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
Linde

The Linde Group Overview

Fully integrated gases and engineering company

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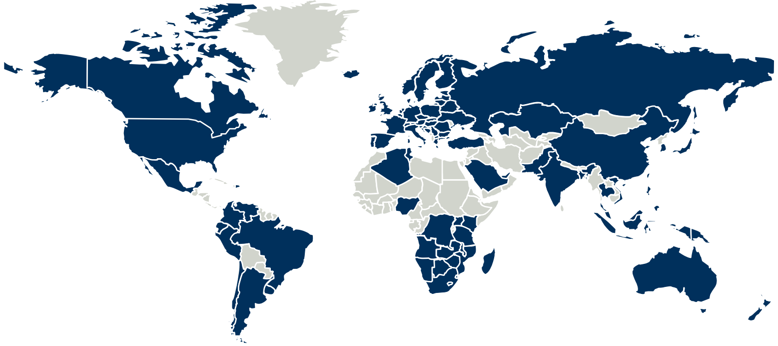
Founded	**1879**
Sales	**~$20 billion**
Employees	**~62,000**
Countries	**>100**



Linde Engineering

Technology-focused

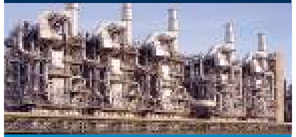
Air Separation

Global #1

Hydrogen/Syn Gas

Global #2

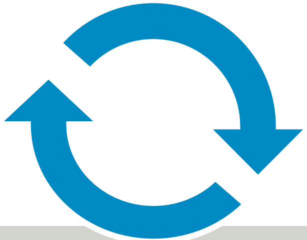
Olefins



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)

Source	Budget Period 1 Dec 2011 – Feb 2013	Budget Period 2 Mar 2013 – Aug 2014	Budget Period 3 Sep 2014 – May 2016*	Total
DOE Funding	$2,670,173	$10,441,507	$3,107,167	$16,218,847
Cost Share	$667,543	$3,237,450	$776,792	$4,681,785
Total Project	$3,337,716	$13,678,957	$3,883,959	$20,900,633

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

DE-FE0007453 Project Participants

Partner/ Organization	Lead contact(s)	Key Role(s)
DOE-NETL	Andrew P. Jones, Project Manager	-Funding & Sponsorship
Linde LLC	Krish Krishnamurthy, PI Stevan Jovanovic, Technical Lead	-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 Michael England	-NCCC Host site (Wilsonville, AL) -Infrastructure and utilities for pilot plant build and operations
Linde Engineering, Dresden	Torsten Stoffregen	-Basic engineering -Support for commissioning -Operations and testing
SFPC (LENA)	Keith Christian	-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 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 CO_2 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

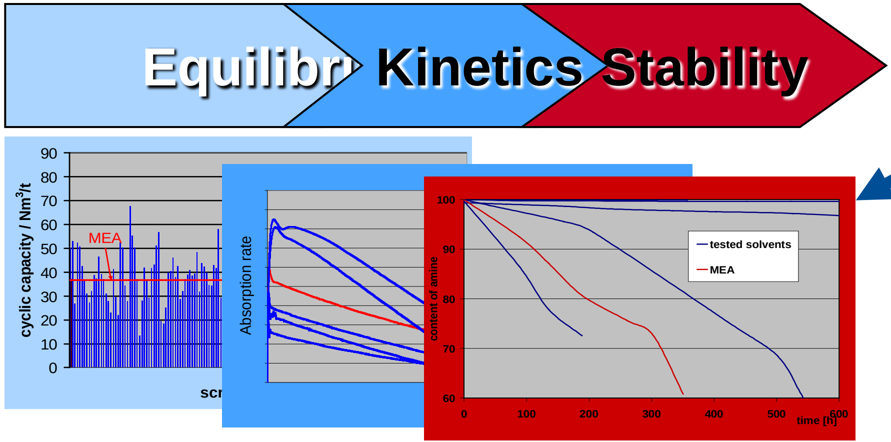
- Post-combustion CO_2 capture technology is flexible and can be applied to both new and existing power plants

- 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

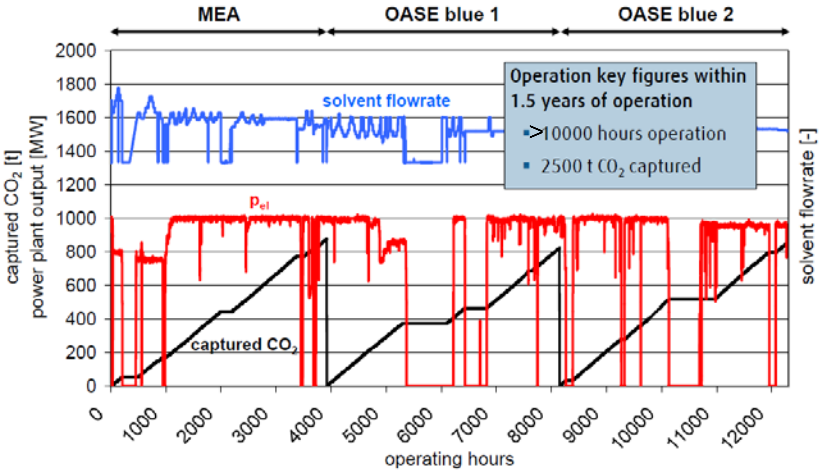


Fundamental Lab Scale R&D: Advanced Solvents Screening, Development,

BASF Miniplant, Ludwigshafen, Germany: Solvent Performance

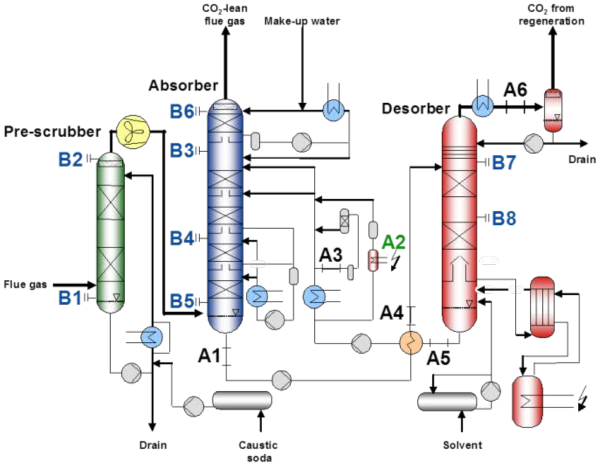
0.45 MWe PCC Pilot, Niederaussem, Germany: Preliminary Process Optimization

