SLIPSTREAM PILOT-SCALE DEMONSTRATION OF A NOVEL AMINE-BASED POST-COMBUSTION TECHNOLOGY FOR CARBON DIOXIDE CAPTURE FROM COAL-FIRED POWER PLANT FLUE GAS

FINAL SCIENTIFIC/TECHNICAL REPORT

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Disclaimer:

Table of Contents

Abbreviations List

PCC	Post-combustion CO_2 Capture
aMWh	Annual net megawatt-hours of power generated at 100% capacity factor
CCF	Capital Charge Factor for a levelized period of 20 years (0.124 in this study)
CF	Plant Capacity Factor (0.85 in this study)
DCC	Direct Contact Cooler
FGD	Flue Gas Desulfurization
LB1	Linde-BASF PCC option previously reported upgraded to supercritical PC power plant using BASF OASE$^{®}$ blue solvent technology and advanced PCC process
SIH	Linde-BASF PCC option using BASF OASE$^{®}$ blue solvent technology with advanced stripper interstage heater PCC process configuration
LB1-CREB	Linde-BASF PCC option using BASF OASE$^{®}$ blue solvent technology with advanced main CO_2-rich/CO_2-lean heat exchanger and cold CO_2-rich bypass exchanger design
COE	Cost Of Electricity, $/MWh
CCS	Carbon capture and sequestration
SP-S	Single Parameter Scaling methodology for TPC estimates
TPC	Total Plant Cost, $
TOC	Total Overnight Cost, $
OC_{FIX}	Fixed Operating Costs
OC_{VAR}	Variable Operating Costs
MT	Metric tonne
TPD	Metric tonnes per day
TSM	CO_2 Transportation, Storage and Monitoring
DOE	U.S. Department of Energy
NETL	National Energy Technology Laboratory
FRP	Fiberglass Reinforced Plastic
GC	Gas Chromatography
LP	Low Pressure
PC	Pulverized Coal
HHV	Higher Heating Value
LEDD	Linde Engineering Dresden
LENA	Linde Engineering North America
EPRI	Electric Power Research Institute
SCS	Southern Company Services
BP	Budget Period
DCS	Distributed Control System

EXECUTIVE SUMMARY

Post-combustion CO_2 capture (PCC) technology offers flexibility to treat the flue gas from both existing and new coal-fired power plants and can be applied to treat all or a portion of the flue gas. Solvent-based technologies are today the leading option for PCC from commercial coal-fired power plants as they have been applied in large-scale in other applications. Linde and BASF have been working together to develop and further improve a PCC process incorporating BASF's novel aqueous amine-based solvent technology. This technology offers significant benefits compared to other solvent-based processes as it aims to reduce the regeneration energy requirements using novel solvents that are very stable under the coal-fired power plant feed gas conditions. BASF has developed the desired solvent based on the evaluation of a large number of candidates. In addition, long-term small pilot-scale testing of the BASF solvent has been performed on a lignite-fired flue gas. In coordination with BASF, Linde has evaluated a number of options for capital cost reduction in large engineered systems for solvent-based PCC technology.

This report provides a summary of the work performed and results from a project supported by the US DOE (DE-FE0007453) for the pilot-scale demonstration of a Linde-BASF PCC technology using coal-fired power plant flue gas at a 1-1.5 MWe scale in Wilsonville, AL at the National Carbon Capture Center (NCCC). Following a project kick-off meeting in November 2011 and the conclusion of pilot plant design and engineering in February 2013, mechanical completion of the pilot plant was achieved in July 2014, and final commissioning activities were completed to enable start-up of operations in January 2015. Parametric tests were performed from January to December 2015 to determine optimal test conditions and evaluate process performance over a variety of operation parameters. A long-duration 1500-hour continuous test campaign was performed from May to August 2016 at a selected process condition to evaluate process performance and solvent stability over a longer period similar to how the process would operate as a continuously running large-scale PCC plant.

The pilot plant integrated a number of unique features of the Linde-BASF technology aimed at lowering overall energy consumption and capital costs. During the overall test period including startup, parametric testing and long-duration testing, the pilot plant was operated for a total of 6,764 hours out of which testing with flue gas was performed for 4,109 hours. The pilot plant testing demonstrated all of the performance targets including CO_2 capture rate exceeding 90%, CO_2 purity exceeding 99.9 mol% (dry), flue gas processing capacity up to 15,500 lbs/hr (equivalent to 1.5 MWe capacity slipstream), regeneration energy as low as 2.7 GJ/tonne CO_2, and regenerator operating pressure up to 3.4 bara. Excellent solvent stability performance data was measured and verified by Linde and BASF during both test campaigns. In addition to process data, significant operational learnings were gained from pilot tests that will contribute greatly to the commercial success of PCC.

Based on a thorough techno-economic assessment (TEA) of the Linde-BASF PCC process integrated with a 550 MWe supercritical coal-fired power plant, the net efficiency of the integrated power plant with CO_2 capture is increased from 28.4% with the DOE/NETL Case 12 reference to 30.9% with the Linde-BASF PCC plant previously presented utilizing the BASF OASE® blue solvent [Ref. 4], and is further increased to 31.4% using a Linde-BASF PCC plant with BASF OASE® blue solvent and an advanced stripper interstage heater (SIH) configuration. The Linde-BASF PCC plant incorporating the BASF OASE® blue solvent also results in significantly lower overall capital costs, thereby reducing the cost of electricity (COE) and cost of CO_2 captured from $147.25/MWh and $56.49/MT CO_2, respectively, for the reference DOE/NETL Case 12 plant, to $128.49/MWh and $41.85/MT CO_2 for process case LB1, respectively, and $126.65/MWh and $40.66/MT CO_2 for process case SIH, respectively. With additional innovative Linde-BASF PCC process configuration improvements, the COE and cost of CO_2 captured can

be further reduced to \$125.51/MWh and \$39.90/MT CO_2 for a further optimized PCC process defined as LB1-CREB. Most notably, the Linde-BASF process options assessed have already demonstrated the potential to lower the cost of CO_2 captured below the DOE target of \$40/MT CO_2 at the 550 MWe scale for second generation PCC technologies.

Project organization, structure, goals, tasks, accomplishments, process criteria and milestones will be presented in this report along with highlights and key results from parametric and long-duration testing of the Linde-BASF PCC pilot. The parametric and long-duration testing campaigns were aimed at validating the performance of the PCC technology against targets determined from a preliminary techno-economic assessment. The stability of the solvent with extended operation in a realistic power plant setting was measured with performance verified. Additionally, general solvent classification information, process operating conditions, normalized solvent performance data, solvent stability test results, flue gas conditions data, CO_2 purity data in the gaseous product stream, steam requirements and process flow diagrams, and updated process economic data for a scaled-up 550 MWe supercritical power plant with CO_2 capture are presented and discussed in this report.

1. PROJECT ORGANIZATION AND STRUCTURE

Linde LLC assembled a capable project team comprised of Linde Engineering North America (LENA), BASF, Linde Engineering Dresden (LEDD), and Electric Power Research Institute (EPRI) to complete the project. The host site was the NCCC in Wilsonville, Alabama, managed by Southern Company Services (SCS). Several site visits and discussions were held with SCS to confirm the specific site location for the slipstream pilot plant to be built as part of this project. Linde LLC was the prime contractor, responsible for overseeing all work and was accountable to the DOE Program Manager. LENA provided the Project Manager for the detailed engineering, equipment supply, and construction and commissioning of the slipstream pilot plant; and therefore, was responsible for the turnkey delivery of the pilot plant. In addition to program management, Linde LLC led Task 2 (Techno-Economic Evaluation on a 550 MWe power plant), Task 9 (Parametric Testing), Task 10 (Long-Duration Continuous Operation), and Task 11 (Final Economic Analysis and Commercialization Plan). LENA was responsible for detailed engineering, equipment procurement, installation and commissioning activities related to the pilot plant, and thus led Task 4 (Pilot Plant Design and Engineering), Task 5 (Pilot plant cost and safety analysis), Task 6 (Supply of Plant Equipment and Materials), and Task 7 (Plant Construction and Commissioning). LEDD and BASF have worked closely in Germany on the implementation of a small pilot plant to test and validate BASF's novel amine-based solvent and process technology. Therefore, LEDD and BASF led Task 3 (Pilot Plant Design Optimization and Basic Design) and Task 8 (Start-up and Initial Operation). BASF also provided all solvent-related expertise and LEDD provided any process-related expertise based on their related experience. Linde LLC, LEDD, and LENA are all members of the Linde Group, with Linde LLC focusing on the U.S. industrial gas business and LENA focusing on the engineering, procurement, and construction business related to a variety of process plants. Linde and BASF have worked together on a number of projects, including a collaboration starting in 2007 on PCC technology utilizing BASF's novel aqueous amine-based solvent process.

EPRI was a key participant in the project and performed an independent validation of the process performance results, including sampling and analysis. EPRI also supported the team on the techno-economic assessment tasks, thereby bringing in key insights from their significant experience in carbon capture and storage. As shown in Figure 1, the project team had an advisory board comprised of representatives from power and utility companies to get input from the final CO_2 capture plant user perspective. Santee Cooper, a South Carolina State Public utility, and Southern Company, a super-regional power company in the southeast region of U.S., agreed to support the developments in this project from a power plant owner perspective. EPRI also participated in the advisory board and provided support from a power and utility industry perspective.

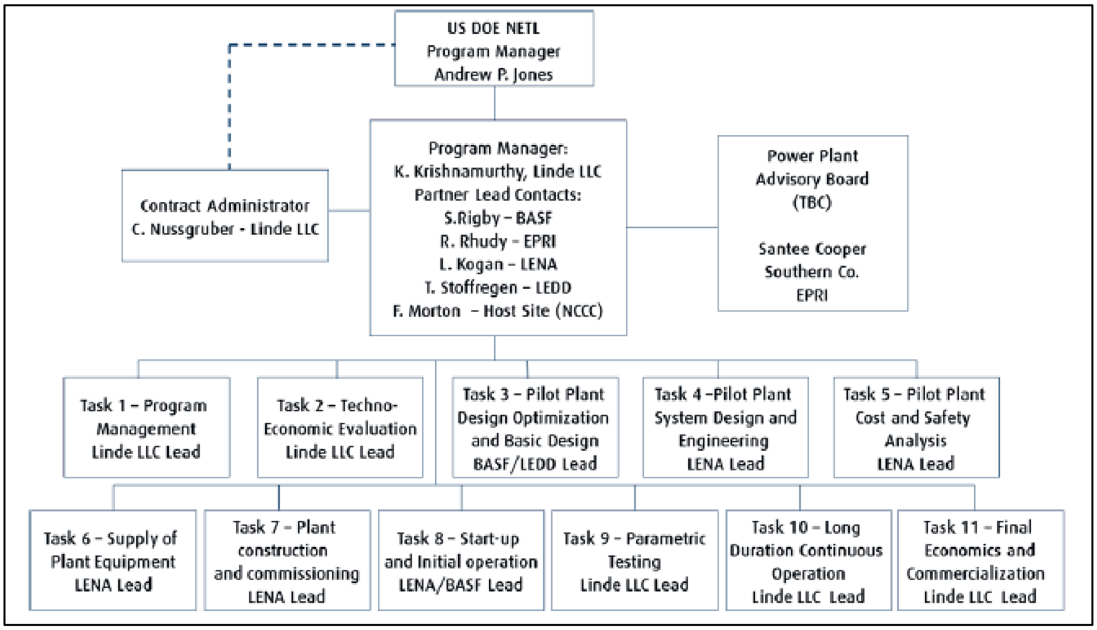

Figure 1: Project Team Organization Structure

The Linde LLC Program Manager set up a series of meetings (in-person, video conference, or teleconference, as appropriate) for communicating project status, progress and key issues. In addition, the team meetings focused on clarifying near-term goals and responsibilities to keep the project on track both in terms of cost and schedule. Detailed milestone reviews and risk assessments were incorporated into the meetings. The DOE Program Manager was informed about the team meetings and invited to participate whenever possible. The initial project kick-off meeting with the DOE Program Manager in November 2011 was used as a platform to bring the project team members on board with regard to the details of the entire project and implementation plan, including planned meetings and other forms of communication. Several contractual aspects were negotiated and agreed upon among the parties. These agreements clearly addressed how intellectual property (IP) rights would be managed and addressed aspects related to both pre-existing and new IP. During the course of the project, any new findings were promptly documented with patent applications to protect IP, as necessary.

2. GOALS AND OBJECTIVES

The overall goal of this project was to demonstrate the Linde-BASF PCC technology by incorporating BASF's novel aqueous amine-based solvent technology in a 1-1.5 MWe slipstream pilot plant and achieving at least 90% CO_2 removal from coal-derived flue gas while demonstrating significant progress toward achievement of the DOE target of less than a 35% increase in the levelized cost of electricity (LCOE). To accomplish this, the project team, which included Linde LLC, BASF, LENA, LEDD, EPRI, and SCS through the NCCC, designed, built and operated the pilot plant at a coal-fired power plant host site that provided the flue gas as a slipstream.

The specific objectives of the project were to:

1. Complete a TEA of a 550 MWe power plant incorporating the Linde-BASF post-combustion CO_2 capture technology to illustrate its benefits relative to the DOE/NETL reference.
2. Design, build, and operate the 1-1.5 MWe pilot plant at a coal-fired power plant host site providing the flue gas as a slipstream.
3. Implement parametric tests to demonstrate the achievement of target performance using data analysis.
4. Implement long-duration continuous tests to demonstrate solvent stability and obtain critical data for scale-up and commercial application.
5. Complete the process Environment, Health and Safety (EH&S) assessment, updated TEA based on the results of the pilot plant testing, and develop a commercialization plan.

The project had three budget periods spanning five years. The objectives for Budget Period 1 (12/1/2011 – 2/28/2013) were to complete the initial TEA, fulfill pilot plant basic and detailed system engineering tasks, and perform a pilot cost and safety risk assessment (EH&S). The objectives for Budget Period 2 (3/1/2013 – 8/31/2014) were to construct and install a 1-1.5 MWe slipstream pilot plant facility incorporating the Linde-BASF PCC technology in preparation for testing of the Linde-BASF PCC technology on actual coal-fired flue gas at the NCCC. The objectives for Budget Period 3 (9/1/2014 – 11/30/2016) were to start up the pilot, complete parametric and long-duration testing, measure and analyze critical plant data, and update the TEA and EH&S assessments based on learnings gained through pilot testing.

3. PROJECT TASKS AND ACCOMPLISHMENTS

This section highlights the accomplishments of the project team in completing each project task referred to in the Statement of Project Objectives (SOPO) of the Project Management Plan (PMP).

Task 1.0 – Project management and planning (All Budget Periods)

This task included management of technical, budgetary and scheduling activities. In completing this task, Linde LLC provided required periodic reports to the DOE/NETL and managed informal correspondence and collaboration. Linde LLC also made technical briefings to DOE/NETL, and presented project results jointly with other project partners at several conferences sponsored by industry and the DOE. The partners provided input to Linde via technical and financial progress reports as well as their respective final report sections. Linde monitored the progress of the project against its original plan, reviewed and updated the project management plan on a frequent basis, and reported on budget and schedule variances to the DOE. Any issues arising from the review were documented and discussed with DOE/NETL and appropriate remedial actions were jointly addressed.

Specific accomplishments from Task 1.0 included:

1. The project kick-off meeting was held at DOE-NETL facilities in Pittsburgh, PA on November 15, 2011 and the formal project start date was agreed to be December 1, 2011. The Linde LLC prime contract with DOE was signed in early February 2012.
2. The PMP was submitted and accepted by DOE-NETL in March 2012. Updates were made at appropriate times during the project. For instance, eight award modifications were processed and several involved schedule and/or budgetary adjustments.
3. All sub-contract drafts were prepared and negotiations initiated with partners. Each of the required sub-contracts was signed and concluded within the framework and terms agreed upon. The statement of work was agreed upon by all partners.

4. The terms of the Technology Collaboration and Host Site Agreement between Linde LLC and SCS were agreed upon and the contract document was finalized with signatures from each party on January 10, 2013. The Host Site Agreement was executed between Linde LLC and SCS representing NCCC. Any conflicting provisions between the Linde cooperative agreement on this project and the SCS cooperative agreement on the NCCC facility were resolved by review and input from DOE-NETL.
5. A continuation request to proceed to Budget Period 2 (BP2) was prepared and a meeting was held with the DOE-NETL on January 14, 2013 for progress reporting and requesting continuation of the project into BP2.
6. A continuation request to proceed to BP3 was prepared and a meeting was held with the DOE-NETL on June 9, 2014 for progress reporting and requesting continuation of the project into BP3.
7. The PCC pilot project was presented at a peer review meeting held in March 2013. Recommended actions from the peer review panel to the project team were as follows:
   - Define and establish quantitative project milestones
   - Project the potential improvements that could achieve the DOE's 35% COE increase goal for PCC
   - Rigorously evaluate the solvent via scale-up
   - Strive to identify and address the potential risks associated with new packing materials
8. Several project progress presentations and publications were made through out the project. A comprehensive list of presentations and publications is provided in the Appendix at the end of this report. In reference to each presentation and/or publication number listed in the Appendix section, the following presentations/publications were made in the completion of Task 1.0: 1, 4, 5, 7, 8, 9, 11, 13, 14, 19, 20, 23, 25, 26, and 27.

