde LLC	Krish Krishnamurthy Stevan Jovanovic Devin Bostick	-Prime contract -Overall program management -Operations and testing
BASF	Sean Rigby (BASF Corp) Gerald Vorberg (BASF SE)	-OASE® blue technology owner -Basic design -Solvent supply and analysis
EPRI	Richard Rhudy	-Techno-economics review -Independent validation of test analysis and results
Southern Co./NCCC	Frank Morton Justin Anthony	-NCCC Host site (Wilsonville, AL) -Infrastructure and utilities for pilot plant build and operations
Linde Engineering, Dresden	Torsten Stoffregen Dirk Bauersfeld Annett Kutzschbach	-Basic engineering -Support for commissioning -Operations and testing
Linde Eng. – North America	Luis Villalobos Drew Amis; Edgar Perez	-Detailed engineering -Procurement and installation

Project Objectives

Overall Objective

— Demonstrate Linde-BASF post combustion capture technology by incorporating BASF's amine-based solvent process in a 1 MWe 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 MWe power plant incorporating the Linde-BASF post-combustion CO_2 capture technology to illustrate the benefits

— Design, build and operate the 1MWe 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

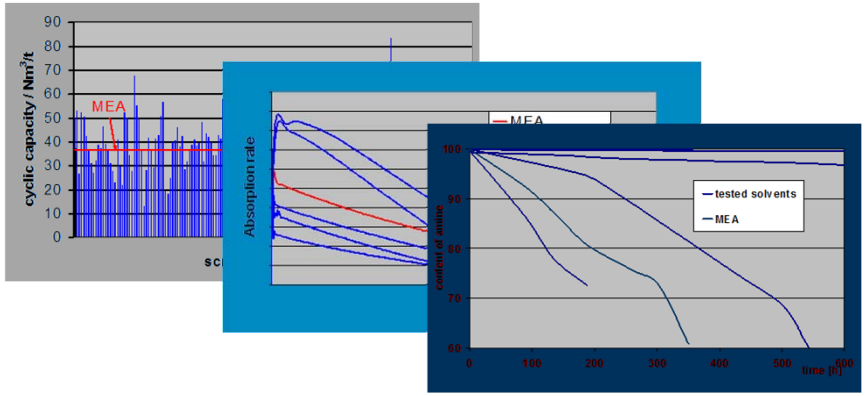
BASF OASE® blue Technology Development

Adopted and optimized for PCC applications

Equilibria

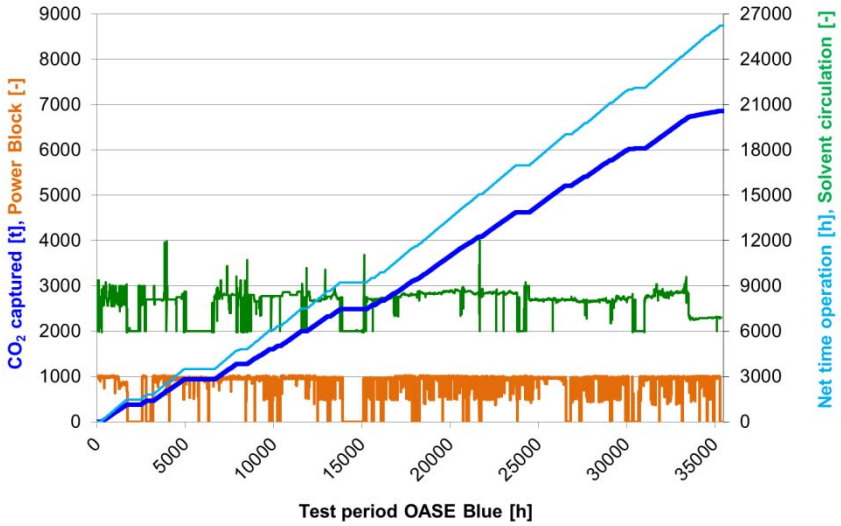
Kinetics

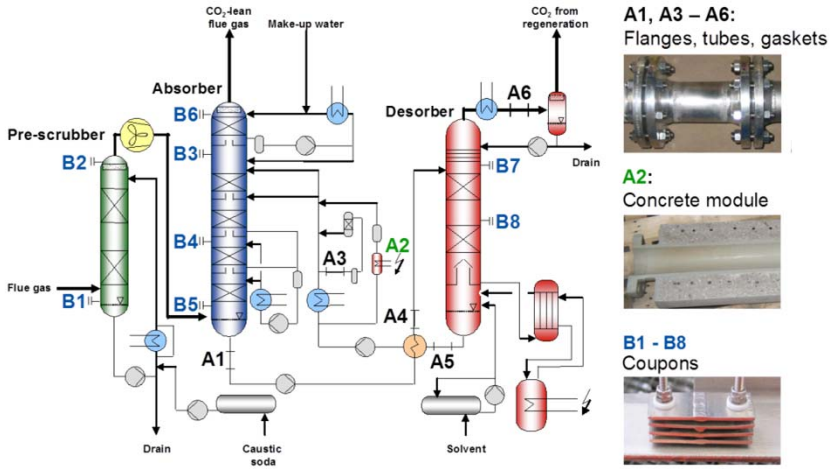
Stability

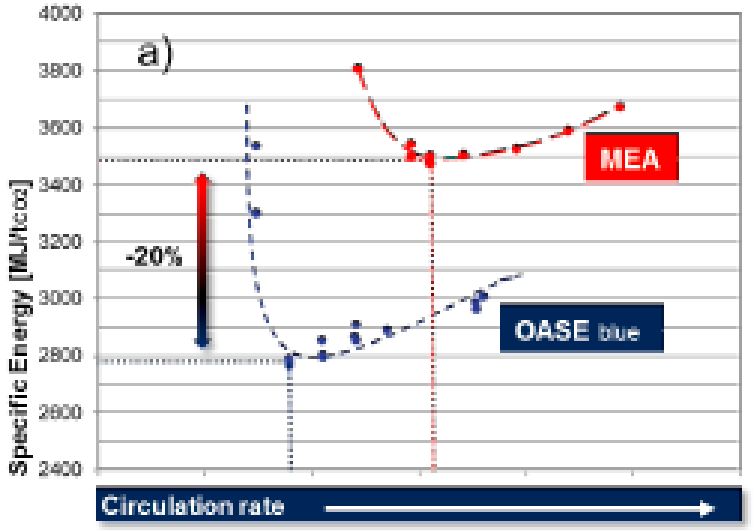


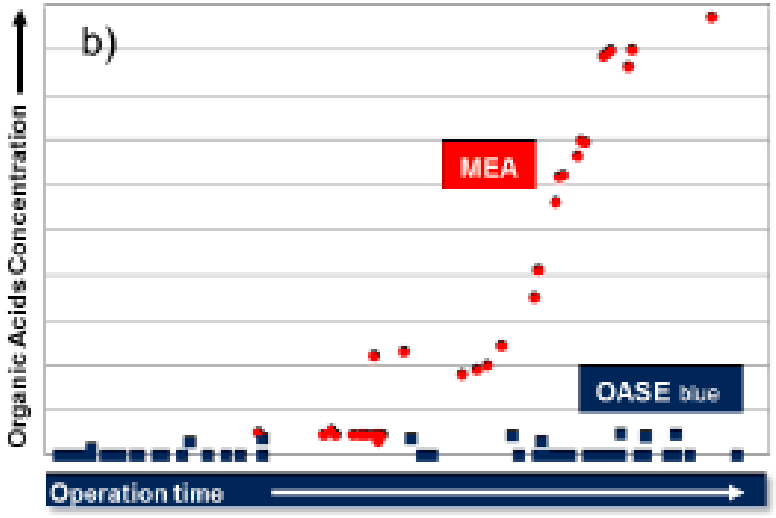
Lab scale	Mini plant	Pilot: 0.45MWe	Pilot: 1-1.5 MWe
— Ludwigshafen, Germany — Advanced solvent screening, development, optimization	— Ludwigshafen, Germany — Solvent performance verification	— 2009, Niederaussem — Process optimization, materials testing	— 2014, Wilsonville, AL — Design improvements, emissions confirmation