Niederaussem Pilot Plant: Main results of Phase I



Operation key figures within 1.5 years of operation

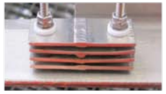
- >10000 hours operation
- 2500 t CO_2 captured

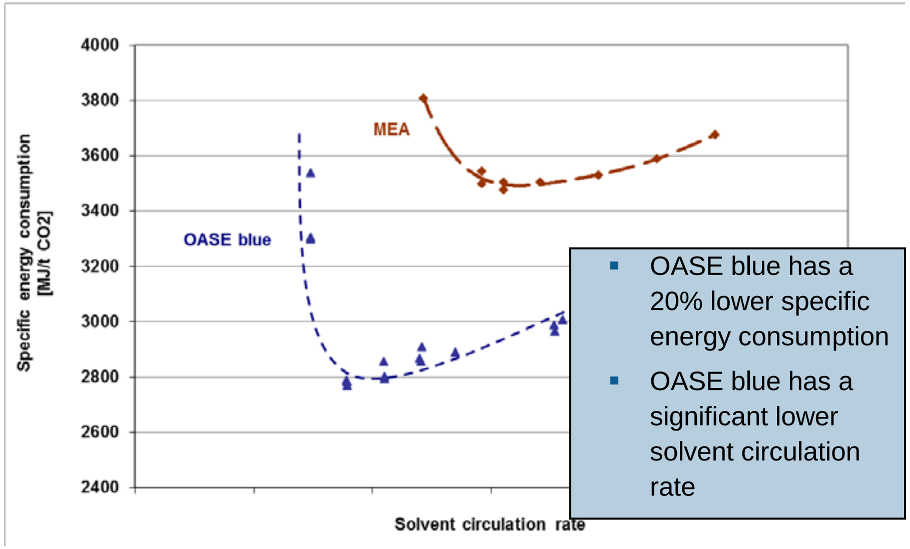


A1, A3 – A6:
Flanges, tubes, gaskets

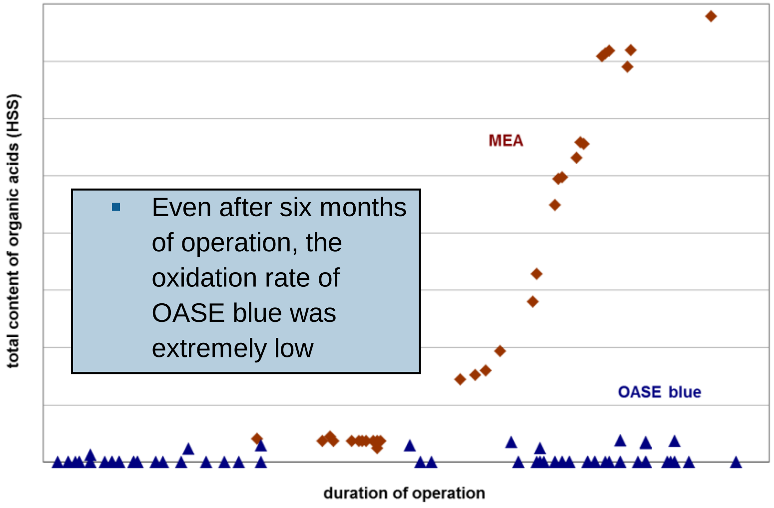
A2:
Concrete module

B1 - B8
Coupons





- 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

Source: Kyoto GHGT11

Pilot Plant Niederaussem Test run history

Phase 2 focus: Long term testing evaluating materials, solvent degradation and emissions reduction