Budget Period 1 (12/1/2011 – 2/28/2013)

Task 2.0 - Techno-economic evaluation on a 550 MWe power plant

This task focused on the modelling of a 550 MWe power plant integrated with PCC for the purposes of demonstrating the benefits of the Linde-BASF PCC technology relative to a reference case defined by DOE-NETL.

Specific accomplishments from the completion of Task 2.0 included:

1. The TEA of a 550 MWe sub-critical pulverized coal (PC) fired power plant utilizing Illinois No. 6 bituminous coal as fuel, integrated with a Linde-BASF PCC plant incorporating BASF's OASE® blue aqueous amine-based solvent, was completed during the first quarter of 2012. The TEA evaluated two scenarios demonstrating their benefits over conventional monoethanolamine (MEA) solvent-based PCC processes. The first design option, LB-1, is the Linde-BASF PCC system with an optimized configuration and operating parameters. This design option with the BASF solvent together increased the efficiency of the baseline DOE plant by 3.15% and resulted in a projected levelized cost of electricity (LCOE) increase of 62.2% over the DOE baseline. The second design option, LB-2, included the optional integration of waste heat recovery and power cogeneration from the regeneration steam prior to use at low pressure for internal PCC heat and power requirements on the LB-1 design. This design option increases the efficiency of the plant by 1.35% over LB-1 and 4.5% over the baseline DOE plant, and it resulted in a projected LCOE increase of 58.8% over the DOE baseline. The calculated results from this accomplishment included PC plant efficiency with and without CO_2 capture and itemization of the parasitic losses, itemized capital cost estimates of the integrated plant, heat and material balances, and the LCOE with and without carbon capture. A

sensitivity analysis was also included to show the impact of key operating and cost parameters on the LCOE.

2. A presentation on the TEA was made to DOE-NETL, including responses to questions received as part of the topical report review, on May 4, 2012. The updated topical report was completed and issued and has now been posted on the project website.
3. In reference to each presentation and/or publication number listed in the Appendix section, the following presentations/publications were made in the completion of Task 2.0: 2, 3, and 12.

Task 3.0 – Pilot plant design optimization and basic design

This task involved the development of a basic design package for the Linde-BASF PCC pilot plant tested at NCCC.

Specific accomplishments from the completion of Task 3.0 included:

1. The basic design and engineering of the 1-1.5 MWe pilot plant was completed by LEDD with associated drawings and documents issued to enable detailed engineering to proceed. The basic design and engineering package included the following:
2. Design basis
3. Process design, including process flow diagrams, process description, material balance, utility consumption, emissions, and effluents
4. Equipment design, including equipment list, process data sheets, equipment data sheets, and mechanical data sheets
    - Absorber column dimensions: 152 ft. length, 40 inch diameter. Absorber column shell and internals material: stainless steel
    - Stripper column dimensions: 80 ft. length, 28 inch diameter. Stripper column shell and internals material: stainless steel
    - Utility requirements: cooling water supply from battery limit at 90˚F and 73 psia, steam supply from battery limit at 348˚F and 115 psia, demineralized water from battery limit at 60˚F and 59.5 psia.
    - Flue gas supply conditions: 12.95 mol% CO_2 (dry), 104˚F, and 14.4 psia.
5. Piping and instrumentation diagram along with piping details
6. Instrumentation and measurement details with alarms, interlocks, and shut-down details
7. Electrical load list and preliminary diagrams
8. Operations and analysis instructions for the final operations manual
9. Plant safety information, including safety relief valve information. The absorber was sized as a 1 m diameter column and based on the available flue gas and utilities from the NCCC, it was expected that the pilot plant could be operated up to 30 tons/day CO_2 capacity (equivalent to 1.5 MWe capacity slipstream) with a potential upside for reaching even higher peak capacity.

Task 4.0 – Pilot plant system design and engineering

This task focused on the pilot plant system design and detailed engineering.

Specific key accomplishments from the completion of Task 4.0 included:

1. The detailed engineering of the pilot plant was completed as of December 2012 and accomplished to the level required for reasonable cost estimates. The pilot plant was designed for installation on a 57 ft. x 51 ft. concrete slab containing the free-standing absorber and stripper columns and six modules containing the other vessels, heat exchangers, circulating pumps and other equipment. The tallest piece of equipment in the pilot plant was the absorber with a height of 165 feet from the grade. The

30%, 60% and 90% 3-D model reviews of the pilot plant, integrated with the overall site layout, were completed. The 30% model review was critical to identifying any further design changes required and enabled finalization of the design basis and specification. The 60% model review enabled the equipment design and layout to be finalized so that equipment and module packages could be completed. The 90% model review was aimed at a final detailed engineering review, including confirmation that all actions from earlier reviews were either completed, or appropriately assigned for completion.

2. Equipment, module, and construction packages were completed and firm price quotations were received from multiple vendors for each category. The firm cost estimates for the various packages allowed the compilation of costs for the total pilot plant build in Budget Period 2.
3. A topical report on the detailed engineering of the pilot plant was completed and issued in February 2013.

Task 5.0 – Pilot plant cost and safety analysis

This task involved an initial pilot plant cost and safety risk assessment.

Specific key accomplishments from the completion of Task 5.0 included:

1. Linde process safety review (PSR) requirements, which were performed in project stages, were applied to complete PSR1 (project initiation and definition), PSR2 (project award/start) and PSR3 (design). Several design reviews, including design for safe and reliable operations, were completed. Significant results from the PSRs included:
    - Identification of satisfactory safety and utility supplies needed for safe operation of the pilot plant such as emergency spill kits, eye wash stations, and emergency showers. Actions were taken to ensure all required protective devices and equipment were placed on site as per both Linde and Southern Company safety standards.
    - Identification of anticipated likely effluents including atmospheric condensation, cooling tower blowdown/fume, drainage from firewater runoff, gas vents, liquid releases, and solid wastes
    - Clarification that lightning, wind and other important climatic considerations were adequately addressed in pilot plant design
2. A formal hazard and operability (HAZOP) study was completed with actions from the meeting assigned to various partners; the majority of the actions were completed with pending actions compiled for completion during construction and operations phases. Significant results from the HAZOP study included:
    - Identification of all hazards and corresponding hazard mitigation procedures related to either 1) an increase, 2) a decrease, or 3) a reversal in process flowrate, temperature, or pressure at any point in the process
    - Identification of all hazards related to process leakages and loss of containment
    - Documentation of proper safety equipment actions such as pressure relief valves and safety control loops/trips along with cause of action
3. The National Environmental Policy Act (NEPA) form for the NCCC host site was updated in conjunction with BASF and SCS/NCCC with the completed form submitted to DOE-NETL. This form was accepted by DOE-NETL for the entire project, thereby approving performance of work defined for Budget Periods 2 and 3.
4. A preliminary EH&S risk assessment topical report was submitted to DOE-NETL in December 2012 and now been posted on the project website.
5. Vendor packages were developed for the pilot and firm cost estimates were obtained.

6. As shown in the Appendix, presentation/publication number 6 was associated with the completion of Task 5.0.

Budget Period 2 (3/1/2013 – 8/31/2014)

Task 6.0 - Supply of plant equipment and materials

This task focused on arranging the supply of plant equipment and materials to the pilot plant erection site.

Specific key accomplishments from the completion of Task 6.0 included:

1. Overall procurement purchase orders and fabrication contracts were completed in June 2013, as per the defined project milestones.
2. The civil and foundation work for the pilot plant was completed by SCS/NCCC in 2013. NCCC upgraded the direct contact cooler (DCC) at their site to accommodate the Linde flue gas capacity required during pilot plant operations, as per original agreement.
3. The fabrication of the modules was completed during December, 2013. The modules were inspected by Linde engineers at the fabrication shop for quality assurance and necessary modifications were made. The modules were then shipped to the NCCC site in January 2014.
4. Shop fabrication of other major equipment, such as the analyzer building and solution storage tank, was completed. This equipment was delivered to the NCCC host site in January 2014.
5. The fabrication of the columns (absorber and stripper) and column internals (structured packing, distributors, support plates, etc.) was completed in March 2014, and the columns were delivered to the site. The stripper, including the internals, was shipped from the fabricator shop and hoisted and anchored in place on the pad. The absorber was shipped in three sections and the internals and distributors for the bottom two sections were installed at the NCCC host site. The absorber column sections were sequentially hoisted using a crane and bolted in place.

Task 7.0 – Plant construction and commissioning

This task involved activities related to the construction and commissioning of the PCC pilot plant at NCCC.

Specific key accomplishments from the completion of Task 7.0 included:

1. The final PSR4 was completed on January 8, 2014 and issued on February 19, 2014. Significant results from PSR4 included:
   - Identification and elaboration of a safety management system including a safety orientation/training conducted by Southern Company for on-site workers as well as a site-specific health, safety and environment safety training provided by Linde
   - Identification of hazards related to process tie-ins to supply lines and designation of responsible personnel needed for control of critical utilities such as electrical supplies
2. The on-site installation of all pilot plant modules, columns and major equipment (analytical container, solution storage tank, etc.) was completed at the NCCC in March 2014.
3. Work related to the installation of inter-connecting piping and electrical, instrumentation and control components for the columns, modules, NCCC utility supply interface points, and the analyzer building was completed to achieve mechanical completion of the 1-1.5 MWe pilot plant in July 2014. A comprehensive and prioritized action items punch-list was developed as a result of the pre-start up safety review meeting and an assessment of the completed pilot plant against the P&IDs. The punch-list items were addressed before the start-up of pilot operations.

4. Pre-commissioning activities began on June 23, 2014 and continued through December 2014. The system was thoroughly cleaned and flushed with demineralized water and potash in early July 2014 to prime it for loading of the amine solvent. Complete rinsing of the system with demineralized water was performed to remove any residual potash and achieve a desired pH level.
5. All hydro- and pneumatic-pressure testing was completed during the week of June 16, 2014.
6. The fire and gas detection alarms were installed before the startup of pilot operations.
7. All of the motors (pumps and blower) were bump-tested and the motor logic drive was programmed and tested on the Distributed Control System (DCS).
8. Off-module instruments were installed, and continuity and loop checks were performed on all instruments and control wiring.
9. An initial site Factory Acceptance Test (FAT) on the DCS in the analyzer container was performed from March 17-20, 2014. The final programming of the DCS was commenced and security licenses were issued.
10. A draft version of the data acquisition software program to collect information and transmit it remotely for reporting and analysis was prepared and incorporated with the DCS.
11. The remote monitoring system for viewing the DCS computer screens was tested and found to be functional.
12. Heat tracing and insulation of off-module piping were 98% and 95% completed before the start-up of pilot operations, respectively.
13. Mechanical completion of the 1-1.5 MWe pilot plant was achieved in July 2014.
14. A pre-start-up safety review (PSSR) was completed on July 17, 2014 to identify any safety and process critical items that required attention prior to commissioning.
15. A comprehensive review of the as-built mechanical system installation was performed against the updated, marked-up version of the P&IDs to identify deviations that needed to be addressed.
16. A commissioning and start-up schedule was prepared and commissioning activities were initiated while the punch-list items were addressed.
17. Machine start-up and water recirculation tests were performed in August 2014 to establish functionality and operability of system components.
18. In reference to each presentation and/or publication number listed in the Appendix section, the following presentations/publications were made in the completion of Task 7.0: 10, 15, and 16.

Budget Period 3

Task 8.0 - Start-up and initial operations

This task focused on activities for start-up and initial operations of the Linde-BASF PCC pilot. To complete this task, Linde LLC, supported by LENA, LEDD and BASF, started up the 1-1.5 MWe pilot plant in January 2015 and brought it into operation after solvent delivery (~about 2,600 gallons for first delivery to pilot) by gradually ramping up the solvent recirculation, flue gas, and reboiler steam flowrates. Critical plant data such as flue gas flowrate, pressure drop across absorber column, cooling water and steam supply conditions, and absorber and stripper sump levels were recorded by the DCS and pilot plant instrumentation. Automated functionality and appropriate action of plant safety interlock systems were established by tuning the control loops and performing suitable system loop checks. Checks were also performed to confirm data transfer between the pilot plant control system and the NCCC operations control room. Following this, a series of instrument calibrations involving all measurement and analytical devices was performed and verified. In addition, calculated performance metrics of interest such as specific regeneration energy (MJ/kg CO_2) and CO_2 capture rate were integrated into the control system for monitoring pilot plant performance. The pilot plant was initially operated at a steady condition for a 1-2 day period of time to confirm stability of its operation. Ramping tests were performed by adjusting the inlet flue gas flow to different capacities at an appropriate and safe rate. The overall flexibility and stability of the process was determined, and changes were made to the control loops to stabilize the pilot plant under a variety of test conditions.

Specific key accomplishments from the completion of Task 8.0 included:

1. LENA addressed and completed the punch-list tasks and also conducted required modifications on the pilot plant during a planned power shutdown at the NCCC host site.
2. Additional water recirculation tests were performed in November and December 2014 to establish functionality and operability of system components.
3. An additional potash flush was completed in November 2014 for passivation of the system.
4. The solvent was delivered to the site on December 10, 2014 and loaded into the pure solution storage tank next to the Linde pilot.
5. The lean solution pump was upgraded to provide sufficient head for the entire stripper operating pressure range.
6. Safety integrated loops (SIL) were installed for the absorber and stripper level control to prevent absorber over-pressurization. The proper documentation required for the SIL rating was also compiled.
7. Several control valve trims were changed to allow for proper controller operation over the entire operating range.
8. Two of the magnetic flow meters in the wash water control loops of the absorber were changed to Coriolis-type flow meters because the actual conductivity of the water in these loops was below the threshold requirement for proper functioning of the magnetic flow meters.
9. Insulation and heat tracing missing from a few critical sections was installed. Heat tracing control loop configurations were finalized.
10. Instrument measurement re-ranging and calibration checks were performed as appropriate to allow for accurate data analysis. Updated instrument data sheets were prepared. The DCS was updated with the new calibrations and instrument ranges.
11. The solvent was loaded into the system on January 10, 2015.
12. Continuous operation of the pilot was established for 24 hours a day and 7 days per week with resources organized around two 10-hour shifts each day.
13. The following benchmarks were achieved:
    - 1,600 hours of solvent circulation
    - 1,402 hours of steam use for either solvent circulation or CO_2 regeneration
    - 783 hours of operation processing coal-derived flue gas
14. 90% CO_2 capture rate was achieved. The CO_2 capture rate was adjusted by changing the steam flow rate to the reboiler of the stripper column. Overall, flue gas with an equivalent of 570 metric tonnes of CO_2 was processed and 501 metric tonnes of CO_2 were captured.
15. On-site laboratory and titration equipment were installed and procedures for solvent analysis were developed based on input from BASF. Preliminary analytical measurements of the solvent were performed in the laboratory and the accuracy of the solvent amine, water and CO_2 concentration measurements was verified.
16. Daily batch analysis for water, amine and CO_2 concentrations in the CO_2-rich and CO_2-lean solvent as well as wash water circulating loops was performed using titrations. These measurements provided the information required to correctly adjust the water balance of the pilot plant during operation to achieve the target solvent water content. For analysis confirmation, a significant number of samples were also analyzed by NCCC using gas chromatography (GC). The solvent analysis measurements performed by Linde and NCCC showed excellent consistency during testing, affirming their accuracy and precision.

17. A CO_2 product purity of 99.9% on a dry basis was consistently achieved and verified by an overall material balance assessment and an installed O_2 sensor on the CO_2 product line stream. Excellent overall mass and energy balance closures were achieved.
18. The maximum plant capacity of 1.5 MWe (~15,500 lbs/hr flue gas) was demonstrated.
19. The regenerator steam consumption of < 2.8 GJ/tonne CO_2 was achieved.
20. Regenerator operating pressure was set at 2 bara for initial operations. Operation at regenerator pressures up to 3.4 bara was performed at the end of parametric testing in November and December of 2015.
21. The initial operation and testing phase validated the functionality of the following:
    - High-capacity structured packing in the absorber sections
    - Gravity-flow absorber interstage cooler
    - Operation of the blower downstream of the absorber with the absorber operating at slightly below atmospheric pressure
    - Unique reboiler design offering a potential for cost savings at large scale
22. Required on-site operator and safety training were completed before the start of operations. All of the required safety processes (both NCCC & Linde requirements) were established and followed throughout the testing periods, including routine safety checklists according to company standards (energy control procedure, hazardous work permit, job safety analysis).
23. In reference to each presentation and/or publication number listed in the Appendix section, the following presentations/publications were made in the completion of Task 8.0: 17 and 18.