Niederaussem Pilot Plant: Operations and test results



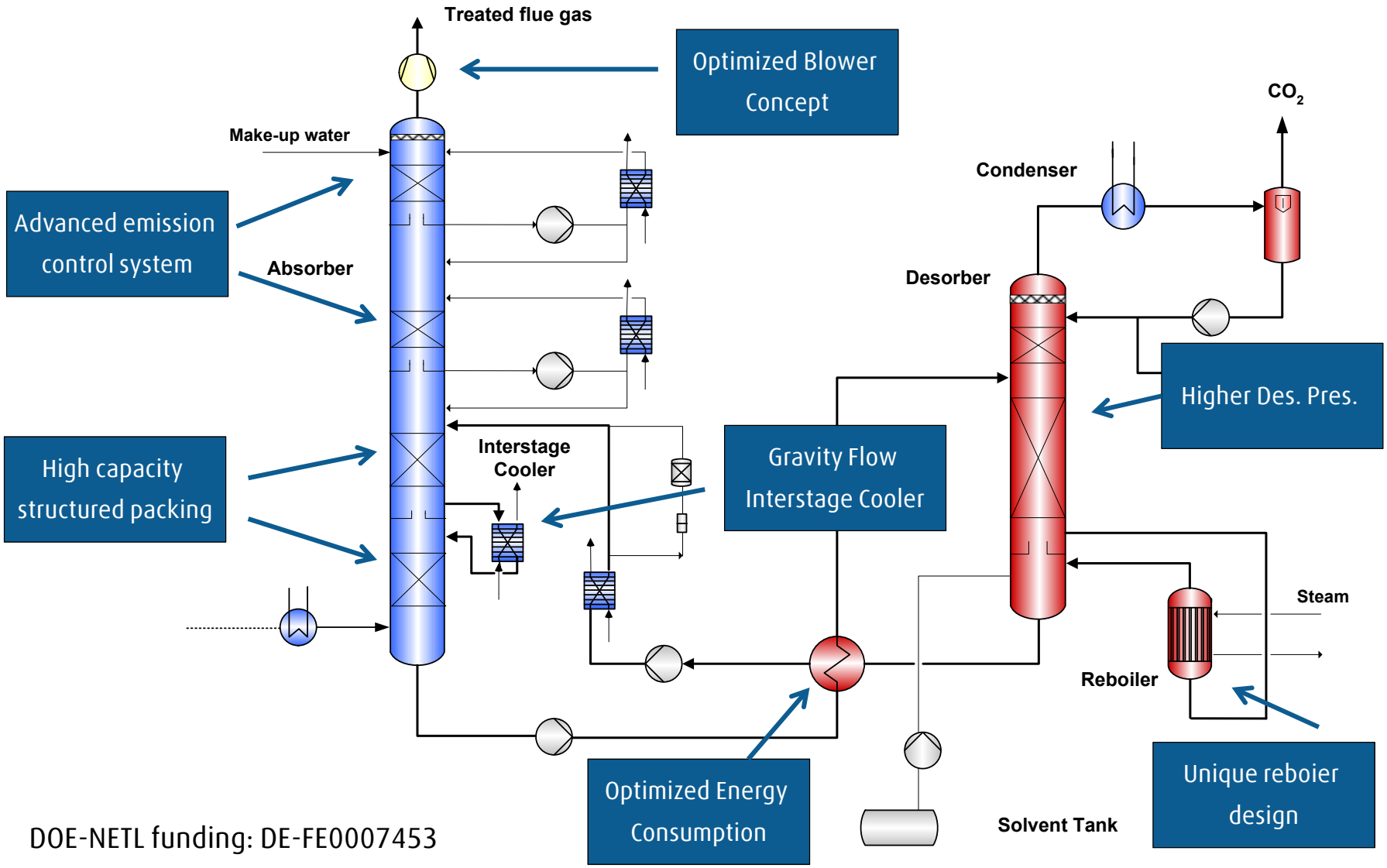






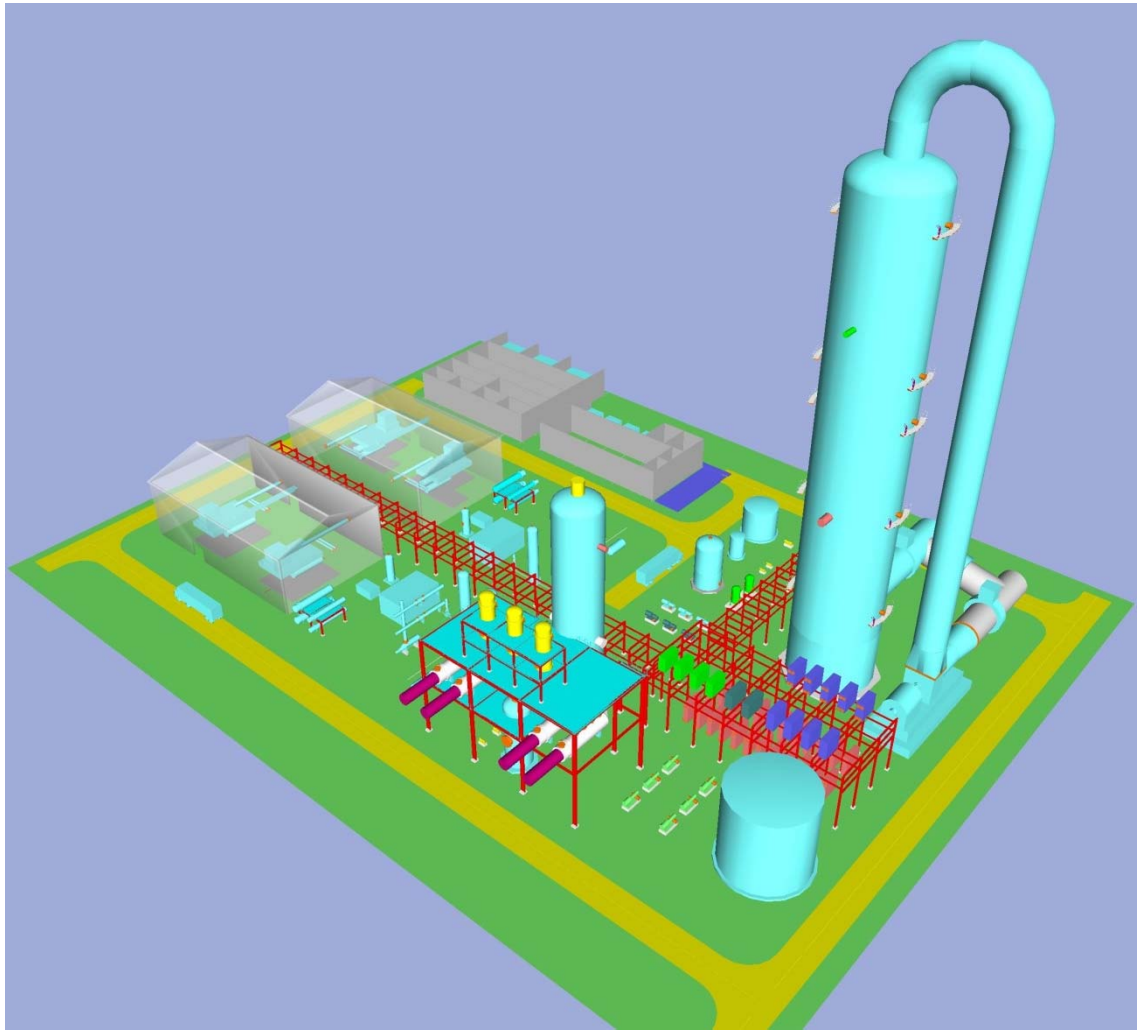
Note: Specific energy above is intrinsic and does not include process or heat integration