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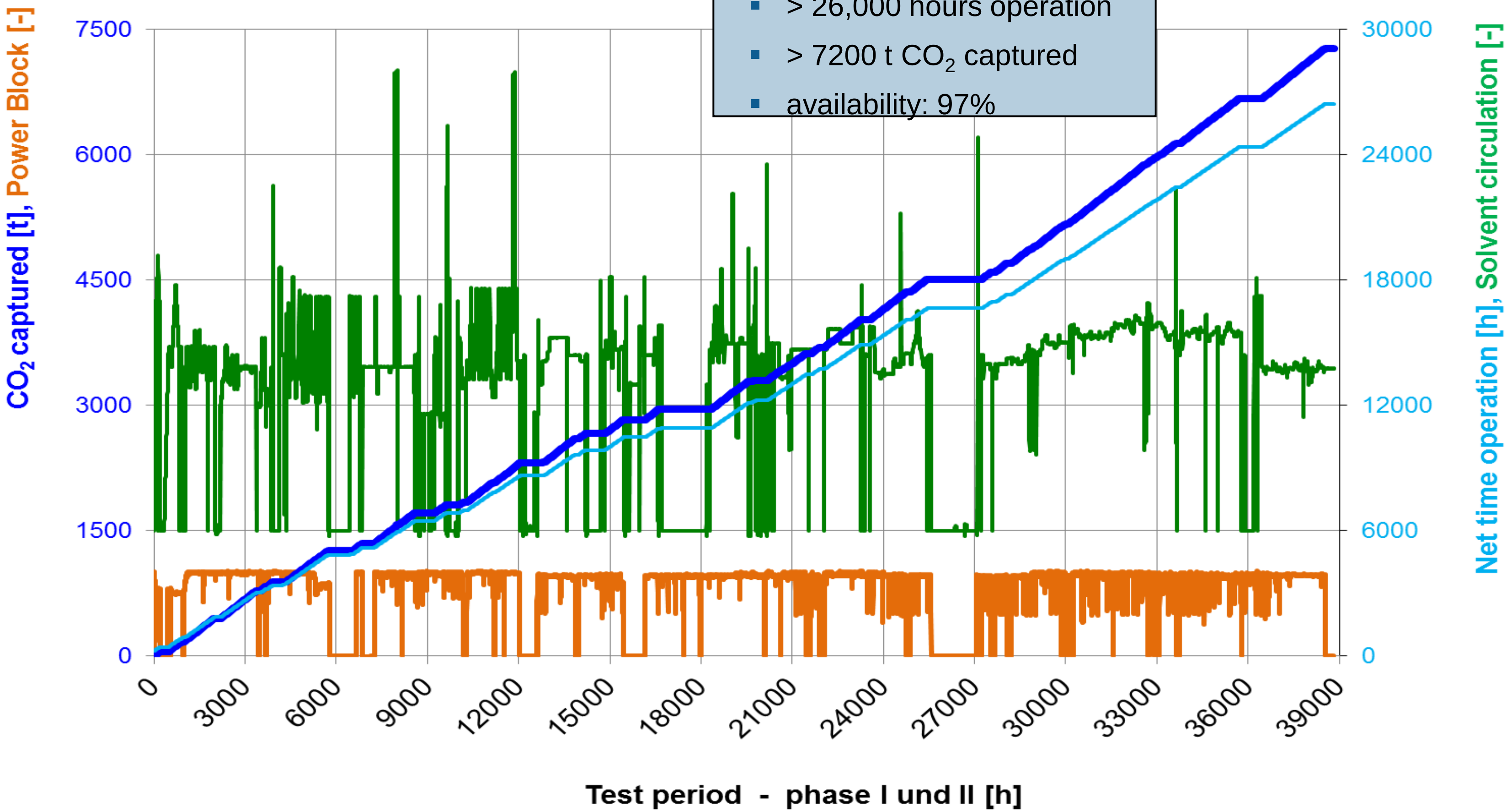
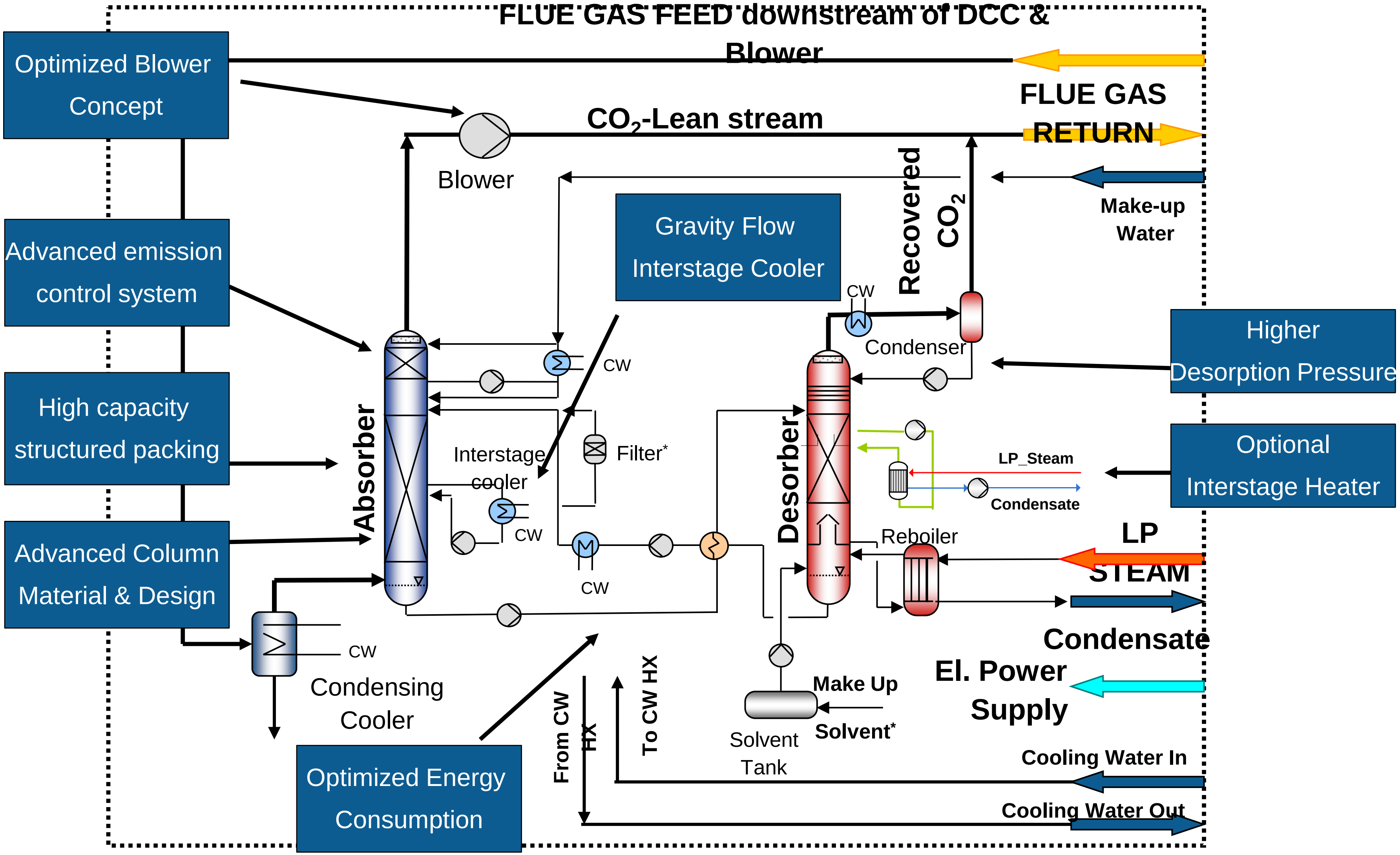
Status: Phase I and II (Dec 2013)