Task 9.0 - Parametric testing

This task focused on the parametric testing of the PCC pilot plant. In completing this task, the project team worked together to formulate a parametric test plan to evaluate pilot plant operation over a wide range of conditions and determine how the actual performance compared against performance targets defined during earlier bench- and small pilot-scale tests, such as specific regeneration energy (MJ/kg CO_2). In addition to flue gas flow rate, other critical parameters included solvent circulation rate, regeneration pressure, and absorber intercooler temperature. Output variables for the critical parameter settings above and the OASE® blue solvent included CO_2 capture rate, CO_2 loading in the CO_2-rich (absorber bottom) and CO_2-lean liquid (regenerator bottom), pressure drop across the system, steam flowrate requirements, and CO_2 pressure at the stripper outlet. All of these parameters were evaluated and confirmed through tests performed.

Specific key accomplishments from the completion of Task 9.0 included:

1. A parametric testing plan for the Linde-BASF PCC pilot was developed in January 2015 before the start of parametric testing to ensure that all critical process variables and parameters could be evaluated within the project schedule.
2. The first parametric tests were completed at the end of March 2015 at a flue gas flow rate of 10,500 lbs/hr with the solvent circulation rate varying between 80% and 120% of the targeted design flow rate. For these first tests, the capture rate was held at the 90% target and all other key variables, such as flue gas inlet temperature to the absorber, regenerator pressure, and absorber intercooler temperature were held constant.
3. The Linde pilot plant was restarted for a second campaign at NCCC at the beginning of May 2015. Overall, through June 8, 2015:
    - 2,200 hours of solvent circulation was achieved.
    - 2,000 hours of steam flow was achieved for either solvent circulation or CO_2 regeneration.
    - 1,300 hours of operation processing coal-derived flue gas was achieved.

4. Parametric tests were performed with the flue gas temperature (varied from 86°F to 104°F) and CO_2-lean solution cooler outlet temperature to the absorber as parameters in early June 2015.
5. Approximately 100 hours of successful testing was achieved at the higher flue gas flow rate of 15,500 lbs/hr (equivalent to 1.5 MWe capacity slipstream) at the end of May and early June 2015.
6. The tests incorporated a fully functional dry-bed configuration for amine emissions reduction in the treated gas.
7. The wash water flowrates in the wash sections were adjusted to minimize pressure drops in the absorber column.
8. The valve in the two-phase flow line transferring the CO_2-rich liquid from the rich-lean heat exchanger to the regenerator was adjusted to prevent perturbations in the CO_2 product flow rate.
9. A detailed process flowsheet model of the Linde pilot plant was developed using Unisim Design chemical process modeling software.
10. Two main testing periods during the parametric test campaign were achieved (May 1, 2015 through August 15, 2015 and October 1, 2015 through December 22, 2015) over a wide range of test conditions.
11. The parametric test campaign was completed on December 22, 2015 with the following accomplishments:
    - 5,096 hours of solvent circulation
    - 3,841 hours of steam flow for either solvent circulation or CO_2 regeneration
    - 2,589 hours of operation processing coal-derived flue gas
12. The average CO_2 capture rate since the start of operations, including time taken during ramping the pilot plant and that between tests, was 89%.
13. Parametric tests were performed in November 2015 with the regenerator operating at 3.4 bara and at varying solvent circulation rates.
14. Isokinetic measurements were performed on the treated gas leaving the absorber to quantify amine emissions to benchmark results against those from earlier measurements taken in August 2015.
15. Aerosol characterization measurements were performed on the flue gas line upstream of the absorber to assess the impact of operating conditions in the absorber on the aerosol particle count.
16. The isokinetic measurements were performed under different test conditions, such as varying CO_2-lean solution temperature, absorber outlet gas temperature, absorber interstage cooler temperature, and wash water temperature. The impact of dry-bed operation and wet wash water circulation on amine emissions was also evaluated.
17. A steam injection system was installed in the flue gas line to test the influence of injecting steam into the flue gas on aerosol formation and aerosol-driven solvent emissions from the absorber through the treated flue gas process stream.
18. A detailed analysis of the measurements taken during the three isokinetic test campaigns in 2015 was performed during Q1 2016 during the shutdown of PC4. The results of the analysis clearly demonstrated that target performance such as low specific regeneration energy (GJ/tonne CO_2) and target CO_2 recovery rate (%) for the process had been achieved. This analysis also identified the conditions that are favorable to emissions reduction.
19. Data from the parametric testing campaigns was analyzed to determine conditions favorable to minimizing the reboiler steam consumption. A process modification for enhancing internal heat recovery involving a stripper-interstage-heater (SIH) configuration was identified jointly with BASF based on observations of the lean-rich heat exchanger temperature profile. Process simulations showed that the SIH configuration can reduce the specific energy consumption to 2.3 GJ/tonne CO_2 based on specific site conditions. A detailed assessment of the techno-economics of the SIH option was performed as part of the final updated TEA (Task 11.0).

20. The team began work to develop a plan to demonstrate solvent stability using a long-duration continuous test.
21. A scope of work for pilot plant decommissioning was developed to describe the demolition work and incidental services required for the disassembly and removal of the 1-1.5 MWe Linde-BASF PCC pilot plant after the conclusion of long-duration continuous testing.
22. In reference to each presentation and/or publication number listed in the Appendix section, the following presentations/publications were made in the completion of Task 9.0: 21 and 22.

Task 10.0 – Long-duration continuous operation

This task involved long-duration continuous operation of the pilot plant. The setup for long-duration testing of the 1-1.5 MWe pilot plant was similar to the parametric test campaign, but the main difference was that the pilot was operated for a continuous period at one process condition without interruption. To complete this task, a long-duration test campaign of 1,500 hours was performed. Fresh solvent was used for long-duration test and was delivered to the site on May 4, 2016 in totes with a total delivery volume of ~2,850 gallons. The input test conditions for long-duration testing were based on the performance mapping conducted at the end of the parametric test campaign, where an optimum operating condition was identified. The focus of the data analysis for long-term testing was on solvent stability and performance.

Specific key accomplishments from the completion of Task 10.0 included:

1. Long-duration testing was planned with NCCC and began on May 20, 2016.
2. Long-duration testing lasted from May 20, 2016 through July 29, 2016.
    - 1,520 hours of steady operation of the pilot plant was achieved at the end of July 2016 with the capture of 1,217 tons of CO_2 from 1351 tons of CO_2 in the flue gas at an average capture rate of 90.1%.
3. Regenerator pressure was kept at 3.4 bara and the flue gas flowrate was maintained at 10,500 lb/hr (1 MWe capacity slipstream) throughout the entire long-duration test campaign, ensuring stable process conditions
4. Process sample setup, collection and analysis were performed by EPRI and their contractor Chicago Bridge & Iron Company (CB&I) for their independent validation of pilot plant performance during the week of June 13, 2016.
    - Continuous sampling of the flue gas, treated gas and CO_2 product gas was performed for 3 days for composition analysis.
    - Several batch samples of the NCCC's DCC condensate were collected and both onsite and offsite analysis were performed for a number of trace contaminants.
5. Several solvent samples were collected and measured over the course of the long-duration test period to determine the concentration of any solvent degradation components. The results of the solvent analysis by both Linde and BASF revealed that very little solvent degradation occurred over the course of the parametric and long-duration test periods. This low solvent degradation rate leads to a decreased solvent make-up rate during operation and a lower overall operating and maintenance cost for the Linde-BASF PCC technology at scale.
6. The useful life (in years) and makeup rate of the OASE® blue solvent during operation was estimated based on the results of parametric and long-duration testing using degradation and other solvent loss data, including data for solvent emissions with the treated gas leaving the absorber (in units of kg solvent per tonne CO_2 captured).
7. An assessment and estimation of the projected near-term and long-term costs of mass-produced solvents and other novel materials was performed by the suppliers (in appropriate normalized form).

8. Corrosion and emissions data for HAPs metals, NO_x, SO_2, and SO_3 were collected during long-duration testing to show that the overall system design and operation was not impacted by material issues and complies with regulatory emissions requirements.
    - Table A-1 in the Appendix shows the results of the analyzed corrosion coupon and spool piece samples from the Technical Expertise Materials Engineering Group at BASF. Analysis of corrosion coupons and spool pieces in the pilot revealed that no measurable degradation was found on the materials tested, indicating that the solvent did not react significantly with the materials and that their use in the PCC plant should be further considered if they can reduce overall PCC plant capital cost. Figure A-1 shows the locations of each corrosion coupon and spool piece as installed at the pilot plant in reference to Table A-1.
    - Figures 8 and 9 show the HAPs metals, NO_x, SO_2, and SO_3 emissions data collected by EPRI in their independent analysis of the Linde-BASF PCC technology. EPRI independent emissions analysis showed that the Linde-BASF PCC pilot plant produced no significant added HAPs metals, NO_x, SO_2, or SO_3 emissions. Performance data was collected on a daily basis to assess and demonstrate the consistency of results from the pilot plant.
9. The results of EPRI's independent performance measurements were analyzed and compared against Linde-derived performance data measurements. The performance results evaluated by EPRI for CO_2 capture %, CO_2 product purity (O_2 ppm levels), and specific reboiler regeneration energy consumption (MJ/kg CO_2) were very consistent with the results attained by Linde. EPRI's full testing report is included in the Appendix at the end of this report.
10. As shown in the list in the Appendix, presentation/publication number 24 was associated with the completion of Task 10.0.

Task 11.0 - Final economic analysis and commercialization plan

This task focused on the completion of an updated TEA for the Linde-BASF PCC technology integrated with a 550 MWe supercritical coal-fired power plant including commercialization plan. In completing this task, Linde LLC updated the TEA performed during Task 2 of Budget Period 1 by incorporating new data for the PCC plant obtained through pilot-scale parametric and long-duration testing as well as novel process innovations for future designs. This updated TEA also provided insights into a commercialization plan by highlighting key design and construction features required for cost-effective erection of a Linde-BASF PCC plant at commercial-scale. An update to the EH&S assessment was also performed based on data from the pilot plant and other information gained during the operation of the pilot plant, such as air quality surrounding the pilot plant, analysis of HAPs metals, NO_x, SO_2, and SO_3 emissions from the pilot plant, and the rate of buildup of degradation components in the solvent. Lastly, the pilot plant columns, modules, and equipment were decommissioned and removed from the NCCC host site while required asset management activities were completed.

Specific key accomplishments from the completion of Task 11.0 included:

1. A pilot plant decommissioning plan was discussed with Southern Company and their onsite contractor Caddell. Linde Engineering completed specifications for a lift plan to define the major equipment removal sequence, including the columns and the modules, and a contractor was selected to define the detailed lift plan. Specifications for the removal of major equipment, piping, and modules as metal scrap were also prepared with quotes received from two scrap removal contractors. A selection was made and further details were addressed with this contractor for coordination of the scrap removal with the sequence of the equipment removal from its location.
2. Decommissioning of the pilot plant began in August 2016, following completion of the long-duration test, and progressed according to plan and schedule.

3. Work was initiated to complete the updated TEA and EH&S reports. The updated TEA and EH&S reports were finalized on January 9, 2017. The TEA included critical plant cost data and a construction strategy for commercialization. An updated state-point data table for the OASE® blue solvent is shown in Table A-3 in the Appendix. Main highlights of the updated EH&S assessment included:
   - Analysis of process data and confirmation that little to no added emissions of HAPs metals, NO_x, SO_2, or SO_3 are produced from the Linde-BASF PCC process, and that no significant concentration of the OASE® blue solvent could be found in the air surrounding the plant.
   - Comprehensive identification of process hazards along with corresponding consequences and risk mitigation actions and safeguards
   - Extensive assessment and identification of solvent properties and corresponding risk prevention measures and guidelines
4. A final testing report was provided to NCCC on January 9, 2017 summarizing key results and learnings from the testing of the Linde-BASF PCC pilot.

As a summary to the section above, Table I lists each project task and its associated key objectives and compares these tasks against completed accomplishments by the project team.

Table I: Project tasks and key objectives compared against accomplishments

Task #	Task description	Key objectives	Accomplishments
1	Program Management and Planning	- Complete a project management plan (PMP) - Implement the plan to progress the project according to agreed cost and schedule	- PMP completed and updated multiple times to remain current - Project cost and schedule plan completed
2	Techno-economic evaluation (TEA)	- Complete a techno-economic analysis on a 550 MW_e coal-fired power plant incorporating the Linde-BASF PCC technology - Define the pilot plant performance targets	- TEA completed and submitted to DOE. Presentation about TEA provided to DOE on May 4, 2012. - Pilot plant performance targets defined
3	Pilot plant design optimization and basic design	- Define the pilot plant design basis and the key features incorporated - Complete the basic design and engineering	- Pilot plant design basis completed including key features - Basic design and engineering completed
4	Pilot plant system design and engineering	- Complete the detailed design and engineering of the pilot plant (ready for build)	- Detailed design and engineering completed for pilot plant as of May 24, 2013
5	Pilot plant cost and safety analysis	- Complete the preliminary environment, health and safety (EH&S) assessment for the pilot plant to be built	- Preliminary EH&S assessment completed - Vendor packages and accurate cost estimates for pilot plant

Task #	Task description	Key objectives	Accomplishments
		- Complete the vendor packages and accurate cost estimates for the pilot plant	completed
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	- Procurement purchase orders and fabrication contracts were completed in June 2013 - Equipment and module purchases completed and transported to site. Modules were shipped to NCCC site in January 2014. - Civils and utilities were prepared for pilot installation in 2013 by SCS/NCCC
7	Plant construction and commissioning	- Complete the installation of the pilot plant at site - Enable mechanical completion of the pilot plant	- Pilot plant was installed at site in March 2014 - Mechanical completion of the pilot plant was accomplished and verified in July 2014
8	Start-up and initial operation	- Complete the instrumentation, analysis and control calibrations on the pilot plant - Complete start-up, operating and shut-down instructions and enable initial pilot plant operations	- Instrumentation and control system installation/setup along with calibrations were completed - Instruction manuals for start-up, steady-state operation, and shutdown operations completed - BASF solvent was delivered to NCCC site on December 10, 2014 and loaded into plant on January 10, 2015 - Initial pilot plant operations started in January 2015
9	Parametric testing	- Develop a parametric testing plan - Implement parametric testing and data analysis to confirm that pilot plant meets or exceeds target performance	- Parametric testing plan completed - Data analysis started with confirmation that pilot meets target performance - Parametric testing campaign was completed on December 22, 2015

Task #	Task description	Key objectives	Accomplishments
10	Long-duration continuous operation	- Develop a long duration test plan and implement - Based on data analysis, demonstrate solvent stability and long term performance.	- Long-duration test plan completed and implemented with 1,520 hours of steady operation achieved at the end of July 2016 - Excellent solvent stability and long-term performance evaluated and verified
11	Final economics and commercialization	- Update the EH&S assessment and complete report - Update TEA (550 MWe plant as a basis) and develop commercialization plan	- Updated EH&S assessment conducted with new report completed and submitted to DOE (January 2017) - Updated TEA completed with report written and submitted to DOE (January 2017), which included commercialization plan

4. PILOT TEST DATA AND RESULTS

This section describes the activities involved in completion of Tasks 6, 7, 8, 9 and 10 as outlined in Table I of Section 3. During the overall test period including startup, parametric testing and long-duration testing at the NCCC, the pilot plant was operated for a total of 6,764 hours, of which, testing with coal-derived flue gas was performed for 4,109 hours. The pilot plant testing demonstrated all of the performance targets, including CO_2 capture rate exceeding 90%, CO_2 purity exceeding 99.9 mol% (dry), flue gas processing capacity up to 15,500 lbs/hr (equivalent to 1.5 MWe capacity slipstream), regeneration energy as low as 2.7 GJ/tonne CO_2, and regenerator operating pressure up to 3.4 bara. The emission control feature incorporated in BASF's patented dry-bed configuration was validated during long-duration testing. During parametric testing, significant research was performed in conjunction with NCCC and Southern Research to characterize aerosol particle number concentration and size distribution in the flue gas as well as the impact of aerosol particles on amine emissions from the process. Pilot plant operating parameters that minimize amine emissions during operation with flue gas containing high concentrations of aerosol particles were also identified through tests performed. Pilot testing validated the performance benefits of several unique equipment features incorporated in the pilot plant design, including high-capacity structured packing, gravity-driven absorber interstage cooler, blower positioned downstream of the absorber, and a unique reboiler configuration that minimizes solvent inventory and promotes a fast response to energy input requirements. The pilot plant incorporated significant instrumentation and control features that enabled automated and stable operation as well as the ability to reliably check and verify mass and energy balance closures with adequate redundancies.

4.1 General Solvent Classification

The advanced Linde-BASF PCC technology tested at NCCC is a result of BASF's comprehensive R&D efforts since 2004 to develop advanced **aqueous amine-based solvents** for efficient CO_2 recovery from low-pressure, dilute flue gas streams from power plants and industrial processes combined with a joint

Linde/BASF collaboration since 2007 to design and test advanced PCC technologies. This section provides highlights of the key characteristics of BASF's CO_2 capture solvent.