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



DOE-NETL funding: DE-FE0007453

Linde-BASF PCC Plant Design for 550 MWe PC Power Plant



- Single train PCC design for ~ 13,000 TPD CO_2 capture
- 40-50% reduced plot area to 180m x 120 m

Key Budget Period 1 (Design & Engineer)
Project Milestones Successfully completed

BP1 (Dec. 1, 2011 – Feb. 28, 2013)

- 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 MWe 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 analyis for the 1 MWe pilot plant to be tested at NCCC (01/31/2013) - Completed 02/15/2013 √

Key Budget Period 2 (Procure & Build)
Project Milestones Successfully Completed

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BP2 (Mar. 1, 2013 – Aug. 31, 2014)

- 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√

BP3 Project Schedule (Continuous availability of site and utilities)

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ID	Task Name	Start	Finish
1	**1. Project management and planning**	12/1	8/31
2	**8. Start-up and initial operation**	12/1	2/27
3	8.1 Control system tuning and system checks	12/1	12/31
4	8.2 System calibrations at initial operation	1/1	2/27
5	**Pilot plant operations validated and ready for testing**	2/27	2/27
6	**9. Parametric testing**	3/2	8/28
7	9.1 Test plan development	3/2	3/31
8	9.2 Data collection and analysis	3/2	6/30
9	9.3 Data validation and process evaluation	5/1	8/28
10	**Performance validated against targets**	8/28	8/28
11	**10. Long duration continuous operation**	9/1	5/31
12	10.1 Long term operation test plan development	9/1	9/29
13	10.2 Data collection and analysis	10/1	5/31
14	10.3 Assessment of long term performance	12/1	5/31
15	**Long term operability and solvent stability demonstrated**	5/31	5/31
16	**11. Final economic analysis and commercialization plan**	6/1	8/31
17	11.1 Updated economic assessments	6/1	7/29
18	11.2 Commercialization plan development	6/1	8/31
19	**Technology advantages demonstrated/Ready for commercial**	8/31	8/31
20	**Project Close**	11/30	11/30

Mechanical completion and commissioning

- Mechanical completion of the 1 MW_e pilot plant achieved : July, 2014

- Pre-start up safety review and comprehensive system installation checks against P&ID and design intent performed to identify issues to address prior to start up

- Machine start-up and water recirculation tests were performed in August 2014 to establish functionality and operability of system components.

Linde-BASF 1 MW_e pilot plant at the NCCC

Pilot plant start-up and initial operations

- OASE® blue solvent delivery and loading into the NCCC pure solution storage tanks completed in December 2014. Initial solvent loading into the system performed on January 10, 2015
- Stable operations achieved within one week
- Start-up & initial operations phase goals:
  - –Tune control loops and establish continuous and steady operation
  - –Calibrate instruments/analyzers and check out mass and energy balance closures
  - –Validate functionality of the unique features in pilot plant
  - – Demonstrate initial performance and compare against targets