- > 26,000 hours operation
- > 7200 t CO_2 captured
- availability: 97%



Linde-BASF advanced PCC plant design*



Optimized Blower Concept

Advanced emission control system

High capacity structured packing

Advanced Column Material & Design

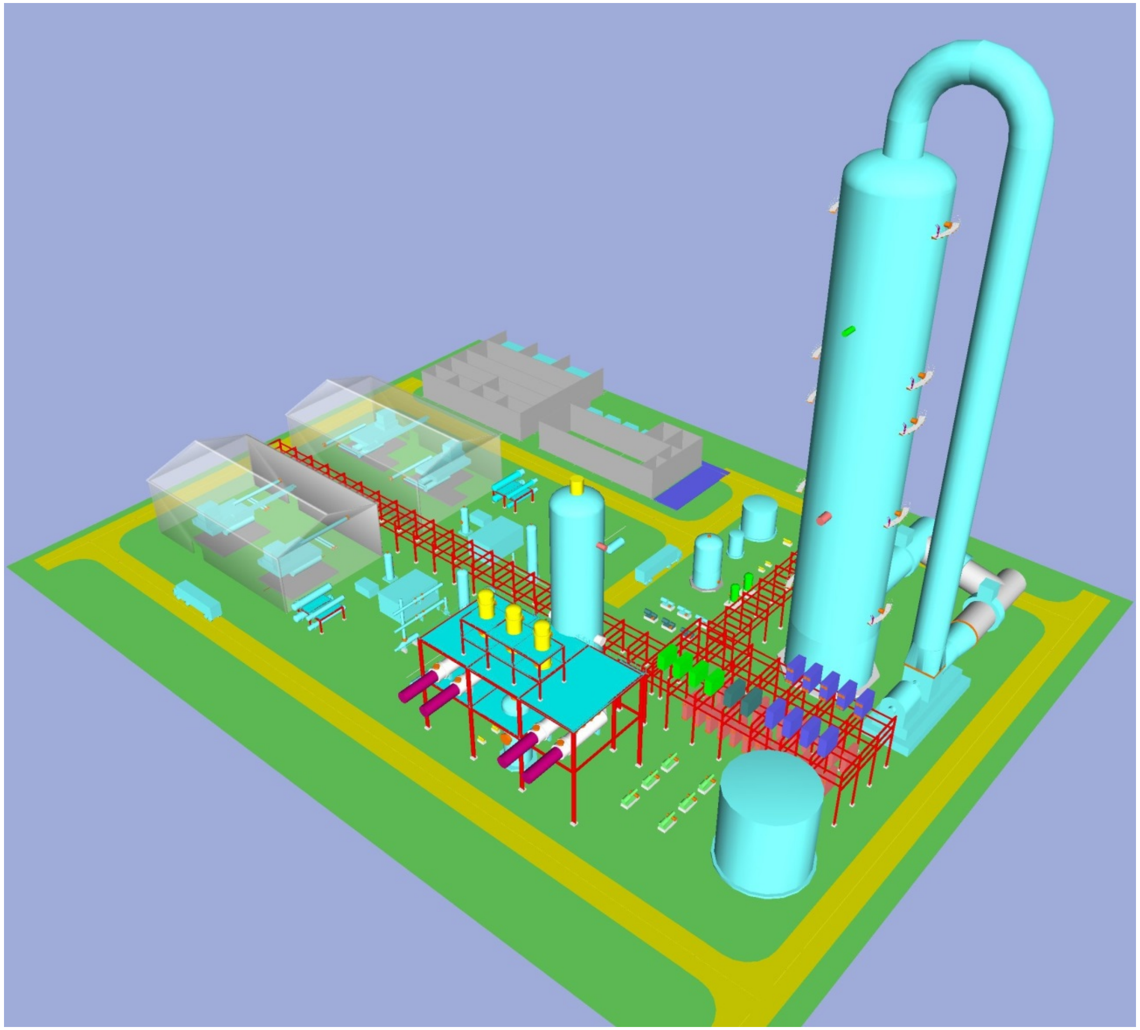
Optimized Energy Consumption

Gravity Flow Interstage Cooler

Higher Desorption Pressure

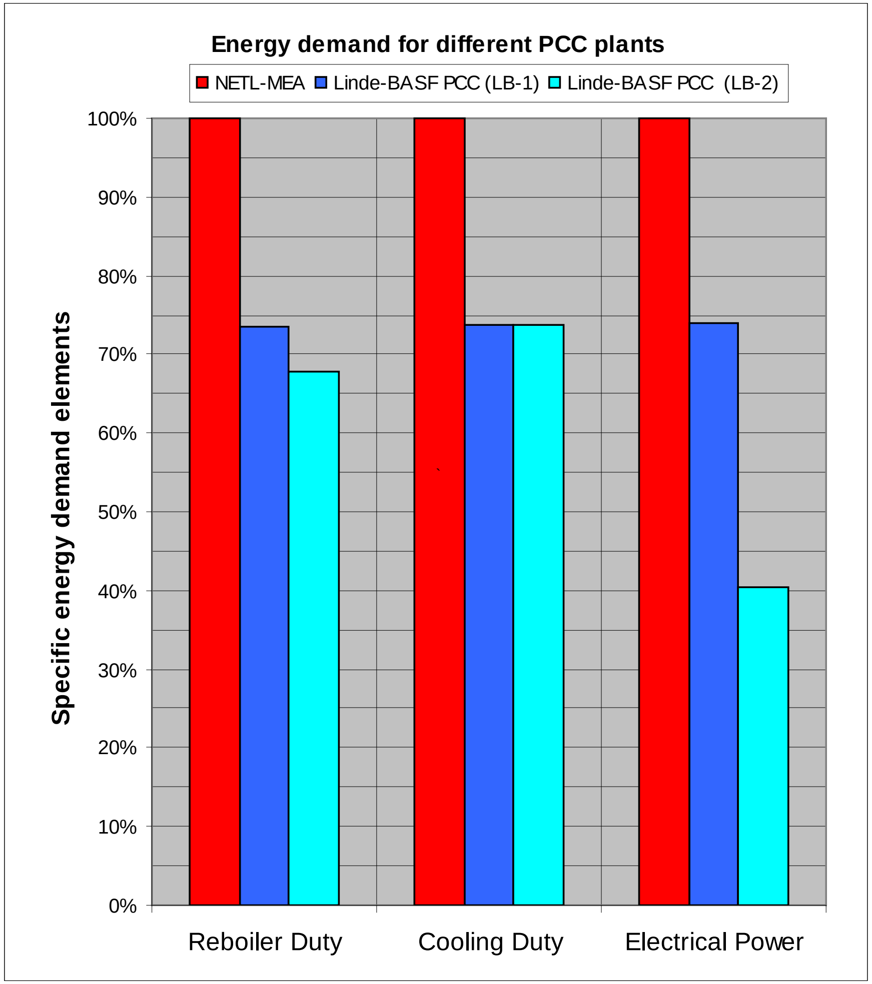
Optional Interstage Heater