With climate change becoming an increasing concern globally, BASF’s gas treatment team has been actively leveraging its expertise to become a leading contender in the race to make carbon capture and storage (CCS) commercially viable. Over the years, BASF’s gas treatment portfolio has continuously expanded. Beyond extensive offerings in technology and gas-treating chemicals, the world’s largest chemical company can supply additional technical support services, such as customized onsite training of its customers’ personnel on the optimized operations of gas treatment processes and equipment. BASF recently began marketing its entire gas-treating portfolio under the trade name OASE®, where OASE® blue is the brand for flue gas CO_2 capture. The team considers CCS as the most effective measure in the mid-term to combat further increase of CO_2 emissions into the atmosphere. Based on the success of more than 250 gas treatment plants over several decades for ammonia, oxo-syngas, natural gas, and liquefied natural gas applications as well as experiences in iron ore gas and selective sulfur gas treatment, BASF decided to systematically develop a new chemical solvent technology targeting the specific requirements of large-scale carbon capture applications. Besides low pressure and large volume systems that need to consider emissions to meet environmental requirements, PCC from power plants presents the additional challenge of very low driving forces for CO_2 mass transfer. The oxygen-containing atmosphere is aggressive to amines, and high energy efficiency is critical to the commercial success of such CO_2 capture processes. Consequently, the most important parameters for the development of solvent-based PCC technologies are energy demand, cyclic capacity, solvent stability, reactivity, volatility, environmental sustainability, and availability.

BASF’s screening process assessed over 400 substances, which were pre-selected based on molecular weight, vapor pressure, alkalinity, and safety data. About half of the candidates were further investigated for vapor-liquid equilibrium, reaction kinetics, and stability data. About 20 component mixtures were then subjected to a proof-of-concept run in BASF’s mini plant where the complete CO_2 capture process was verified. This valuable tool showed early on in development whether a chemical solvent had the potential for further testing at the pilot-scale using real power plant off gases containing CO_2.

In parallel, BASF monitored the energy industry’s approaches towards carbon capture and contributed to several research projects within the 6th and 7th integrated framework programs of the European Union. During the CASTOR and CESAR projects, the BASF team exchanged experiences with relevant players in the community and transferred significant gas treating know-how from the petrochemical industry to the energy and energy-related institutes.

Together with Linde, BASF is a partner in a pilot project steered by RWE Power at the German energy provider’s Coal Innovation Center in Niederaussem, Germany, near Cologne. The Niederaussem PCC pilot plant using coal-fired off gas was constructed, commissioned, and started up in 2009. Despite the relatively small dimensions of the pilot and capacity to capture only 7.2 tonnes of CO_2 per day from a flue gas slipstream of the power plant, several critical process parameters were successfully tested. In particular, reliable data on energy consumption and long-term stability were generated, which helped to serve as an experimental basis for the Linde-BASF PCC pilot plant tested in Wilsonville, AL at NCCC in 2015 and 2016.

Based on this work and the invaluable feedback from experience at over 300 plants operating with OASE® technology, BASF can already guarantee excellent performance at today’s state of development. Process performance parameters verified from past experience include CO_2 capture rate, flow rate/capacity, reboiler duty, process emissions, circulation rate, and CO_2 product purity. Today, an OASE® blue process can be safely and reliably operated to achieve these performance objectives. Integration of the aqueous amine-based OASE® blue solvent with advanced Linde design and equipment innovations offers further potential for process optimization improvements and overall capital and operating cost reductions for the PCC process.

4.2 General Process Description and Process Flow Diagram

In completing Tasks 6 and 7, the Linde-BASF PCC plant constructed and tested in Wilsonville, AL from 2015-2016 was designed to recover 90 percent of the CO_2 contained in the flue gas from a coal-fired power plant downstream of a flue gas desulfurization (FGD) unit and purify the CO_2 product (> 99.9 vol% CO_2 on a dry basis with < 100 vol. ppm O_2). The major sections of the PCC plant included: a flue gas cooler upstream of the absorber, a flue gas blower downstream of the absorber, a CO_2 absorber column with a gravity-flow interstage cooler and two absorption sections with structured packing and internals, two water wash sections at the top of the absorber, and a solvent stripper column operable at higher pressure (3.4 bara) with a unique level-controlled reboiler. The Linde-BASF PCC pilot plant components were designed and operated with the final goal of minimizing the energy requirements for CO_2 removal and compression relative to DOE/NETL Case 12 reference conditions [Ref. 1]. A simplified process flow diagram for the Linde-BASF PCC technology pilot plant is shown in Figure 2. This process flow diagram highlights the major technology improvements for the Linde-BASF PCC pilot that result in significantly enhanced energy performance and overall capital and operating cost reductions compared to a standard MEA solvent-based PCC plant. These technology innovations are described further below.

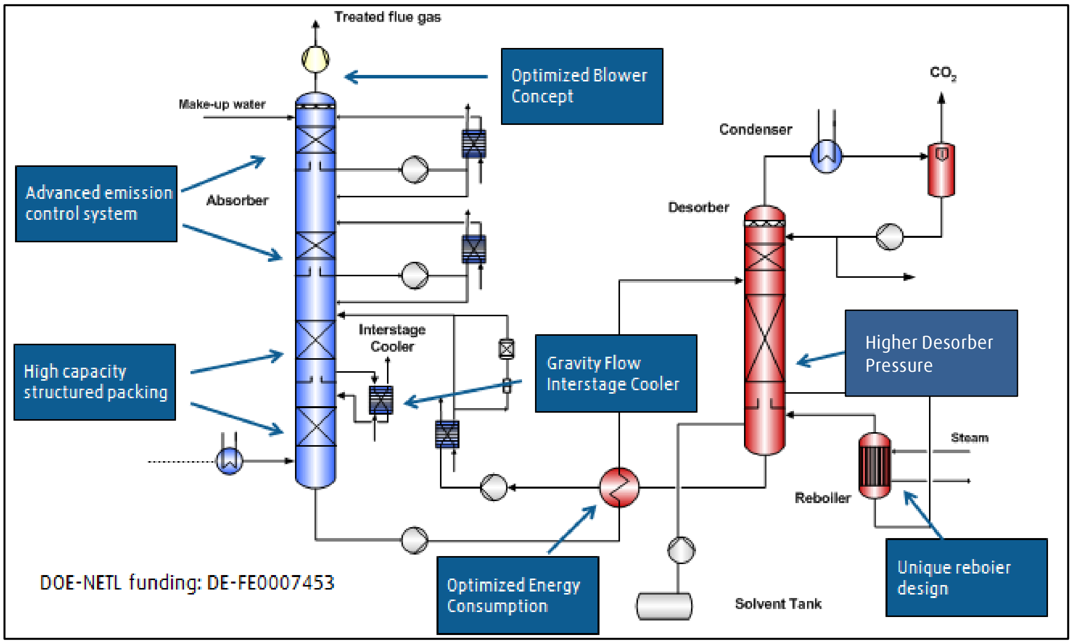

Figure 2: Process flow diagram of Linde-BASF PCC Pilot Plant in Wilsonville, AL at NCCC.

Flue Gas Blower Placed Downstream of Absorber

The following benefits are afforded for the Linde-BASF PCC process through use of a flue gas blower positioned downstream of the absorber column.

1. Significantly reduced cooling duty requirements (~30% reduction compared to DOE/NETL Case 12 reference for equivalent PCC plant integrated with 550 MWe coal-fired power plant) since it is not

necessary to cool down the flue gas stream beyond the CO_2 absorption requirements, as is normally done to compensate for a significant temperature rise (up to 30°F) across the flue gas blower [Ref. 1].

2. Notably reduced separation system electrical power requirement (~13% compared to DOE/NETL Case 12 reference), due to the substantially lower molar flowrate of CO_2-depleted flue gas downstream of the absorber as compared to the flue gas flow rate upstream of the absorber. This difference in flowrate is a result of the 90% absorbed CO_2 from the flue gas within the absorber bed into the BASF OASE® blue solvent [Ref. 1].

CO_2 Absorber with Gravity-Flow Interstage Cooler

The CO_2-lean BASF OASE® blue amine-based solvent flows down through the absorber bed and absorbs CO_2 from the flue gas, which flows from the bottom to the top of the column and to the water wash units. Since the exothermic absorption reaction of CO_2 into amine-based solvents increases the temperature of the flue gas inside the absorber and consequently reduces the equilibrium content of CO_2 in the liquid-phase, it is of utmost importance to maintain a low, relatively constant temperature throughout the entire absorber. In addition to cooling the CO_2-lean amine solvent solution within an external cooler before it is injected to the top of the absorber, a significant solvent temperature rise within the column can be efficiently suppressed through use of an interstage cooler, as shown in Figure 2. Linde's gravity-driven interstage cooler design eliminates the need for an external interstage cooler pump and control components, and consequently leads to a simplified design as well as a reduced capital cost for the absorber integrated with interstage cooler when implemented at scale.

High-Performance Structured Column Packing

The Linde-BASF PCC technology also utilizes the most advanced structured packing for the absorber to promote efficient hydraulic contact of the gas and liquid phases, which along with increased CO_2 reaction rates with BASF's OASE® blue solvent, facilitates a fast approach to the equilibrium CO_2 concentration in the solvent liquid-phase. Consequently, the capacity of the absorber, one of the most critical parameters for a large-scale CO_2 absorption plant, is dramatically increased. In addition, the advanced structured packing reduces the pressure drop across the column, which decreases the flue gas blower capital cost and electrical power consumption. The structured packing selection was determined by optimization of various structured packing options offering higher capacities while trading off on the mass-transfer efficiency.

Absorber Water Wash Section

Within a certain range of flue gas aerosol particle concentrations, an efficient reduction in solvent emissions from the process can be achieved through use of a patented dry-bed configuration consisting of two water wash sections at the top of the absorber. In addition, design improvements upstream of the PCC plant that minimize solvent-carrying aerosol formation in the flue gas to the CO_2 absorber can substantially suppress solvent losses. The CO_2-depleted flue gas that leaves the absorber bed still carries a small amount of solvent. Cold water sprayed from the top of the wash units effectively scrubs the solvent from the flue gas - an effect that is enhanced by a significantly reduced equilibrium composition of the solvent components in the vapor-phase as a result of the reduced outlet temperature at the top of the absorber. An external plate-and-frame heat exchanger in the water recirculation loop transfers the required cooling duty to the absorber water wash sections from the cooling water supplied by the central cooling water system.

High Desorber Column Pressure

Long-duration testing of the Linde-BASF PCC technology at the Wilsonville, AL pilot in 2016 demonstrated the feasibility of using elevated desorber/stripper column pressures. While the absorber operated at slightly sub-atmospheric pressure, solvent regeneration during the long-term test campaign was performed in the stripper at an operating pressure of 3.4 bara (49.3 psia) at the top of the column. Compared to CO_2 desorption at atmospheric pressure, this higher pressure operation significantly reduces electrical power requirements (33.77 MW required for CO_2 compression using the Linde-BASF PCC technology integrated with a 550 MWe PC power plant vs. 44.89 MW for DOE/NETL Case 12 reference) and capital cost for CO_2 compression at the commercial-scale PCC plant. 3.4 bara was chosen as the upper limit for stripper pressure considering the increasing solvent degradation expected at higher stripper temperatures, which correspond to higher stripper pressures. The significant difference in compression energy required for the DOE/NETL Case 12 reference vs. the tested Linde-BASF PCC process technology is a result of the substantially lower inlet CO_2 compression pressure for Case 12 compared to the Linde-BASF process (24 psia vs. 49.3 psia) for a CO_2 compression pressure ratio of 2 per compression stage [Ref. 1].

Unique Reboiler Design

The reboiler tested at the Wilsonville, AL Linde-BASF pilot utilized a unique design aimed at reducing overall capital costs and solvent inventory inside the reboiler during operation. Reduced solvent inventory in the reboiler offers faster responses to dynamic changes in CO_2 product flow rate requirements compared to standard reboiler designs. In addition, a novel reboiler control loop was used to control the level of condensed steam in the reboiler as a means of controlling the surface area of steam contacting the reboiler walls in the heating process, leading to enhanced flexibility and optimization of steam condensation heating duty input into the reboiler. In addition to the reboiler, which used a plate-and-shell exchanger, an advanced plate-and-frame heat exchanger design was used for the CO_2-lean/CO_2-rich solution cross exchanger that recovered heat from the CO_2-lean solution to elevate the temperature of the CO_2-rich solution entering the stripper column. The advanced Linde-BASF cross exchanger design tested at the Wilsonville, AL PCC pilot reduced capital costs and maximized heat transfer surface area and associated efficiency compared to previous designs.

Process boundary limits and associated elements describing how the Linde-BASF PCC pilot plant was integrated with the E.C. Gaston power plant at NCCC are illustrated in Figures 3 and 4.

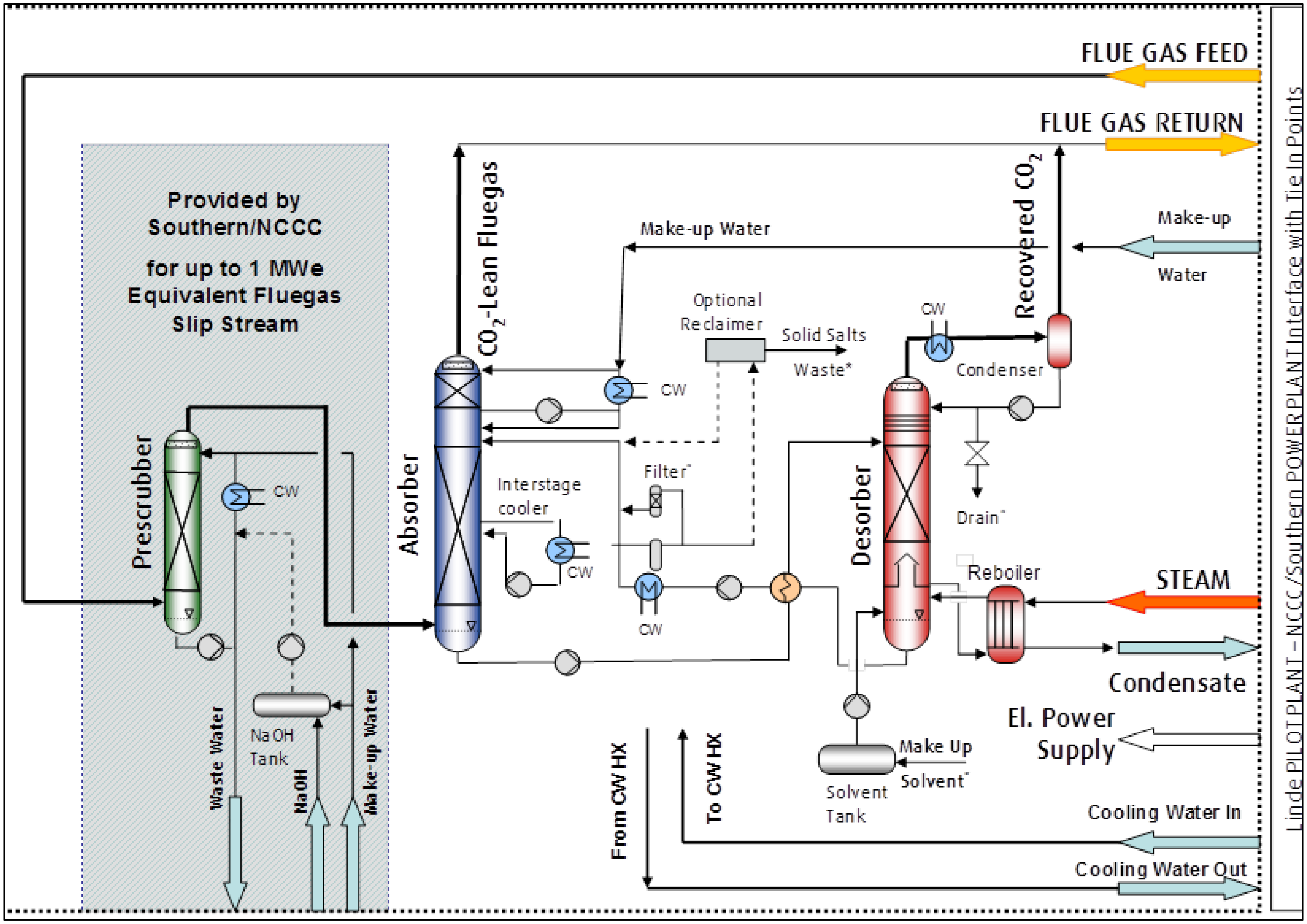

Figure 3: Integration of Linde-BASF pilot plant with E.C. Gaston power plant from pilot perspective.