Linde-BASF 1 MW_e pilot plant at the NCCC

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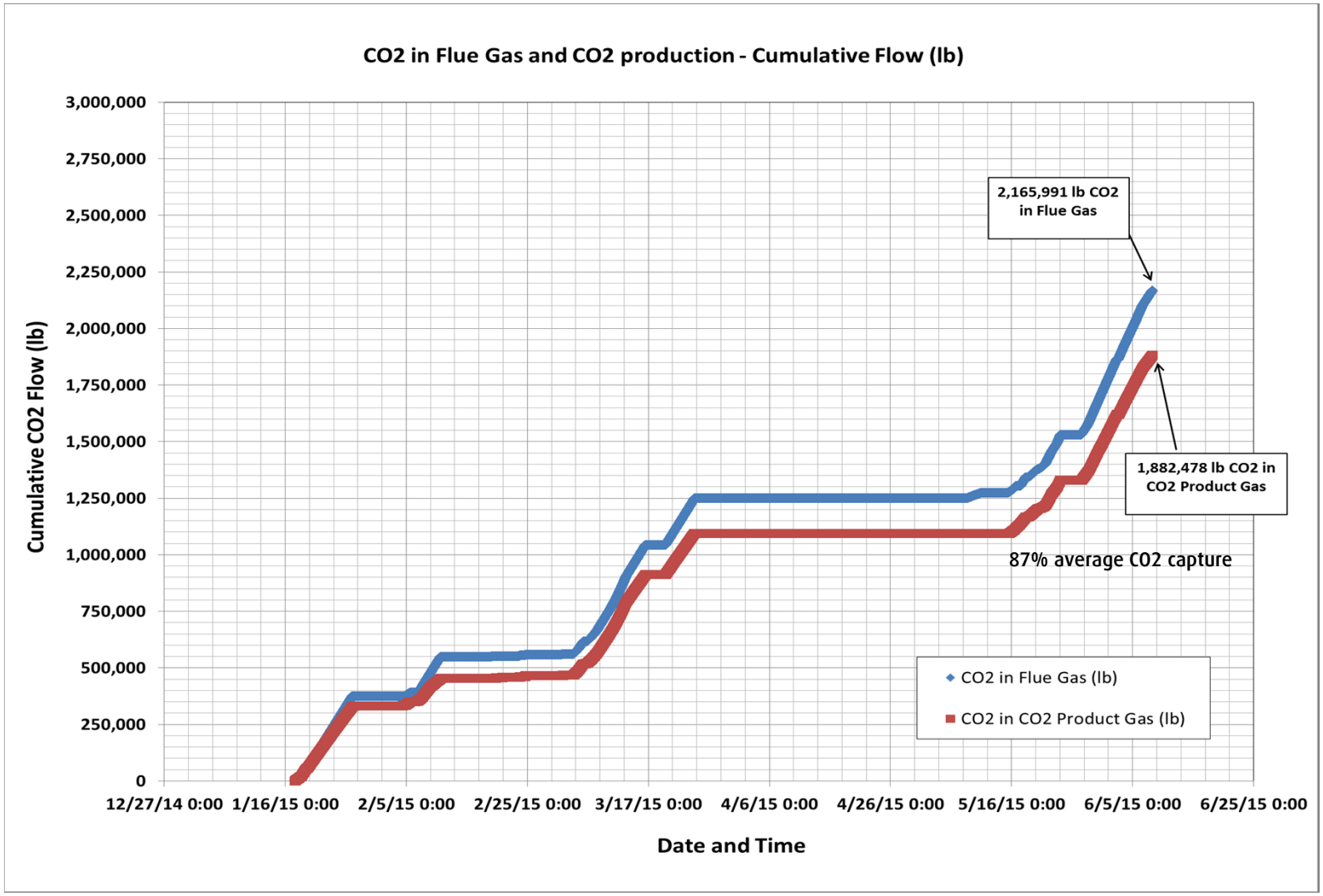
Pilot plant operations philosophy and run time