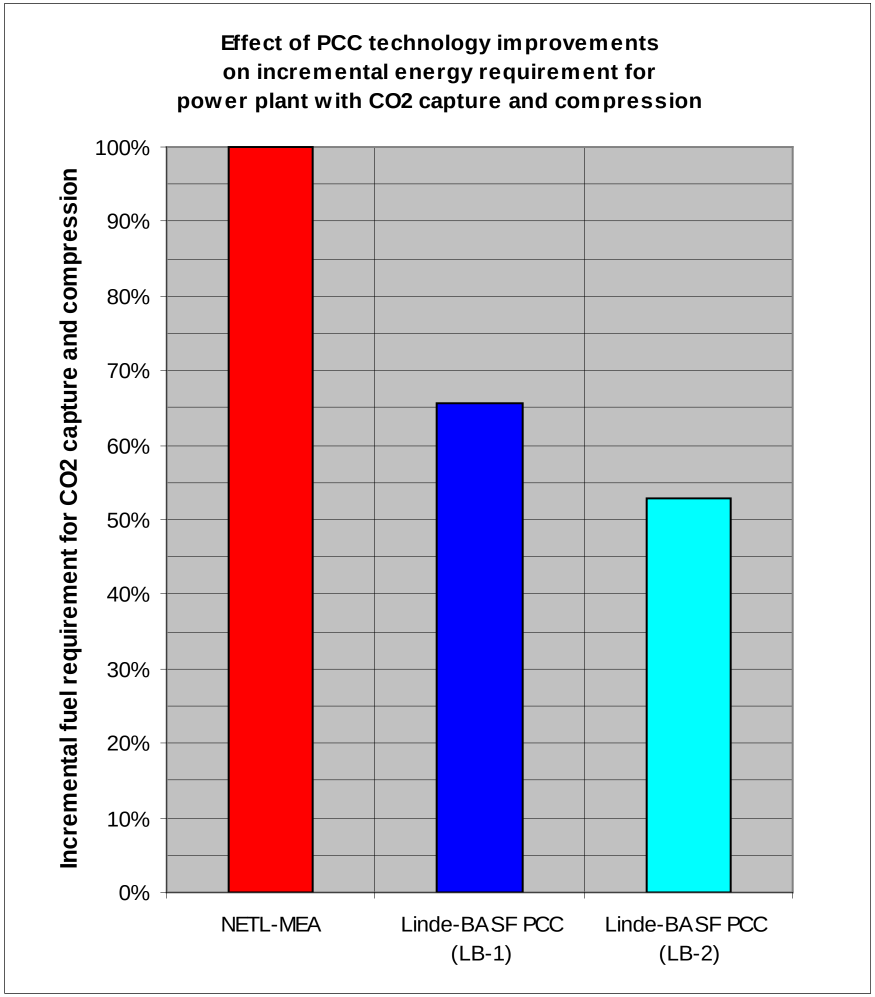
Linde-BASF PCC Plant Design for 550 MWe PC Power Plant



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

Comparative PCC Performance Results
Linde-BASF vs Reference DOE/NETL Case*





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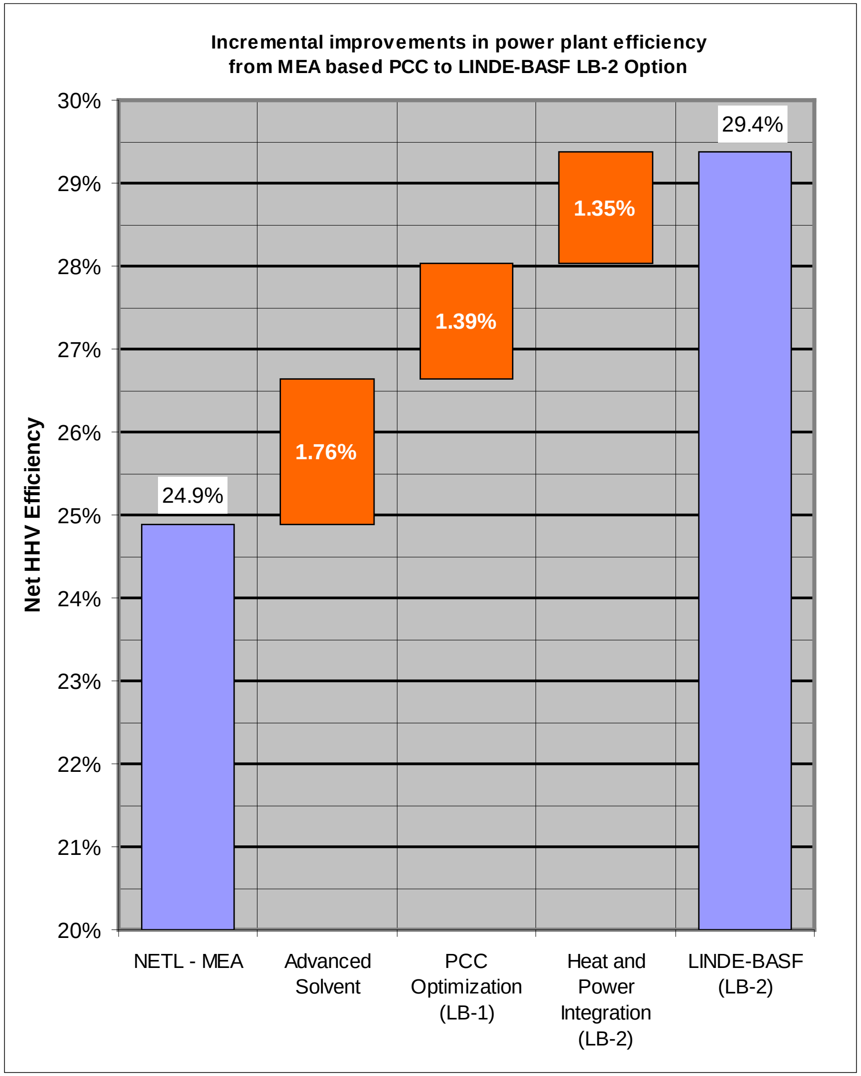
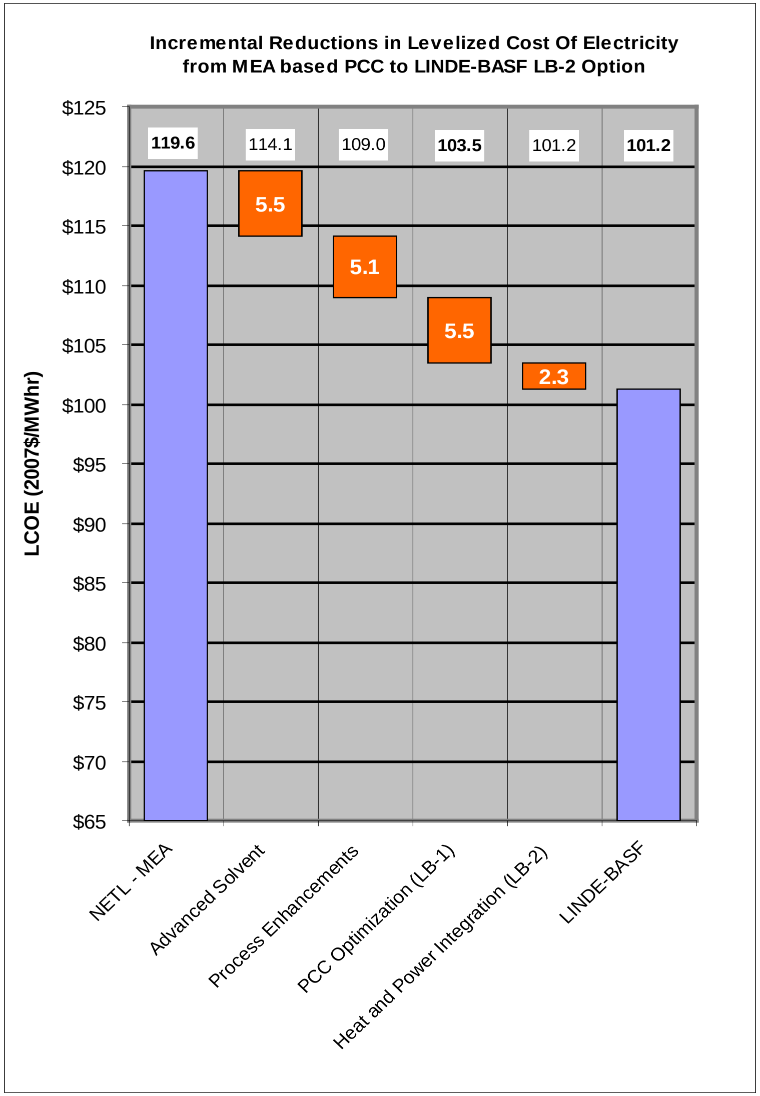
[*] Reference Case # 10 of DOE-NETL 2007/1281 Report