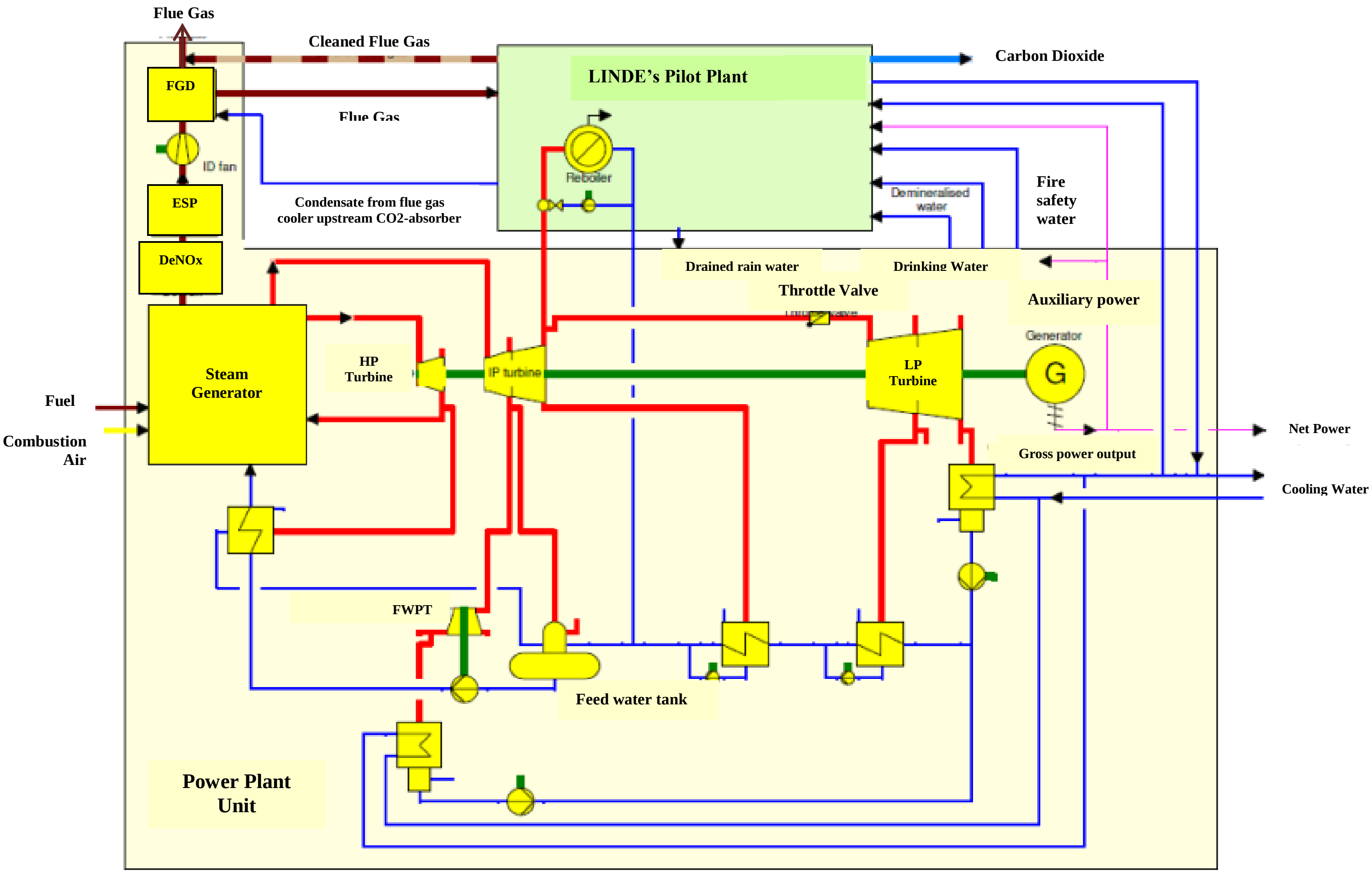

Figure 4: PCC pilot integration with E.C. Gaston power plant from power plant perspective.

4.3 General Process Operating Conditions

Process condition ranges from the Linde-BASF PCC pilot testing in Wilsonville, AL are summarized in Table II. The daily CO_2 mol% in the flue gas varied significantly in magnitude, ranging from 11 to 12 mol% CO_2 (dry) in the early morning and peaking to as much as 13 to 13.5 mol% CO_2 in the early afternoon. The resulting daily fluctuations in CO_2 recovery rate were controlled as closely as possible to achieve stable and consistent operation while maintaining low specific regeneration energy relative to a standard MEA solvent-based PCC plant. To provide actual plant data, the hourly average fluctuations of the flue gas CO_2 mol% (dry basis) are presented in Figure 5 from long-duration testing. The discontinuity in data during the following periods was caused by interruptions in the flue gas supply: 5/20/16 through 5/24/16, 6/3/16 through 6/4/16, 6/12/16 through 6/14/16, and 7/8 through 7/10/16.

Table II: Typical operating ranges during pilot testing in Wilsonville, AL.

Flue gas into absorber	
Flowrate (lb/hr)	7,500 to 15,750 (10,500 base)
Temperature (˚F)	86 to 104
Pressure (psig)	-0.3 to 0.5
CO_2 mol% (dry)	11 to 13.5
CO_2-depleted gas out of absorber	
Flowrate (lb/hr)	5,800 to 13,000
Temperature (˚F)	86 to 115
Pressure (psig)	-0.6 to 0.2
CO_2 mol% (dry)	0.5 to 2
CO_2 product gas out of stripper	
Flowrate (lb/hr)	1,300 to 2,300
Temperature (˚F)	70 to 100
Pressure (psig)	14.7 to 34.6
CO_2 mol% (dry)	99.9
CO_2-lean solution cooler	
CO_2-lean solution temperature to absorber (˚F)	104 to 140
Absorber inter-stage cooler	
Absorber inter-stage cooler operation	On (104˚F) / Off
Solvent circulation and CO_2 capture	
Solvent circulation rate	Varied from 80% to 120% of design
CO_2 capture rate	90% typical; varied from 85% to > 95%

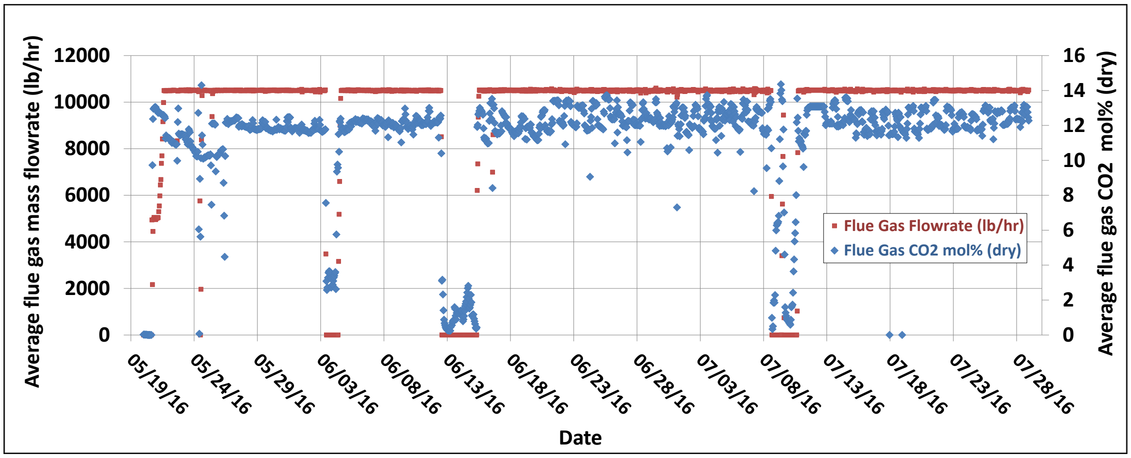

Figure 5: Hourly average flue gas mass flowrate (lb/hr) and CO_2 mol% (dry) during long-duration test campaign in 2016.

4.4 Tests on Solvent Stability

In completion of Task 10, the stability and long-term performance of BASF's OASE® blue solvent was evaluated and confirmed. Solvent stability can be measured in terms of both the energy consumption, used as an indicator of solvent performance, and via solvent composition measurements including analysis of known solvent degradations components such as heat stable salts (HSS). During each testing period, major components of the solvent (amine, water, and CO_2) were analyzed daily, and the results were compared to a desired solvent composition on a CO_2-free basis. Process parameters, such as the treated gas temperature, were adjusted daily to provide a stable plant water balance as needed to maintain the desired solvent composition. In addition, batch samples of CO_2-lean and CO_2-rich solvent liquid were collected on a regular basis and shipped to BASF Corporation analytical laboratories in Wyandotte, Michigan for detailed analysis of contaminants and HSS. As shown in Figure 6, the measured HSS content in the solvent during testing was consistently far below an HSS threshold that BASF has experimentally determined to be a degradation level above which the energy consumption of the process per kg of CO_2 captured begins to increase. The low HSS content indicated that no significant solvent degradation occurred during testing in 2015 and 2016. HSS in the solvent does not leave in the treated or CO_2 product gas streams, and the HSS concentration is not reduced when new solvent is added to the process, so it accumulates over time during routine operation. Demonstrating the accuracy and consistency of HSS measurement methods, the Linde and BASF experimental HSS data show excellent uniformity during both 2015 and 2016 testing periods. These results confirm the superior stability performance of the OASE® blue technology compared to other PCC solvents for commercial plants. Based on the solvent stability data measured during parametric testing, the solvent inventory only needs to be replaced after several years as a result of HSS buildup in the process.

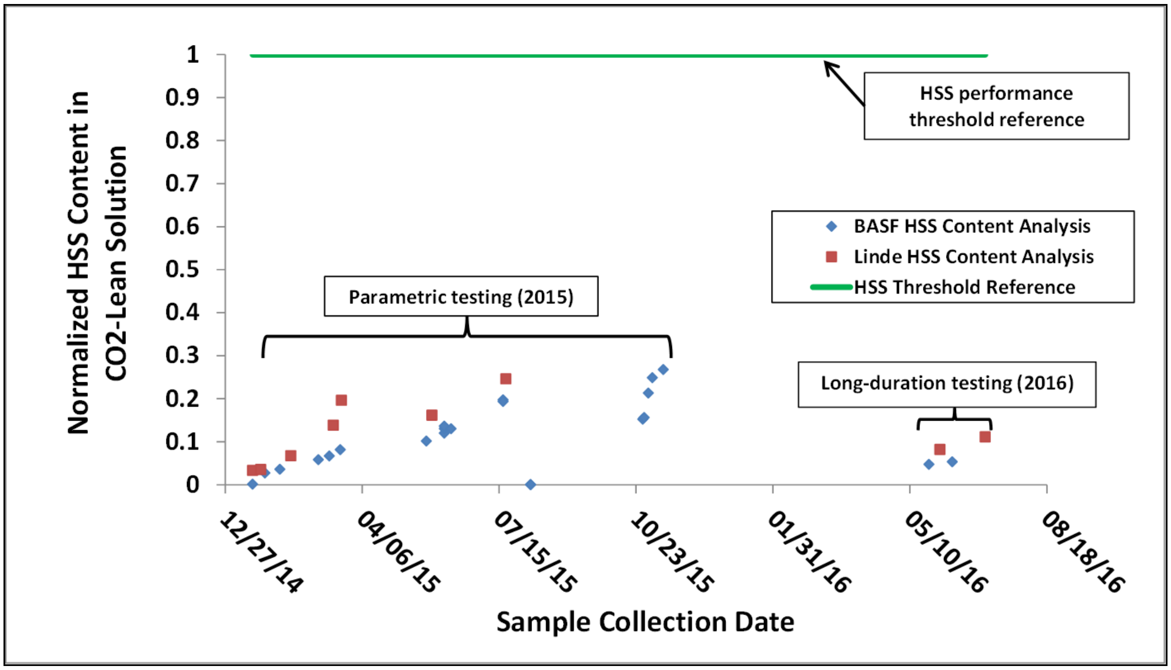

Figure 6: Heat stable salt (HSS) analysis results conducted during parametric and long-term test campaigns for Linde-BASF pilot plant.

Table III presents a summary of the Linde-BASF PCC pilot performance against its targets along with noteworthy accomplishments based on measured operating data from the parametric and long-duration test campaigns.

Table III: Pilot plant 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 Product Purity	99.9 mol% (dry) per target	Achieved. Low O_2 impurity level for EOR applications.
3. Plant Capacity	> 1.5 MWe per design target (> 15,500 lb/hr flue gas)	Achieved. Higher capacity testing performed – 10 days in May-June 2015. An additional week of 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 & CO_2-depleted gas) performed
6. Regenerator operating pressure	Testing performed up to 3.4 bar absolute	High-pressure parametric testing completed in Nov. 2015. Long-duration testing was performed at 3.4 bar(a).
7. Validation of unique features	(i) High-capacity packing (ii) Gravity-driven inter-stage cooler (iii) Blower downstream of absorber (iv) Unique reboiler design	Design options for regenerator heat reduction through heat integration identified. Stripper inter-stage heater (SIH) design can result in ~2.3 GJ/tonne CO_2.

4.5 Normalized Solvent Performance Data and Results from Testing

Figure 7 shows specific regeneration energy data (MJ/tonne CO_2) for the Linde-BASF PCC plant measured during parametric testing in 2015 along with an average specific regeneration energy measured over the course of long-duration testing in 2016. In completion of Tasks 9 and 10, the Linde-BASF technology clearly enables reduced energy consumption compared to a standard MEA-based PCC process (which typically operates at an average of 3,610 MJ/tonne CO_2), and can achieve specific regeneration energies below 2,800 MJ/tonne CO_2 depending on solvent and process conditions. The regenerator was operated at 14.7 psig for most of the 2015 test campaign, but its pressure was increased to 34.6 psig in November 2015 to evaluate the impact of higher pressure on specific regeneration energy. The Niederaussem OASE® blue data series shown is used as a comparison with the measured data at the Linde-BASF PCC pilot plant in Wilsonville, AL to illustrate process and data consistency.

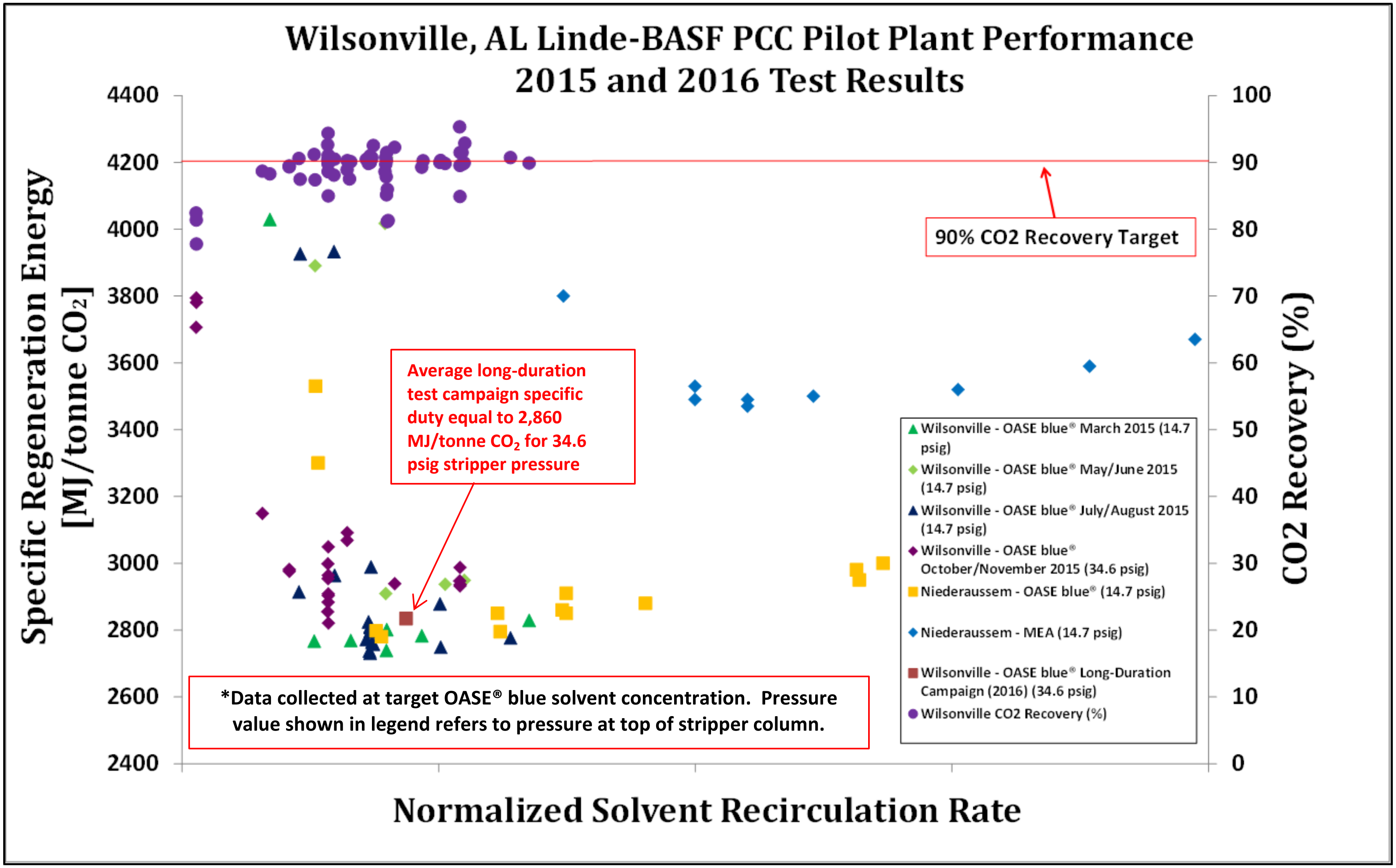

Figure 7: Specific regeneration energy for Linde-BASF pilot tested at Wilsonville, AL during parametric testing in 2015 and long-duration testing in 2016.