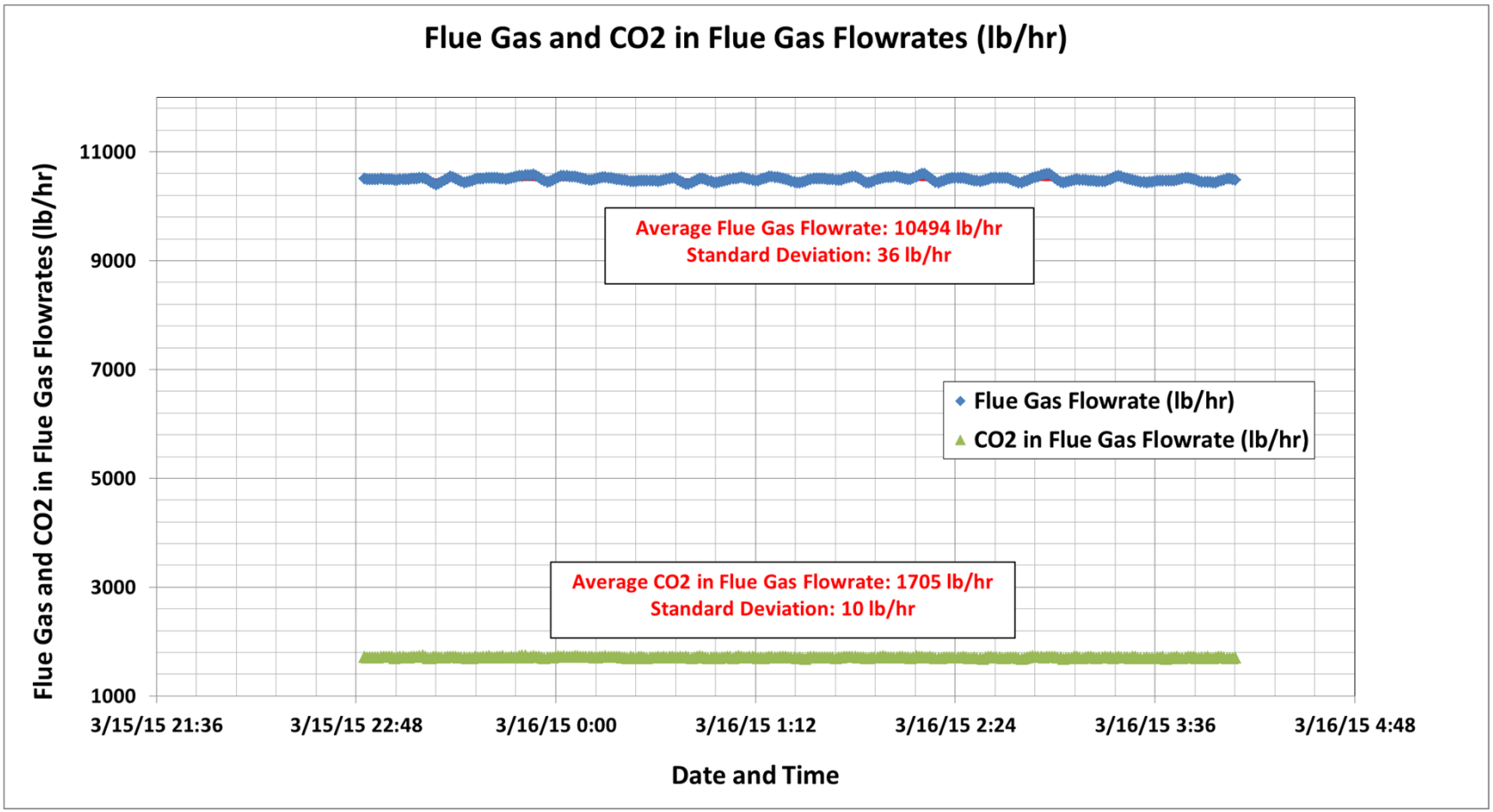
- 24 x 7 operations with 2 x 10 hour shift coverage
- Solvent recirculation continued through entire duration (mostly with steam whenever available) except for minor disruptions.
- System run with flue gas for specific test campaigns

	Time/Date Interval	Hours	Days
Flue Gas	01/16/15 to 06/08/15	1320.2	55.0
Steam	01/16/15 to 06/08/15	1985.0	82.7
Solvent Circulation	01/16/15 to 06/08/15	2193.4	91.4