Power plant efficiency improvements and LCOE reductions with Linde-BASF PCC technology





Source: Project DE-FE0007453 Techno-economic analysis of 550 MWe PC power plant with CO2 capture, May 2012.

Key Budget Period 1 Project Milestones

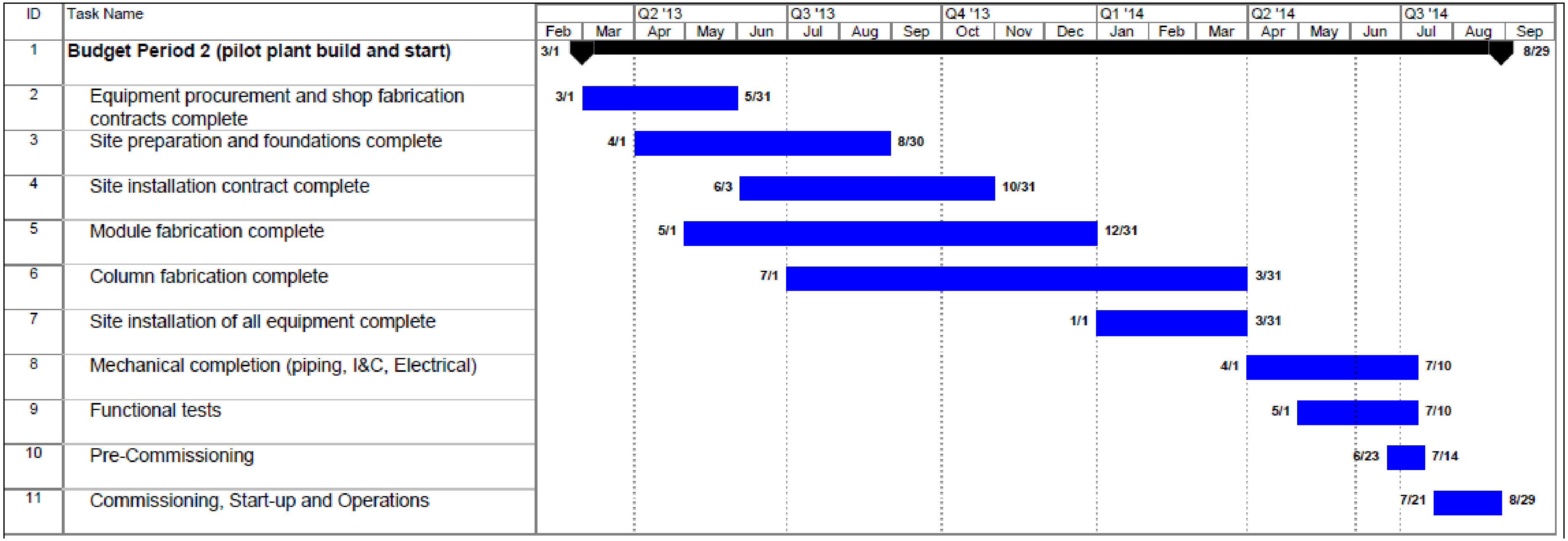
BP1 (Dec. 1, 2011 – Feb. 28, 2013)

- 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 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 analyis 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)

Task #	Task Description	Key Objectives	Accomplishments
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 - Enable mechanical completion of the pilot plant	- All modules, columns and equipment (analytical container, solution storage tank) have been installed at site - 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



ID	Task Name
1	**Budget Period 2 (pilot plant build and start)**
2	Equipment procurement and shop fabrication contracts complete
3	Site preparation and foundations complete
4	Site installation contract complete
5	Module fabrication complete
6	Column fabrication complete
7	Site installation of all equipment complete
8	Mechanical completion (piping, I&C, Electrical)
9	Functional tests
10	Pre-Commissioning
11	Commissioning, Start-up and Operations

- Construction process safety review (PSR4) completed Dec. 9, 2013
- Hazop actions review and updates on actions: Dec 9, 2014, May 30, 2014 & July 16, 2014
- 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

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√ (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

Plate frame Heat Exchangers

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

Process Pumps

Module fabrication and installation in shop (Red Bud, IL)

A single completed module

Module installation & Assembly

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

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Absorber section in fabrication and assembly