4.6 Independent EPRI Analysis

Under Task 10, EPRI conducted an independent performance analysis of the Linde-BASF PCC pilot process in June 2016 during the long-duration test campaign. Figures 8 and 9 show results from EPRI's independent analysis, revealing that little to no added NO_x, SO_2, or HAPs metals were produced from the Linde-BASF PCC pilot process tested at NCCC. The results for SO_3 are not shown here, but the EPRI analysis detected almost no SO_3 at the outlet of the absorber, indicating very little SO_3 in both the inlet and outlet of the absorber. EPRI analysis also verified the low specific regeneration energy (MJ/kg CO_2) of the Linde-BASF PCC technology tested at NCCC. EPRI's full testing report is included in the Appendix section at the end of this report.

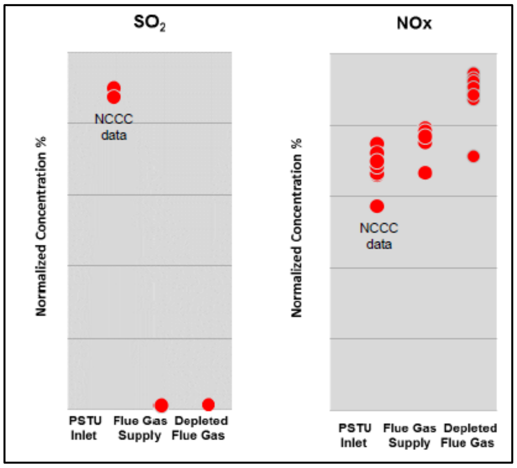

Figure 8: Normalized SO_2 and NO_x compositions (dry mol%) in PSTU inlet, flue gas supply to Linde-BASF pilot, and depleted flue gas leaving absorber. Measurements conducted by EPRI in June 2016 at Linde-BASF PCC pilot plant.

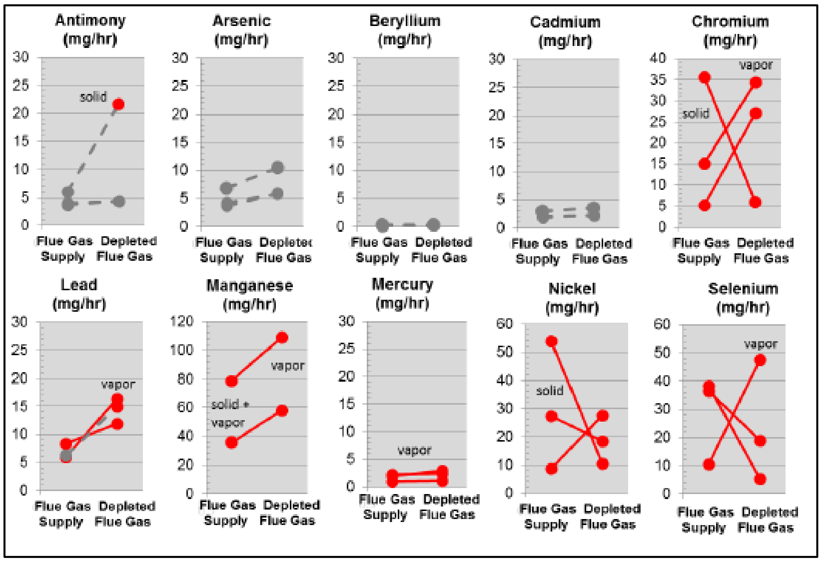

Figure 9: HAPs metals emissions (mg/hr) in flue gas supply to Linde-BASF pilot and depleted flue gas leaving absorber. Gray data points indicate measured data below standard detection limits. Measurements conducted by EPRI in June 2016 at Linde-BASF PCC pilot plant.

4.7 Process Economic Data for PCC plant integrated with 550 MWe PC power plant

In completing Task 11, an updated TEA was conducted for a Linde-BASF PCC plant integrated with a 550 MWe supercritical PC-fired power plant. Highlights of the key results obtained from the updated TEA are presented in this section. Here, the LB1 process option describes a supercritical 550 MWe PC-fired power plant integrated with a Linde-BASF PCC plant that offers a PCC reboiler duty of 2.61 GJ/tonne CO_2. In addition, the SIH process option describes a supercritical 550 MWe PC-fired power plant integrated with Linde-BASF PCC plant utilizing an advanced stripper interstage heater (SIH) design that optimizes heat recovery in the PCC process to further improve energy performance to provide 2.30 GJ/tonne CO_2. Lastly, the LB1-CREB process configuration refers to a supercritical 550 MWe PC-fired power plant integrated with Linde-BASF PCC plant incorporating an advanced CO_2 rich - CO_2 lean solvent cross exchanger and cold CO_2-rich exchanger bypass (CREB) design that further improves energy performance. The LB1-CREB process configuration can offer as low as 2.10 GJ/tonne CO_2 PCC reboiler steam consumption based on conceptual modeling results [Ref. 2 and 3]. The specific energy consumption values for the three process configurations described were determined using process models simulated with BASF's proprietary PCC mathematical modeling software combined with Linde process innovations and techniques. In addition, capital cost estimations for each PCC plant configuration were rigorously assessed using Linde's proprietary cost evaluation tools and databases as well as past experience in the design and construction of commercial-scale process plants. Figure 10 below presents the net higher heating value (HHV) efficiencies (%) for a 550 MWe power plant integrated with each PCC technology option. The higher the power plant efficiency, the lower the coal consumption rate needed to provide the same net power output, leading to significantly reduced operating costs at higher plant efficiencies. Figure 11 illustrates the itemized breakdown of the cost of electricity (COE) composed of fixed operating costs, variable operating costs, capital costs, fuel costs, and CO_2 TSM costs for each of the evaluated Linde-BASF PCC technology options. In addition, Figure 12 shows the cost of CO_2 captured for each evaluated option. It should be noted that as power plant efficiency increases, the flow rate of CO_2 produced decreases due to a reduced coal flow rate needed for the same power production. This decrease in produced CO_2 leads to increasingly smaller incremental reductions in the cost of CO_2 captured for each Linde-BASF process improvement, as illustrated in Figure 12.

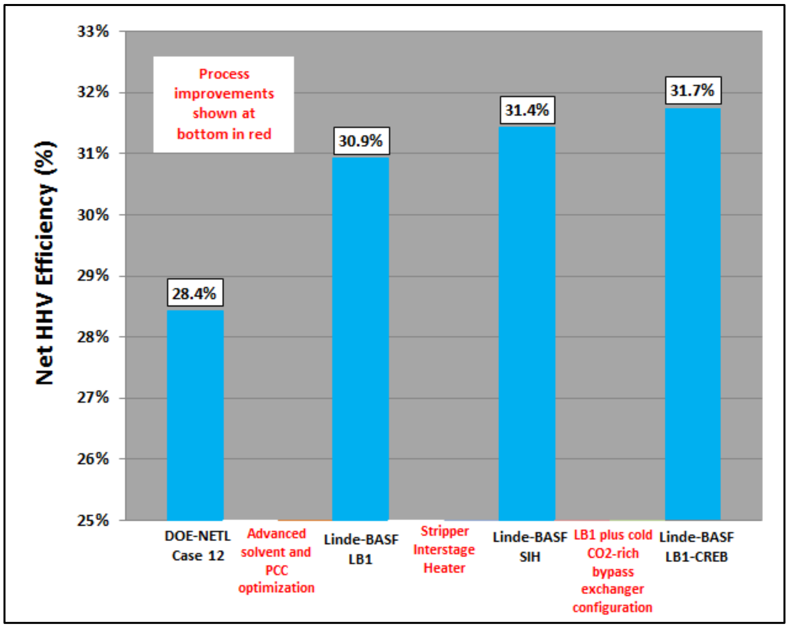

Figure 10: Incremental improvements in net plant HHV efficiency (%) afforded by Linde-BASF PCC technologies.

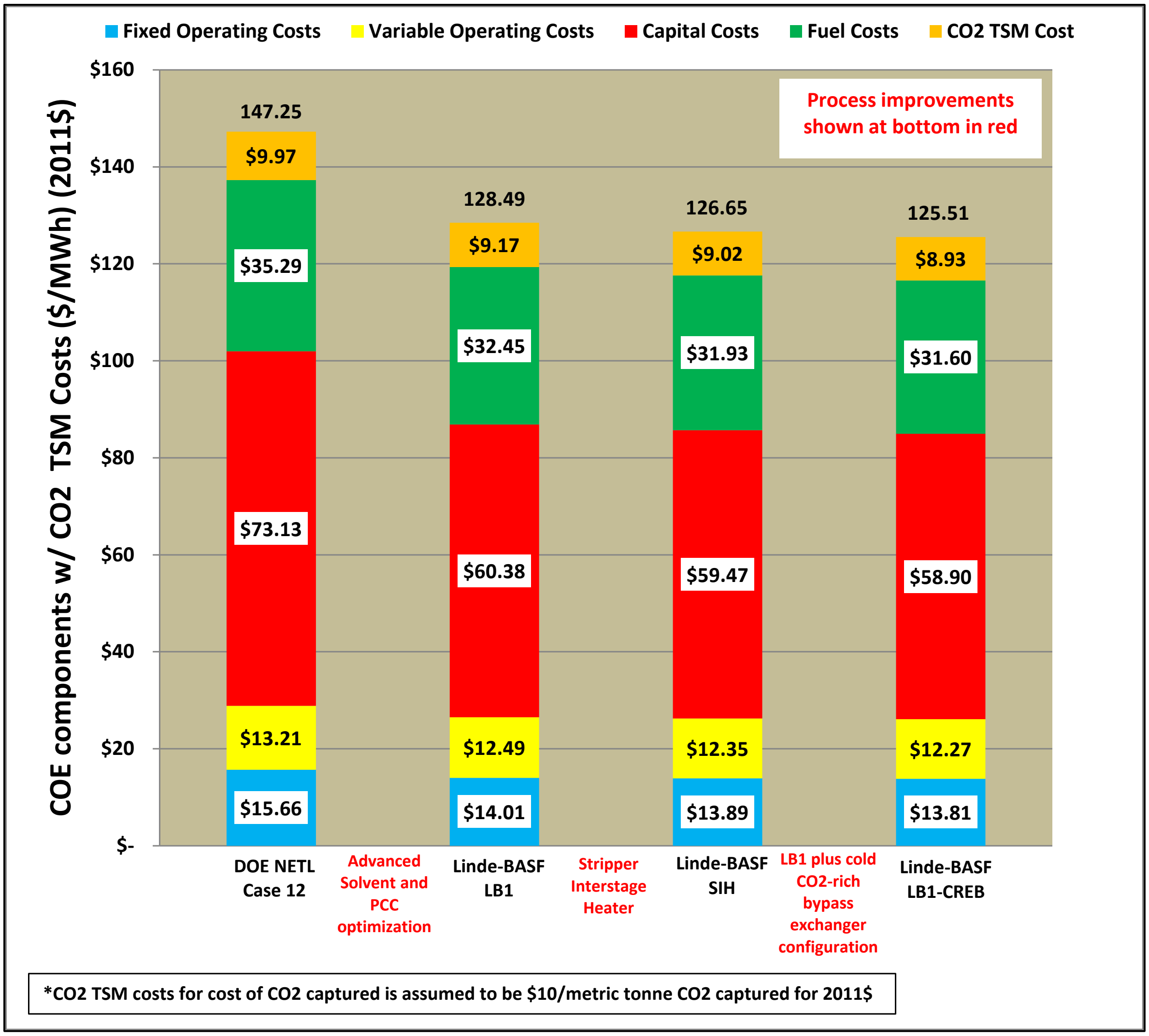

Figure 11: COE components ($/MWh) for different PCC options (SP-S methodology for TPC; CO_2 TSM Cost = $10/tonne CO_2).

$$COE = \{(CCF)*(TOC) + OC_{FIX} + (CF)*(OC_{VAR})]\}/ [(CF)*(aMWh)]$$

OC_{FIX} = *Fixed Operating Costs*

OC_{VAR} = *Variable Operating Costs*

CF= Capacity Factor (0.85 in this study)

CCF = Capital Charge Factor (0.124 in this study)

TOC = Total Overnight Cost

aMWh = Annual net megawatt-hours of power generated at 100% capacity factor

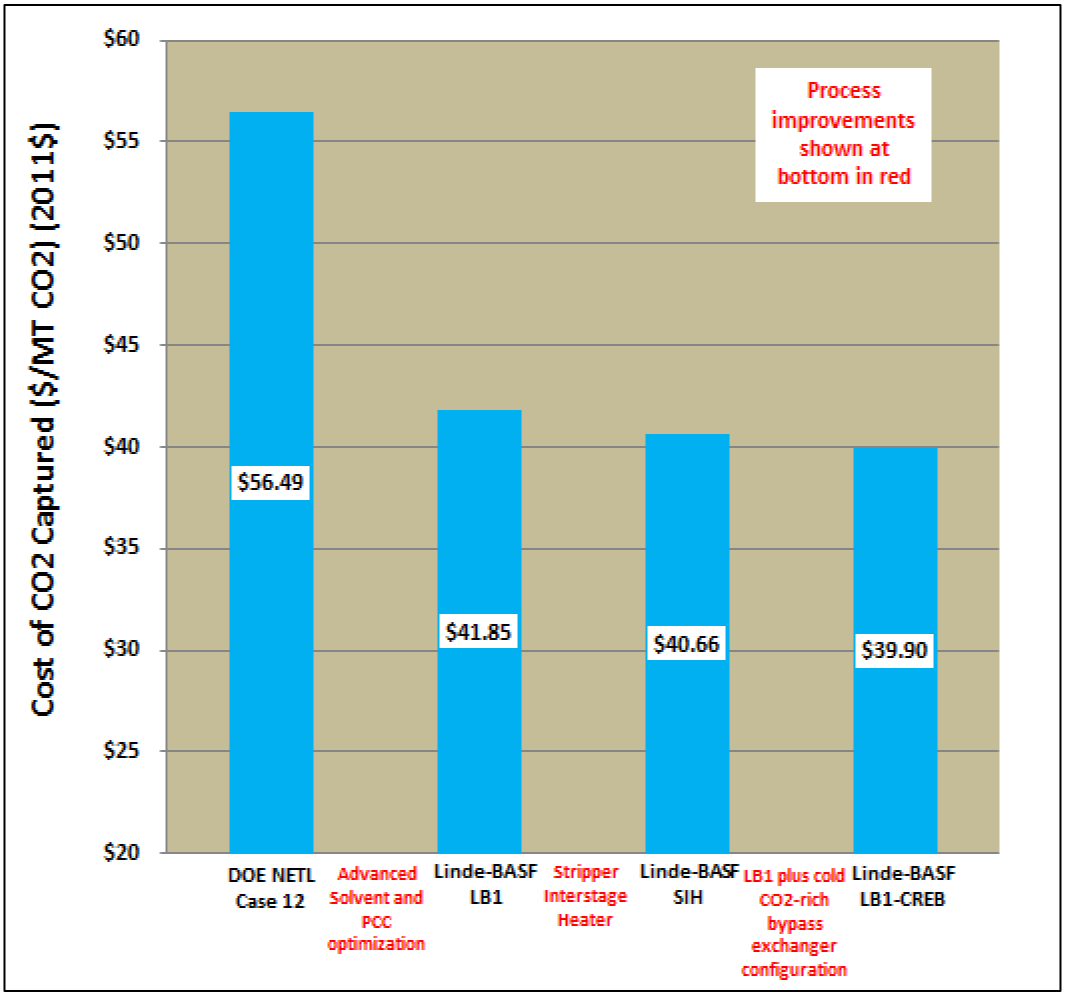

Figure 12: Cost of CO_2 captured ($/tonne CO_2) for different PCC options (SP-S methodology for TPC).

$$Cost\ of\ CO_2\ Captured = \{COE - COE_{reference}\}\$/MWh\ /\ \{CO_2\ Captured\}\ tonnes/MWh$$

It should be noted that the PCC plant capital cost assessment detailed in the updated TEA incorporated use of fiber-reinforced plastic (FRP) material for the DCC piping and piping around the absorber column that contacts low-temperature amine solvent. The use of FRP material in these sections can reduce the capital cost of the PCC plant compared to using stainless steel in many ways. Based on results from the testing and analysis of FRP spool pieces used at the Linde-BASF PCC pilot at NCCC, the FRP material does not degrade to any measurably significant degree when used in the PCC plant in these sections. Therefore, FRP can be considered a reliable and stable material option in these sections for commercial Linde-BASF PCC plants using the OASE® blue solvent.