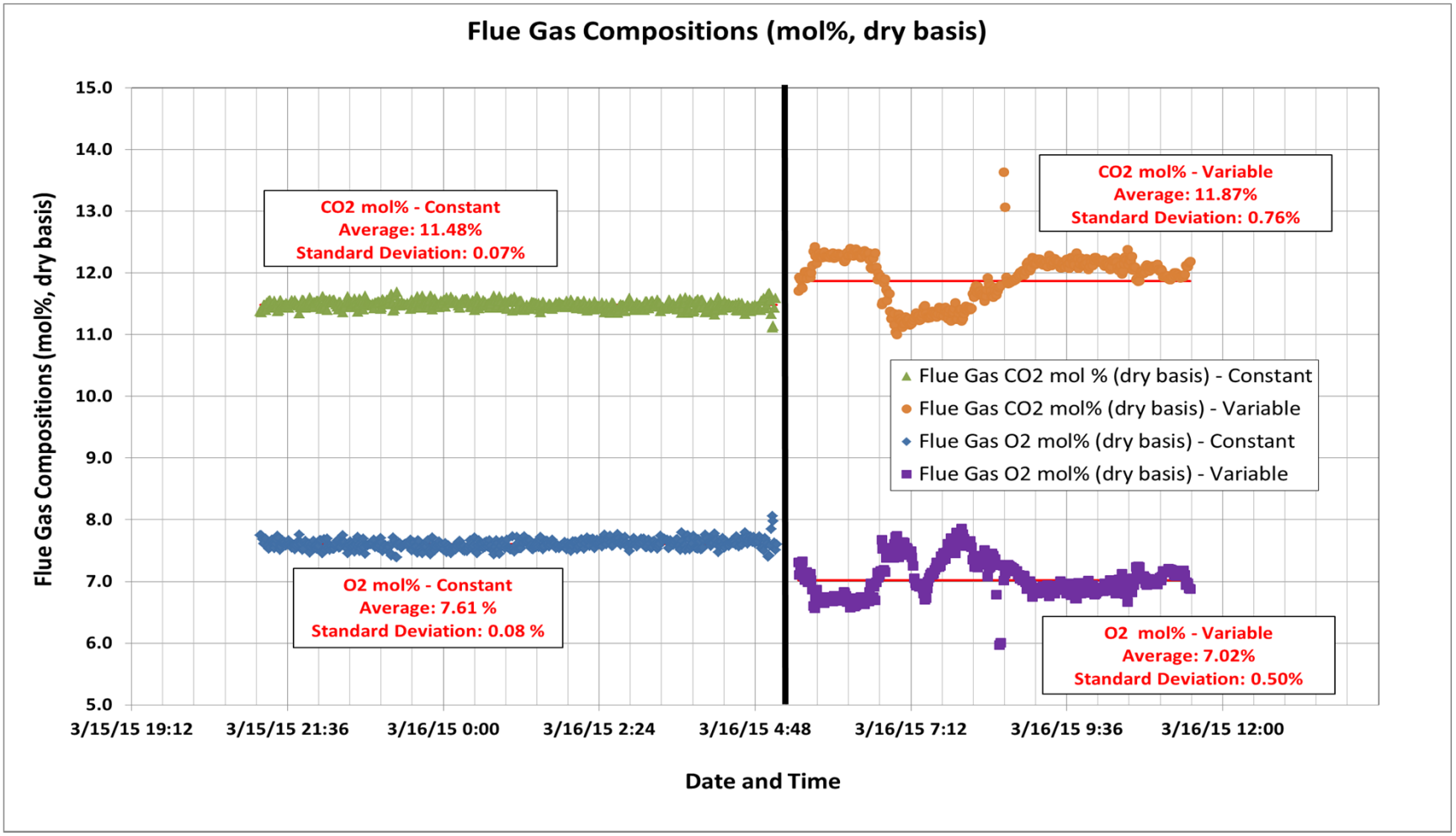
Pilot plant operations and CO2 capture



Flue gas flow rate to the pilot plant is typically very steady



Flue gas composition (11.5% CO2; 7.6% O2) typically steady but showed variations from time to time (±0.6%)



Pilot plant set up and operations: Overall mass balance closures were excellent

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Overall Mass Balance (dry basis)			
Time/Date Interval	Average Mass Flow In (lb/hr)	Average Mass Flow Out (lb/hr)	% Difference
03/15/15 21:10:00 to 03/16/15 11:30:00	10180.02	10234.55	0.53%

CO2 Mass Balance			
Time/Date Interval	Average CO2 Mass Flow In (lb/hr)	Average CO2 Mass Flow Out (lb/hr)	% Difference
03/15/15 21:10:00 to 03/16/15 11:30:00	1729.01	1716.15	0.75%

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
03/13/15 06:00:00 to 03/13/15 07:30:00	2348.66	2332.53	0.69%