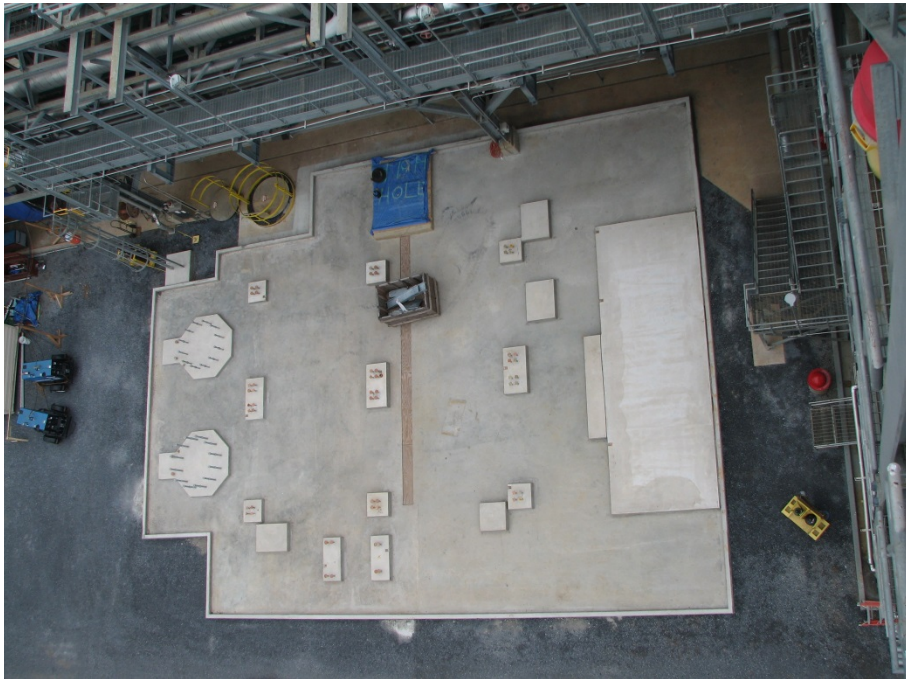
Stripper section in fabrication and assembly

- 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.

NCCC site preparation to accept pilot plant

Rebar Placement

Foundations and Slab Complete



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

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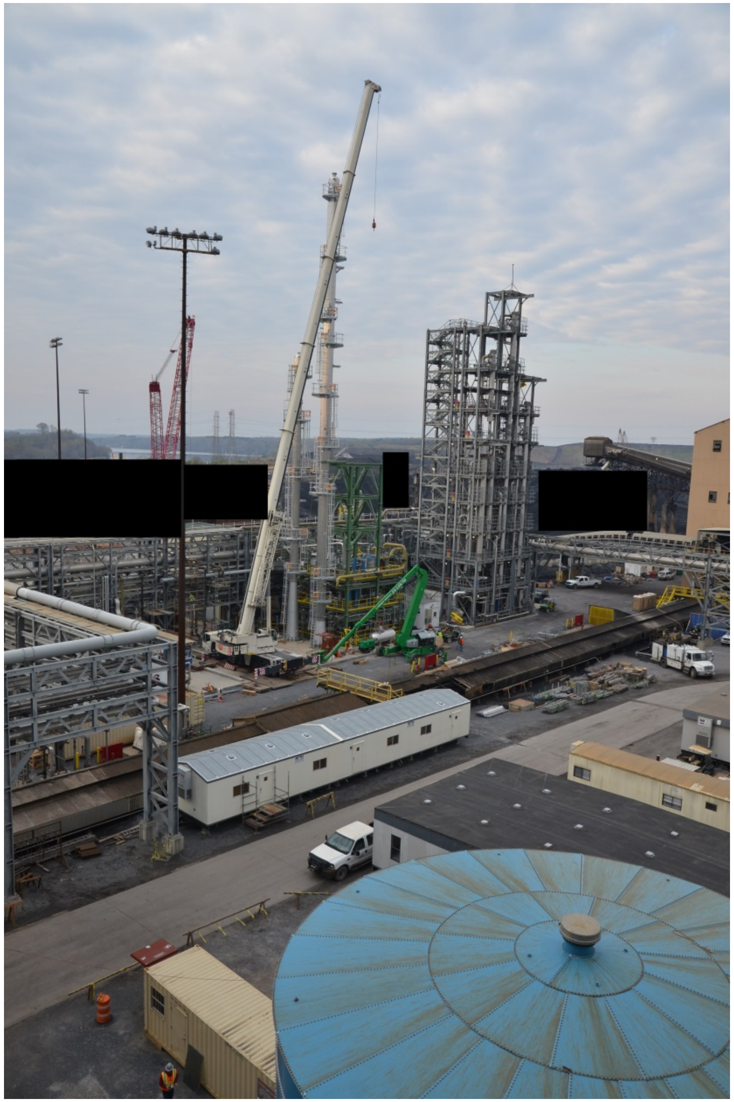
Top section of the absorber lifted into position (left); Column installation complete (right)