4.8 Key Lessons Learned from Pilot Tests

Impact of high concentrations of nano-sized aerosol particles in flue gas on solvent emissions

During parametric testing, higher rates of solvent loss (kg amine/MT CO_2 captured) were measured than expected, leading to a number of operational challenges, including additional solvent deliveries to the plant than planned, difficulty in controlling the stripper column sump level on a day-to-day basis, and high variation in specific regeneration energy due to constantly changing pilot plant solvent amine composition. A baghouse was installed in the E.C. Gaston power plant delivering flue gas to the Linde-BASF pilot in 2016 before the start of long-duration testing. After the baghouse installation, the measured aerosol particle concentrations in the inlet flue gas to the absorber decreased significantly, especially for particle sizes in the range of 100-500 nm in diameter. Based on measured process data, the baghouse provided an effective mechanism to filter out and remove small to medium-sized aerosol particles in the flue gas, leading to substantially reduced aerosol-driven solvent emissions from the PCC pilot evaluated during long-duration testing compared to those measured during parametric testing in 2015.

Understanding mechanisms and operational strategies for maintaining the water balance

A consistent water balance for the Linde-BASF CO_2 capture process tested at NCCC could be maintained through temperature control of the treated gas leaving the top of the absorber column. Inlet water flows to the PCC pilot consisted of water contained in the flue gas entering the absorber, demineralized water fed to the upper wash water sections of the absorber, and water in the solvent that was added to the process from the solvent storage tank. Outlet water flows consisted of water leaving the process through the treated gas at the top of the absorber and water drained from the reflux drum of the stripper. Water was only occasionally drained from the reflux drum during the parametric test campaign to assist in control of the stripper sump level; water was never drained from the reflux drum during the long-duration test campaign as it was not necessary for level control. Due to the NCCC pre-scrubber operating upstream of the Linde-BASF PCC pilot, the flue gas fed to the flue gas cooler of the PCC process was saturated with water at the measured pressure and temperature. Based on water saturation correlations, the water content in the flue gas was determined from the measured pressure and temperature to evaluate the mass flow rate of water entering the absorber in the flue gas. Likewise, due to use of the wash water sections located at the upper half the absorber column, the treated gas was saturated with water and the mass flow rate of water leaving the absorber in the treated gas was similarly calculated. The mass flow rates of demineralized water entering the wash sections and water drained from the reflux drum were measured using calibrated mass flowmeters and controlled via automatic flow control valves. Due to the exothermic absorption of CO_2, an expected temperature rise in the absorber occurred during operation. The absorber interstage cooler mitigated this temperature rise in the column’s lower sections, but the absorption of CO_2 into the CO_2-lean solution entering the absorber above the interstage cooler still increased the temperature of the CO_2-depleted gas flowing up the column. To control the temperature of the gas exiting the absorber, wash water sections with water-cooled, plate-and-frame heat exchangers were positioned at the upper half of the column to reduce the temperature of the CO_2-depleted gas flowing up the absorber. Since the temperature of the treated gas saturated with water at the given absorber pressure determines the water content in the gas leaving the absorber, the water balance of the PCC process was maintained by controlling the treated gas temperature at the top wash section.

At the Linde-BASF PCC pilot at NCCC, the absorber column used automatic level control. In contrast, the stripper level was not directly controlled and fluctuated based on process conditions. The overall process water balance was therefore evaluated using the measured liquid level of the stripper column once the correct solvent water composition was obtained after pilot plant startup. The liquid level in the stripper sump was accurately determined by a differential pressure measurement using the dimensions and positions of the level measurement probes along with the density of the solvent. As the stripper level decreased during operation below a desired threshold (30%, for example), the treated gas temperature leaving the absorber was subsequently reduced by increasing the cooling water flow to the top water wash section heat exchanger of the absorber. This temperature reduction at the top of the absorber allowed more water to be retained in the absorber and moved to the stripper sump through action of the automatic absorber level control valve. Similarly, a decrease in the stripper level was observed when the cooling water flowrate to the top absorber section heat exchanger was reduced. The solvent composition (amine, water and CO_2 wt%) was evaluated with daily GC and titration measurements of CO_2-lean and CO_2-rich solution samples. Based on the results of daily solvent water content analysis, the stripper level was adjusted to meet the desired solvent composition by changing the treated gas temperature. Control of the stripper level was much easier during long-duration testing since the amine content of the solvent was more stable compared to that measured during parametric testing when significant aerosol-driven solvent emissions were experienced. In addition, inherent process stability was improved during long-duration testing because only one operating condition was maintained in contrast to parametric testing when several process variables were changed on a day-to-day basis according to the parametric test schedule.

Evaluation of process parameters with high impact on reducing regeneration energy

The impact of process variables tested on the specific regeneration energy consumption (GJ/tonne CO_2) evaluated during the parametric test campaign in 2015 is summarized in Table IV below.

Table IV: Impact of process variables tested on the specific regeneration energy consumption (GJ/tonne CO_2) evaluated during the parametric test campaign in 2015.

Test Parameter	Impact on specific regeneration energy (GJ/tonne CO_2)
Flue Gas Temperature (ºF)	Flue gas temperatures between 92-96ºF provide improved specific regeneration energy compared to higher flue gas temperatures (104ºF and above)
Absorption Intermediate Cooler Temperature (ºF)	Reduced temperature appears to be beneficial. Absorption intermediate cooler outlet temperature equal to 104ºF offers optimum specific regeneration energy based on test results. It should be noted that the absorption intermediate cooler outlet temperature was only varied as a parameter for 34.6 psig stripper pressure.
CO_2-lean Solution Cooler Temperature (ºF)	CO_2-lean solution cooler outlet temperature equal to 104ºF appears to provide improvement compared to higher temperatures.
Treated Gas Temperature (ºF)	Reduced temperature appears to be beneficial. Treated gas temperatures equal to or below 100ºF provide improved specific regeneration energy compared to higher temperatures.
Pressure at top of regenerator column (psig)	34.6 psig (3.4 bara) stripper top pressure increases specific regeneration energy slightly (~2.2%) compared to 14.7 psig (2 bara) stripper pressure based on comparison between parametric tests conducted at 14.7 psig stripper pressure and long-duration tests performed at 34.6 psig.

5. MILESTONES

Key milestones for the project are listed in Table V for Budget Periods 1, 2, and 3. Table V compares the planned completion date for each milestone with its actual completion date along with a verification method.

Table V: Key Project Milestones for Budget Periods 1, 2, and 3

Budget Periods 1 and 2

ID	Task	Title/Description	Planned Completion Date	Actual Completion Date	Verification Method
a	1	Submit Project Management Plan	03/09/2012	03/09/2012	Project Management Plan file
b	1	Conduct Kick-off Meeting	12/31/2011	11/15/2011	Briefing Document & Meeting Results
c	2	Complete Initial Techno-Economic Analysis on a 550 MW_e power plant	03/31/2012	03/09/2012	Topical Report file
d	3	Complete basic design and engineering of 1 MW_e pilot plant to be tested at the NCCC	06/30/2012	06/20/2012	Results reported in the quarterly report
e	1	Host site agreement executed	01/09/2013	1/14/2013	Host Site Agreement file
f	5	Complete initial EH&S Assessment	12/31/2012	12/14/2013	Topical Report file
g	4/5	Complete detailed pilot plant engineering and cost analysis of the 1 MW_e unit to be tested at the NCCC	01/31/2013	02/15/2013	Bid package is submitted to system integrator/fabricator and submitted to NETL for record; see also Topical Report file
h	1	PCC process and pilot peer review	03/11/2013	03/11/2013	Results reported in Q2 2016 summary report
i	6	Complete purchase orders and fabrication contracts for 1MW_e pilot unit	06/30/2013	06/30/2013	Results reported in the quarterly report
j	6	Complete shop fabrication of equipment and modules and associated engineering checks.	12/15/2013	12/20/2013	Review meeting and minutes of meeting
k	6	Complete site preparation and foundations installation at NCCC and receive pilot	11/15/2013	01/03/2014	Results reported in the quarterly report

		plant.			
l	7	Complete installation of 1MWe pilot unit (columns and modules) at NCCC	02/28/2014	03/28/2014	Presentation file
m	7	Mechanical completion of 1MWe pilot unit at NCCC	05/28/2014	07/25/2014	Presentation file

Budget Period 3

ID	Task	Title/Description	Planned Completion Date	Actual Completion Date	Verification Method
n	8	Complete pilot unit start-up and demonstrate plant operation at steady state	02/28/2015	03/24/2015	Results reported in the quarterly report
o	9	Develop pilot-scale parametric test plan	12/31/2014	12/31/2014	Results reported in the quarterly report
p	9	Complete 1 MW_e pilot scale parametric tests	08/31/2015	12/22/2015	Presentation file
q	10	Develop pilot-scale long duration test plan	04/30/2016	03/31/2016	Results reported in the quarterly report
r	10	Complete 1MW_e pilot scale long duration tests	07/31/2016	07/29/2016	Presentation file
s	11	Complete updated techno-economic analysis	10/31/2016	01/09/2017	Topical Report file
t	11	Complete updated EH&S assessment	10/31/2016	01/09/2017	Topical Report file
u	1	Quarterly reports	Each Quarter	Each Quarter	Quarterly Report files
v	1	Final Report	09/30/2016	02/03/2017	Final Report file

Table VI: Decision Points, Success Criteria, and Associated Accomplishments

Decision Point	Success Criteria	Associated Accomplishment
Completion of Budget Period 1	1. Successful completion of all work proposed in Budget Period 1 2. Demonstrate a 10% reduction in capital costs with Linde-BASF CO_2 capture process 3. Demonstrate a LCOE increase of less than 65% over the baseline 4. Submission of an Executed Host Site Agreement 5. Submission of a Topical Report – Initial Techno-Economic	1. All work completed from Budget Period 1 2. From the updated TEA, capital costs for PCC process including CO_2 compression & drying reduced from $593.5 MM for DOE Case 12 baseline to $320.9 MM for LB-1 process option (45.9%

	Analysis 6. Submission of a Topical Report – Initial EH&S Assessment 7. Submission of a Topical Report – Detailed Pilot Plant Engineering and Cost Analysis 8. Submission and approval of a Continuation Application in accordance with the terms and conditions of the award. The Continuation Application should include a detailed budget and budget justification for budget revisions or budget items not previously justified, including quotes and budget justification for service contractors and major equipment items	reduction) 3. From the updated TEA, LCOE increased from $80.95/MWhr for PC-fired power plant without PCC (DOE Case 11 baseline) to $128.49/MWhr for LB-1 integrated with PC-fired power plant (58.7% increase) 4. Executed Host Site Agreement submitted 5. Topical Report – Initial Techno-Economic Analysis submitted 6. Topical Report – Initial EH&S Assessment submitted 7. Topical Report – Detailed Pilot Plant Engineering and Cost Analysis submitted 8. Continuation Applications for BP2 submitted and approved with the terms and conditions of the award and detailed budgets and budget justifications, as needed
Completion of Budget Period 2	1. Successful completion of all work proposed in Budget Period 2 2. Complete construction and commissioning of the integrated pilot-scale Linde-BASF process 3. Submission of a test matrix for the pilot-scale parametric testing campaign 4. Submission and approval of a Continuation Application in accordance with the terms and conditions of the award. The Continuation Application should include a detailed budget and budget justification for budget revisions or budget items not previously justified, including quotes and budget justification for service contractors and major equipment items	1. All work completed from Budget Period 2 2. Construction and commissioning of integrated pilot-scale Linde-BASF process completed 3. Test matric for pilot-scale parametric testing submitted 4. Continuation Application for BP3 submitted and approved with the terms and conditions of the award and detailed budgets and budget justifications, as needed
End of Project	1. Successful completion of all work proposed 2. Complete continuous testing of	1. All work proposed successfully completed

	the pilot-scale Linde-BASF process for at least 60 days 3. Demonstrate a 20% reduction in capital costs with Linde-BASF CO$_2$ capture process 4. Demonstrate a LCOE increase of less than 60% over the baseline 5. Demonstrate reboiler heat duty of 2.61 – 2.80 GJ/tonne CO$_2$ captured 6. Demonstrate process performance at 3.5 bar abs regeneration pressure (CO$_2$ delivery) 7. Demonstrate stable process performance over the entire parametric and long duration test period to validate solvent stability 8. Submission of a Topical Report - Updated Techno-Economic Analysis 9. Submission of a Topical Report – Updated EH&S Assessment 10. Submission of a Final Report	2. Continuous testing of pilot-scale Linde-BASF process for at least 60 days (1440 hours) completed 3. From the updated TEA, capital costs for PCC process including CO$_2$ compression & drying reduced from \$593.5 MM for DOE Case 12 baseline to \$310.4 MM for SIH process option (47.7% reduction) 4. From the updated TEA, LCOE increased from \$80.95/MWhr for PC-fired power plant without PCC (DOE Case 11 baseline) to \$126.65/MWhr for SIH integrated with PC-fired power plant (56.5% increase) 5. Reboiler duty ranging from 2.72 to 2.86 GJ/tonne CO$_2$ captured achieved at 3.4 bara regeneration pressure (CO$_2$ delivery) 6. Excellent process performance and stability achieved at 3.4 bara regeneration pressure (CO$_2$ delivery) 7. Stable process performance achieved over entire parametric and long-duration test periods to validate solvent stability 8. Topical Report – Updated Techno-Economic Analysis submitted 9. Topical Report – Updated EH&S Assessment submitted 10. Final Project Report submitted to DOE and Final Testing Report submitted to NCCC

6. DELIVERABLES

Linde LLC provided reports in accordance with the Federal Assistance Reporting Checklist and instructions accompanying the Checklist. In addition to the reports identified on the Reporting Checklist, the Recipient provided each of the deliverables listed in Table VII.

Table VII: Project Deliverables

Item #	Deliverable	Planned completion deadline
1	Revised Project Management Plan	30 days after award confirmation
2	Host Site Agreement	60 days prior to the end of Budget Period 1
3	Topical Report – Initial Techno-Economic Analysis	60 days after award confirmation
4	Topical Report – Initial EH&S Assessment	60 days prior to the end of Budget Period 1
5	Topical Report – Detailed Pilot Plant Engineering and Cost Analysis	30 days prior to the end of Budget Period 1
6	Continuation Applications for each Budget Period	90 days prior to the end of the preceding budget period
7	Pilot-scale parametric test plan	Budget Period 2 end date
8	Pilot-scale long duration test plan	12 months prior to the project end date
9	Topical Report - Updated Techno-Economic Analysis	Project end date
10	Topical Report – Updated EH&S Assessment	Project end date

A comprehensive list of each project deliverable outlined in the SOPO with its corresponding verification method or data source is presented in the Appendix Deliverables section.

7. CONCLUSION

Post-combustion CO_2 capture (PCC) technology for coal-fired power plants remains one of the only viable methods to combat further rise in atmospheric CO_2 emissions from the energy industry. Leveraging significant R&D advancements in recent years that allow it to be commercially-feasible, PCC technology offers a sustainable way to preserve the electricity generated by existing U.S. coal-fired power plants in line with global CO_2 emission reduction initiatives. Solvent-based technologies are today the leading option for PCC from commercial coal-fired power plants as they have already been applied in industry at large-scale. Linde and BASF have been working together to develop and further improve a PCC technology incorporating BASF's novel OASE® blue aqueous amine-based solvent. This technology offers significant benefits compared to other processes as it aims to reduce energy consumption using novel solvents that are very stable under the coal-fired power plant feed gas conditions. In coordination with BASF, Linde has evaluated a number of options for capital cost reduction in large engineered systems for solvent-based PCC technology. The final results from parametric and long-duration pilot testing of the PCC process discussed in this report clearly demonstrate the superior performance and cost-saving benefits of the Linde-BASF technology compared to industry standard MEA solvent-based PCC processes. A thorough analysis of the EH&S risks of the Linde-BASF technology has been completed that verifies its safe use and operation at commercial-scale with all potential hazards identified and mitigation processes put in place. A comprehensive finalized TEA conducted on the Linde-BASF PCC process when integrated with a commercial PC power plant has shown the significant potential of the novel technology to reduce the cost of CO_2 captured from coal-fired power plants to below the $40/tonne target set by DOE.

The Linde-BASF technology tested at the Wilsonville, AL pilot at NCCC has been further developed for the purposes of another DOE funding opportunity for a Linde-BASF PCC large pilot anticipated to be built at the Abbott Power Plant near the University of Illinois Urbana-Champaign pending award [DE-FE0026588]. This 15 MWe large pilot would be integrated with the coal-fired Abbott Power Plant to capture 90% of the CO_2 emitted from the power plant, and is planned to be operational by 2019. The large pilot would be permanently kept at the power plant to be used to capture CO_2 following the DOE funding period. It is proposed that this PCC large pilot would be integrated with a CO_2 compression and liquefaction plant that would produce liquid CO_2 to be used for numerous CO_2 utilization applications in the greater Urbana-Champaign, IL area, including Chicago. The large pilot would serve as a CO_2 source to facilitate the growth and expansion of long-term CO_2 utilization clusters in the greater Urbana-Champaign, IL region, such as concrete plants or greenhouses that would benefit from using CO_2. In this regard, a related Linde proposal for a CO_2 utilization effort using CO_2 in concrete and concrete wastewater applications in the greater Urbana-Champaign, IL region was submitted to the DOE on October 3, 2016, as part of DE-FOA-0001622. If awarded, the proposed CO_2 utilization project would create several CO_2 utilization clusters in the greater Chicago area that would be able to use CO_2 captured from the Linde-BASF PCC large pilot to be built and operated at the Abbott Power Plant pending award.