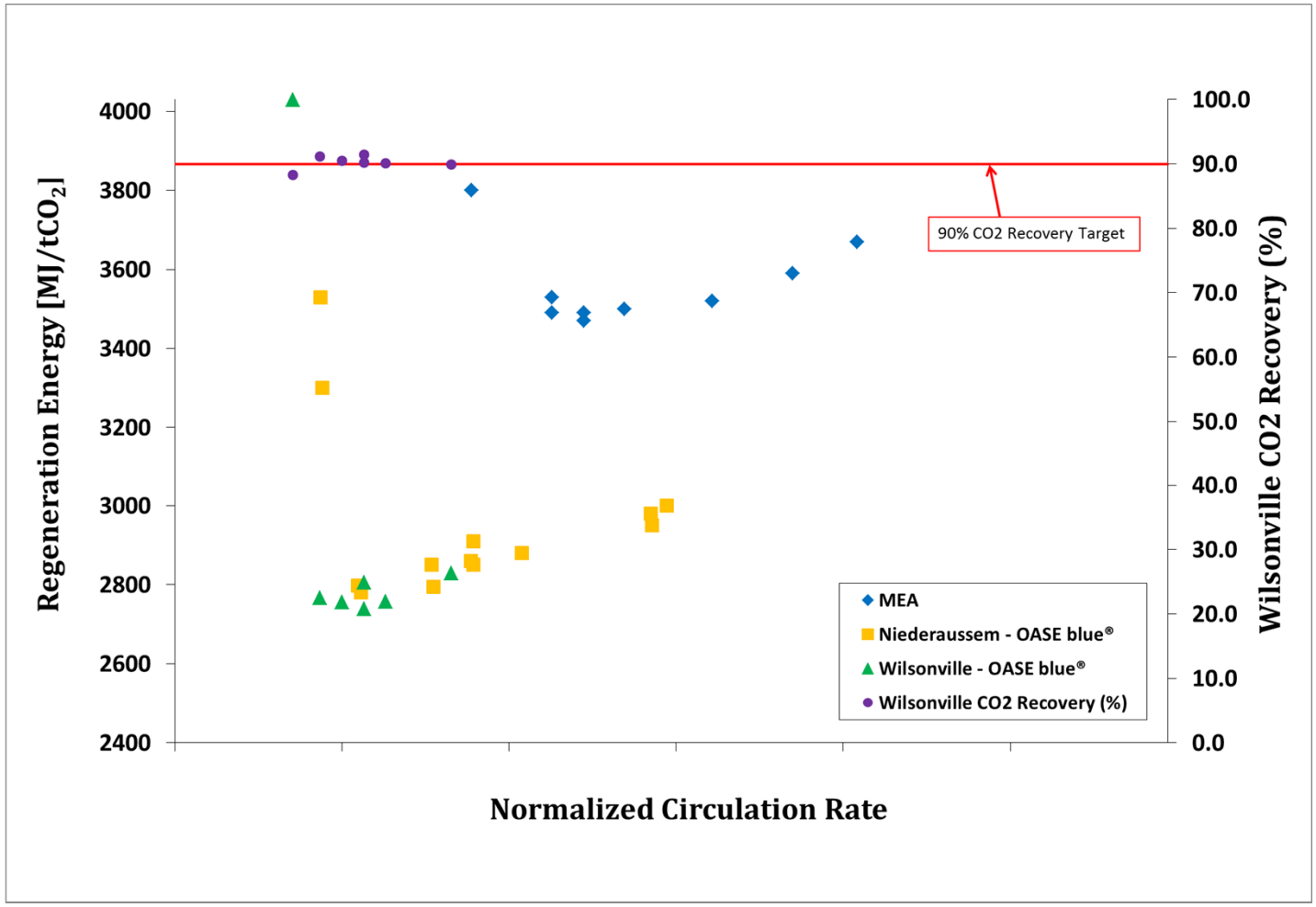
Water balance has an effect on the overall mass and CO2 balance closures

Overall Mass Balance (dry basis)			
Time/Date Interval	Average Mass Flow In (lb/hr)	Average Mass Flow Out (lb/hr)	% Difference
05/30/15 00:00:00 to 05/30/15 02:00:00	14802.36	14409.53	2.65

CO2 Mass Balance			
Time/Date Interval	Average CO2 Mass Flow In (lb/hr)	Average CO2 Mass Flow Out (lb/hr)	% Difference
05/30/15 00:00:00 to 05/30/15 02:00:00	2481.01	2453.03	1.13

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
05/30/15 00:00:00 to 05/30/15 02:00:00	2369.06	2236.91	5.58

Specific energy consumption vs Solvent circulation rate (comparison with MEA and OASE® blue results from Niederaussem)



Test conditions:

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

Pilot plant performance against targets: Initial accomplishments and plans

Performance Attribute	Current achievement against target	Remarks
1. CO2 capture rate	>90% per target	Achieved. Optimized for specific energy.
2. CO2 purity	99.9% dry basis per target	Achieved. Low O2 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
4. Regenerator steam consumption	~ 2.8 GJ/tonne CO2 (same as Niederaussem consumption)	Energy optimization planned during current parametric test campaign.
5. Emissions control validation	Validation of dry bed (BASF patented) operation per design	Further emissions control optimization during next campaign
6. Regenerator operating pressure	-Currently 2 bar compared with 3 bar target	3 bar tests planned at end of parametric tests
7. Validation of unique features	(i) high capacity packing, (ii) gravity driven intercooler, (iii) blower downstream of abs. (iv) unique reboiler design.	Optimization of lean-rich heat exchanger for energy reduction during next campaign

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

Summary and conclusions

- 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; initial operations & testing have demonstrated stable operation, validation of functional features and initial achievement of several key targets
- Continued parametric testing campaign in progress. Parametric tests aimed at energy optimization, emissions minimization and validation of higher pressure regenerator operation. This will be followed by long duration testing (4-6 months) to demonstrate solvent stability.

Acknowledgements & Disclaimer

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DOE-NETL Project Manager: Andrew Jones

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BASF: Sean Rigby, Gerald Vorberg & Gustavo Lozano

Linde: Torsten Stoffregen, Annett Kutzschbach, Dirk Bauersfeld, Stevan Jovanovic, Devin Bostick, Makini Byron, Luis Villalobos, Drew Amis, Edgar Perez

Thank you for your attention!

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