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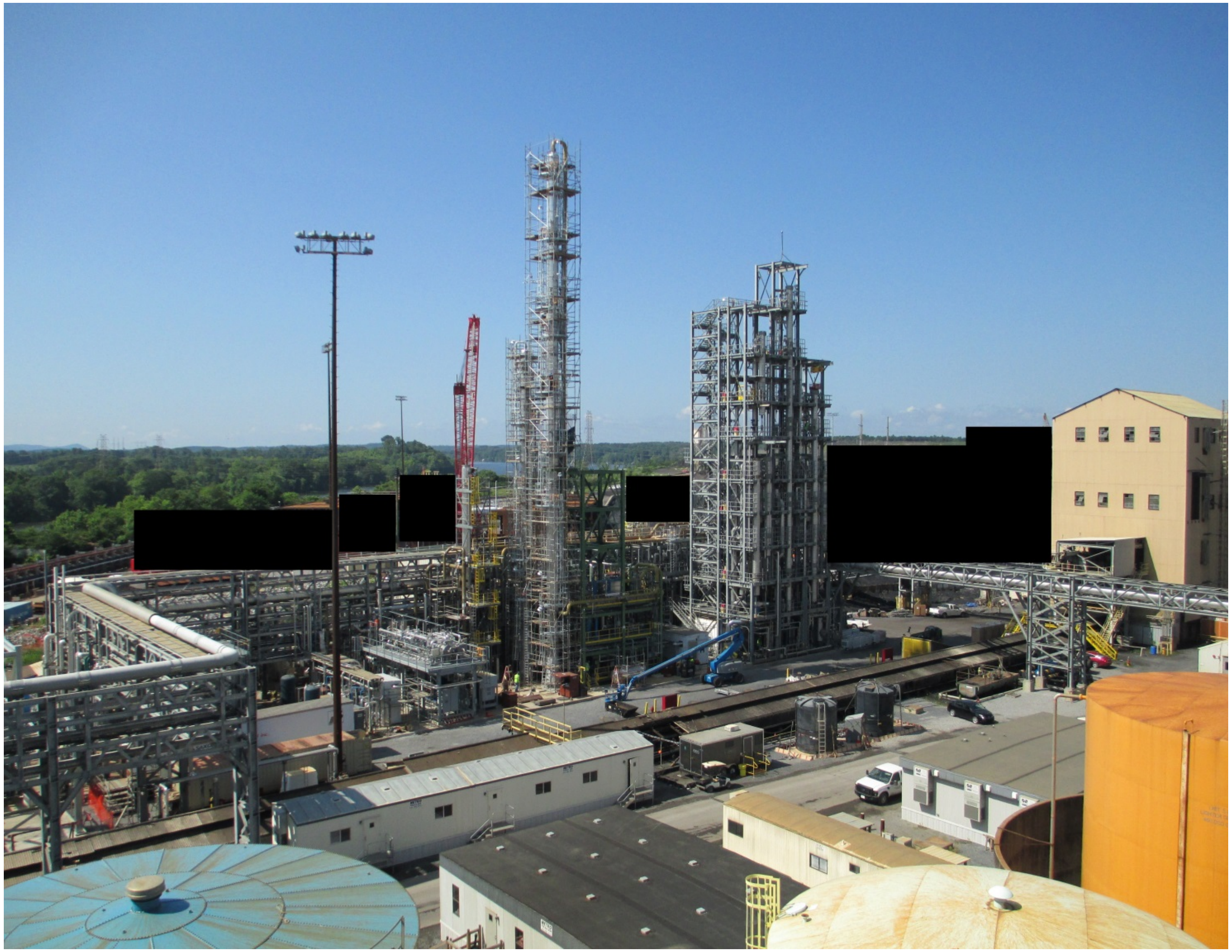
Absorber and stripper column scaffolding to install piping, pipe supports, insulation and heat tracing.

Based on safety assessment, decision made by contractor to scaffold the columns for installation of piping, pipe supports, insulation, heat tracing, and insulation.



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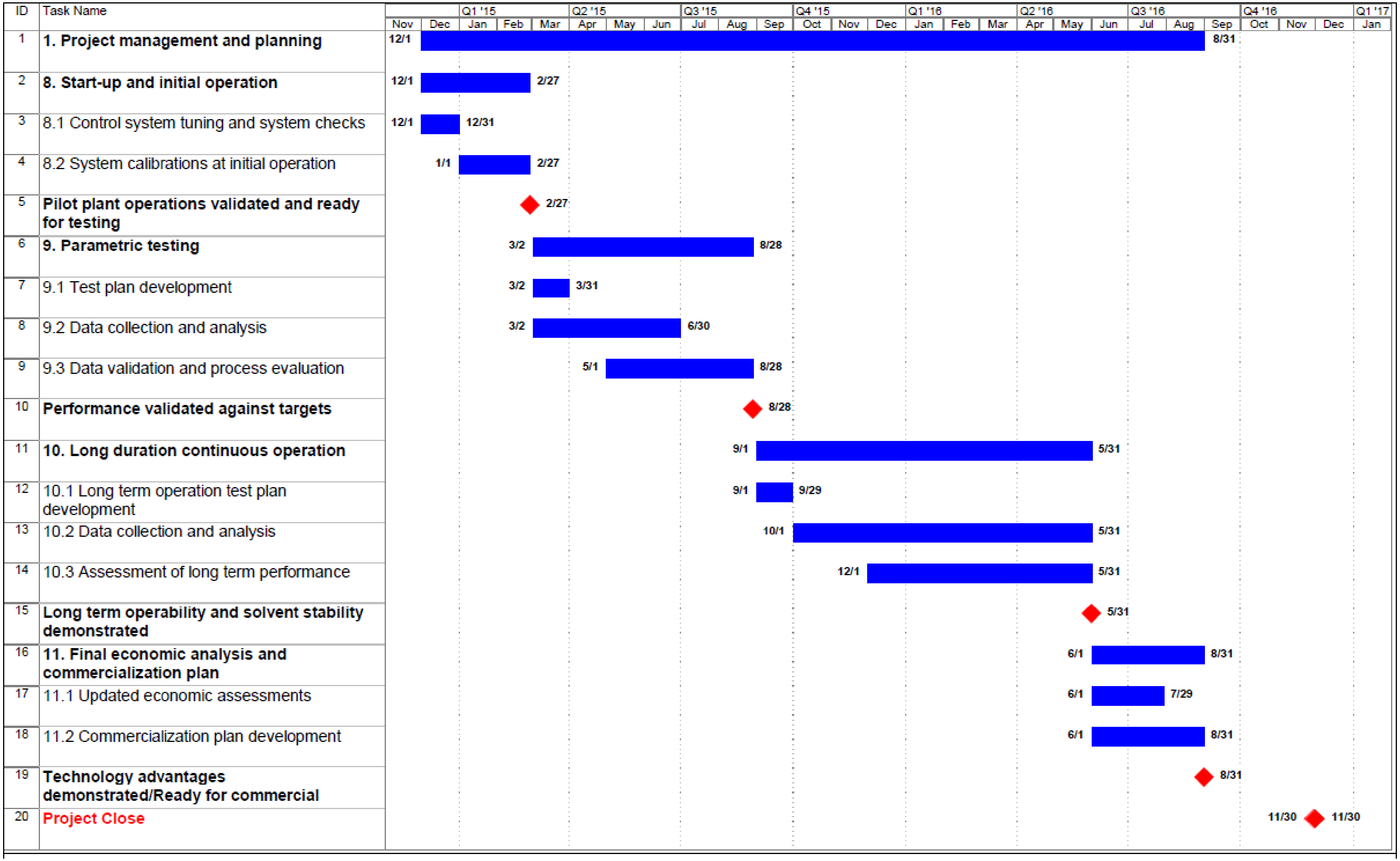
Challenges/Lessons learned in pilot plant build

- 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)



ID	Task Name		
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
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
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
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
20	**Project Close**	11/30	11/30

Acknowledgement and Disclaimer

Acknowledgement: This presentation is based on work supported by the Department of Energy under Award Number DE-FE0007453.

Thank you for your attention!

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