The Linde-BASF SIH PCC process configuration will be evaluated at the 15 MWe large pilot pending DOE award. Results from testing of the SIH process configuration will be evaluated and compared against findings from the TEA conducted for this summary report. Additionally, further process performance improvements will be investigated during testing, and relevant learnings will be documented and shared to continually progress advancement and optimization of the Linde-BASF PCC technology.

APPENDIX

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Table A-1: Results of corrosion coupon and spool piece material analysis conducted by BASF

Material Identifier for Figure A-2	Type	Location in Pilot Plant	Total Number of Coupons/Pieces	Results of Analysis by BASF
B5	**Corrosion Coupons**	**Absorber bottom**	**7**	**No noticeable corrosion (NNC)**
B6	**Corrosion Coupons**	**Absorber top**	**4**	**NNC**
B7	**Corrosion Coupons**	**Stripper top**	**6**	**NNC**
B8	**Corrosion Coupons**	**Stripper center**	**6**	**NNC**
A1	**FRP Spool Pieces**	**Absorber bottom outlet**	**5**	**NNC**
A3	**FRP Spool Pieces**	**CO_2-lean solution cooler outlet**	**5**	**NNC**

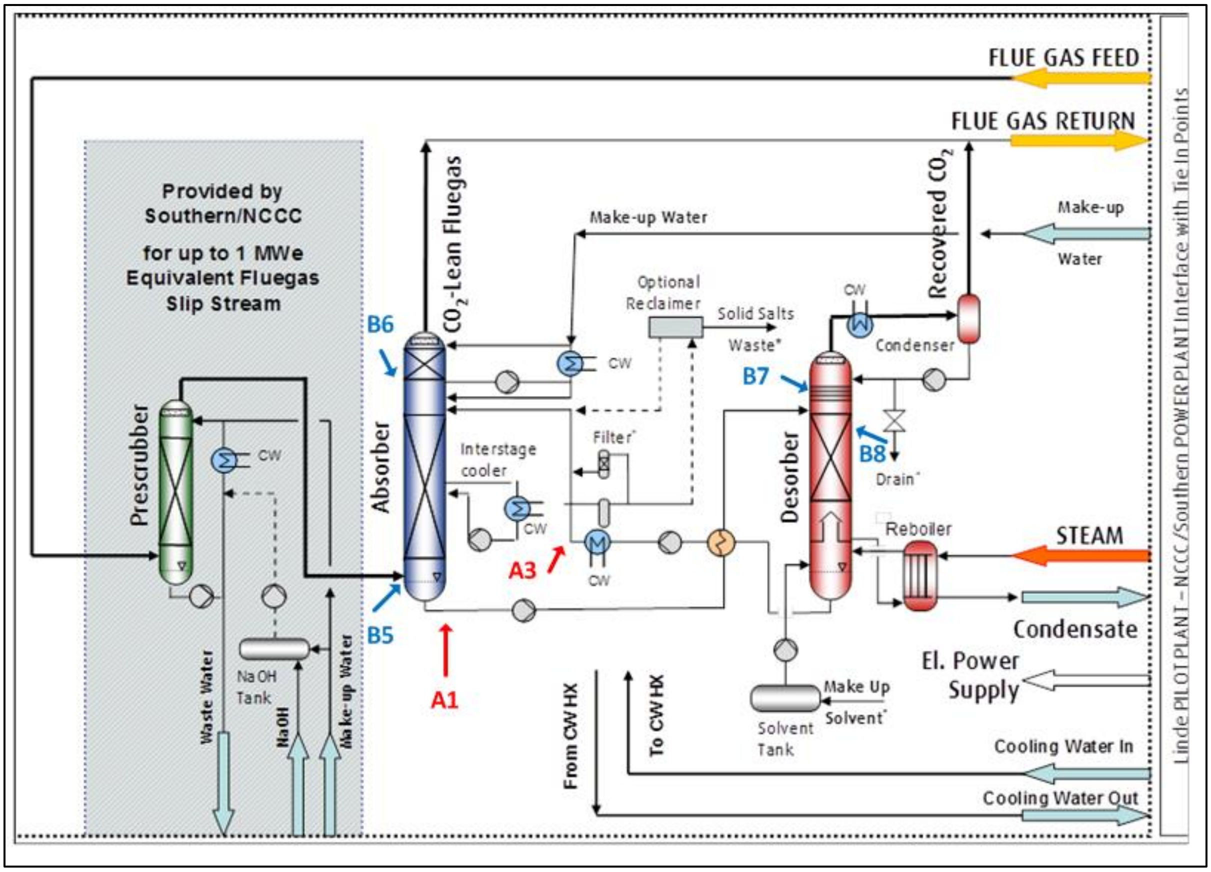

Figure A-1: Locations of corrosion coupons and spool pieces installed at Linde-BASF PCC pilot

Deliverables

Table A-2: Project deliverables as per SOPO and corresponding verification method or data source

Deliverable description as per SOPO	Verification method or data source
Final pilot-plant design package with cost to build	Topical Report – Detailed Pilot Plant Engineering and Cost Analysis
Final Process Flow Diagram, General Arrangement Sketch, and Elevation Sketch with written process description	Topical Report – Updated Techno-Economic Analysis
Pilot plant electricity, heat, and water consumption; waste generation; and management/tie-ins to the existing host facility	Topical Report – Updated Techno-Economic Analysis Project Management Plan
Slipstream feed conditions: pressure, temperature, flowrate, gas composition, contaminant levels that represent the actual flue gas from the PC boiler	Topical Report – Updated Techno-Economic Analysis Final Testing Report to NCCC
Estimated CO_2 delivery conditions: pressure, temperature, flow rate, and gas composition	Final Testing Report to NCCC
General description of start-up, steady-state	Final Testing Report to NCCC

operation, and shut-down procedures for the proposed pilot process	
General description of protocols, reference methods, measurements, and quality assurance for baseline and performance testing	Final Testing Report to NCCC
Experimental results from pilot-scale operations, with selected critical parameters in normalized form	Final Testing Report to NCCC
Updated State-Point Data Table, similar to that provided with the proposal submission	Table A-3 of Final Project Report
Identification of flue-gas clean-up requirements (*i.e.* allowable contaminant levels for contaminants as per Attachment 2 of the FOA)	<5 ppmv SO_x in flue gas is required as per design specifications. <1 ppmv SO_x in flue gas is preferred. SO_x negatively reacts with OASE® blue solvent thereby inactivating its ability to effectively absorb CO_2, so lower levels of SO_x are favorable. Higher NO_x concentrations in flue gas have no significant impact on solvent performance. As shown by analysis of aerosol measurements and solvent emissions data collected in 2016 during long-duration testing, aerosol particles with diameters less than 100 nm in the flue gas with concentrations equal to or below $4*10^6$ particles/cm^3 allow for acceptably low solvent emissions compared to higher aerosol concentrations.
Updated recommendations for system operating pressures (in units of bar), temperatures (in units of ˚C), and working capacity (in normalized form)	Working capacity: 45-55 Nm^3 CO_2/tonne solvent Regeneration pressure: 1.6-3.5 bara Steam temperature to reboiler: 130-175 ˚C Absorption temperature: 30-40˚C
Assessment of chemical and thermal stability for solvent	Final Testing Report to NCCC Final Project Report Topical Report – Updated EH&S Assessment
Experimental results under realistic flue gas and regeneration conditions	Final Testing Report to NCCC
Observations on solvent toxicity data	Topical Report – Updated EH&S Assessment
Updated useful life of solvent (in years) and estimated solvent make-up rate due to degradation and other losses (in units of kg solvent per 1,000 kg CO_2)	Topical Report – Updated Techno-Economic Analysis Final Project Report
Assessment and estimate of projected near term and long-term costs of mass produced solvents and other novel materials performed by the suppliers (in appropriate normalized form)	Topical Report – Updated Techno-Economic Analysis
Updated designs for absorption/desorption equipment and any novel heat transfer equipment that might be employed in a commercial version of the process	Topical Report – Updated Techno-Economic Analysis

Method of heat removal and heat addition to the absorber and stripper, respectively	Topical Report – Updated Techno-Economic Analysis
Steam requirements for stripping (in units of kg steam per kg CO_2 captured)	Topical Report – Updated Techno-Economic Analysis Final Testing Report to NCCC
Estimated pressure drops (in units of bar) for all absorption-cycle components under normal operating conditions	Design pressure drop through absorber from inlet to absorber to inlet of blower in treated gas line is 80-100 mbar. Results from tests showed actual pressure drops of ~50 mbar at 10,500 lb/hr flue gas flowrate.
Estimated costs of major mass and heat transfer equipment	Topical Report – Updated Techno-Economic Analysis
Updated description of absorption/desorption models used to predict equipment performance and capacity as required	Topical Report – Updated Techno-Economic Analysis
Updated Techno-Economic Analysis based on proposed final design configuration and operating conditions when integrated into a 550 MW power plant	Topical Report – Updated Techno-Economic Analysis
Estimated commercial-scale capture and compression plant footprint when integrated into a 550 MW power plant, along with assessment of required base PC plant, design modifications (basis for comparison as per Attachment 5 of the FOA)	Topical Report – Updated Techno-Economic Analysis
Preliminary and Final Technology EH&S Assessments of CO_2 capture technology and solvent	Topical Report – Initial EH&S Assessment Topical Report – Updated EH&S Assessment
Documentation of pilot-plant results and Techno-Economic Analysis	Topical Report – Updated EH&S Assessment Final Testing Report to NCCC
Technology benefits and shortcomings	Topical Report – Updated Techno-Economic Analysis Final Testing Report to NCCC Topical Report – Updated EH&S Assessment
Recommendations for future R&D addressing shortcomings	Topical Report – Updated Techno-Economic Analysis Final Testing Report to NCCC Topical Report – Updated EH&S Assessment
Proposed scale-up strategy for next stage of technology testing and demonstration incorporating both CO_2 capture and compression	Topical Report – Updated Techno-Economic Analysis

Table A-3: Updated State-Point Data Table for BASF OASE® blue solvent

	Parameter	PCC pilot at NCCC in Wilsonville, AL (1-1.5 MWe) (Measured)	Future PCC plants (Projected)	Explanation for projected value for future PCC plants
Solvent properties	Molecular weight (g/mol)	proprietary	proprietary	Same solvent; properties provide excellent performance. Solvent property ranges shown reflect varying concentrations of the solvent amine content.
	Boiling point (ºC)	103	103	
	Freezing point (ºC)	-5 to 25	-5 to 25	
	Vapor pressure at 40ºC (hPa)	approx. 66	approx. 66	
	Concentration (kg amine/kg solution)	proprietary	proprietary	
	Specific gravity (15ºC/15ºC)	1.0 – 1.2	1.0 – 1.2	
	Heat capacity at STP (kJ/(kg*K))	2.7 – 4.1	2.7 - 4.1	
	Viscosity at STP (cP)	1.5 – 7.0	1.5 – 7.0	
	Surface tension at STP (dyn/cm)	30 – 50	30 – 50	
Operating conditions	Absorption pressure (bara)	1.0	0.9 - 1.1	Pressure range is optimal for absorption and available from power plant; maintained with blower.
	Absorption temperature (ºC)	30 - 70	30 - 60	Temperature range is optimal for absorption and achieved with DCC
	Absorption equilibrium CO_2 loading (mol CO_2/mol amine)	proprietary	proprietary	Current absorption equilibrium CO_2 loading provides optimal performance.
	Heat of absorption (kJ/mol CO_2)	proprietary	proprietary	proprietary
	Desorption pressure (bara)	1.6 to 3.4	1.6 to 3.5	Higher desorption pressure reduces downstream compression capital and operating costs; there is an upper pressure limit due to high temperature limitation.
	Heat of desorption (kJ/mol CO_2)	proprietary	proprietary	proprietary
	Steam temperature (ºC)	130-175	130-175	This is based on both the temperature of the steam supplied by the power plant and optimal process steam temperatures determined from models and simulations.
	Desorption equilibrium CO_2 loading (mol/mol)	proprietary	proprietary	Current desorption equilibrium CO_2 loading provides optimal performance.

Pilot Plant Photo

Figure A-2: Linde-BASF 1-1.5 MWe PCC pilot plant installed and tested at NCCC

Full Testing Report from EPRI

ELECTRIC POWER
RESEARCH INSTITUTE

BASF-Linde Post Combustion Carbon Capture Pilot Plant at the National Carbon Capture Center

2016 Test Campaign Results

BASF-Linde Post Combustion Carbon Capture Pilot Plant at the National Carbon Capture Center

2016 Test Campaign Results

Final Report, January 2017

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Linde
BASF
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CONTENTS

FIGURES

TABLES

1

INTRODUCTION

At the beginning of the 21st century, political and technological focus is being given to minimizing carbon dioxide (CO_2) emissions to the atmosphere since this represents the primary greenhouse gas emission from anthropogenic activities. At the recent conference of parties (COP) meeting held in Paris (December 2015[1]), an international agreement to limit the increase in the global average temperature to no greater than 2°C above pre-industrial levels was defined.

A significant source of CO_2 entering the atmosphere is from combustion of coal to generate electric power. The principal proposed method for reducing CO_2 emissions from these existing and new coal-fired plants is separation of the CO_2 produced during coal combustion/gasification and injection of the purified CO_2 into acceptable underground geological reservoirs for long-term storage.

A leading candidate technology for reducing CO_2 emissions from coal-fired power plants is the use of a chemical absorption process to capture the CO_2 content of the flue gases into a solvent, known as a post combustion capture (PCC) system. The solvent (loaded with captured CO_2) is then heated to reverse the capture process, releasing the CO_2 in a relatively pure stream that is suitable for compression and export to an appropriate underground injection site. The entire process is often referred to as CO_2 capture and storage (CCS). Research is currently being conducted around the world to reduce the energy intensity of these CCS processes, thereby reducing the cost penalty associated with the production of low carbon dioxide intensity power.

Project Overview

As part of a research effort that focuses on improving efficiency and lowering carbon dioxide emission intensity from coal-fired power plants, Linde and BASF have constructed a pilot carbon capture facility at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama. The processing rate of flue gas flow rate through this facility represents the equivalent of a 1 MWe stream, is supplied from the neighboring coal fired power plant, Unit 5 of the Alabama Power E. C. Gaston Electric Generating Plant.

The process design characteristics and solvent properties are the intellectual property of Linde and BASF and are not discussed in detail in this report. The Electric Power Research Institute (EPRI) has been directed to assess the performance of the system through independent testing at the system boundaries. This includes the capture performance of the system along with any changes to the flue gas composition in terms of SO_2, SO_3 and NOx along with trace hazardous air pollutants (HAPs) metals.

The PCC facility is shown in Figure 1-1.

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[1] United Nations Framework Convention on Climate Change – Conference of Parties, Twenty-First Session Paris 30th November – 11 December 2015 https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Figure 1-1
Linde-BASF PCC pilot facility

Project Goals and Objectives

The overall objectives of the EPRI assessment of the Linde-BASF system are focused on the following key areas:

- Capture Performance – the total quantity of CO_2 removed from the flue gases being processed and the energy consumption needed to deliver the capture.
- SO_2/SO_3 Capture – assessment of any potential interaction with the SO_2 or H_2SO_4 components in the flue gases passing through the absorber.
- HAPs Metals and Hg Removal – sampling of the solids loading of the flue gas to determine changes in loading of various metal species.

Test Methodology

The test campaign was scheduled and executed over a four day period towards the end of the planned Linde/BASF testing operations in 2016. Each test day focused on a different set of priorities. The first day involved equipment set-up, calibration, and initial velocity checks. For each of the remaining three days, the flue gas feed was held steady throughout each day of testing.

Following EPA testing methods and protocols, flue gas samples were extracted isokinetically at two pilot plant stream locations:

- Inlet to the PCC absorber column
- Outlet from the PCC absorber column

The flue gas flow rate, temperature profile, and pressure were measured at multiple traverse points as part of isokinetic sampling for each of these locations. Each stream was analyzed for SO_2 and SO_3 concentrations, for HAPs metals and for mercury, depending on the type of test being conducted. The flue gas composition of O_2, CO_2, NO_x and total hydrocarbons (THC) was measured continuously during each testing period.

Roles and Responsibilities of Each Organization

The roles and responsibilities of the various organizations associated with the EPRI testing the Linde/BASF pilot plant at the NCCC include:

- **NCCC** (http://www.nationalcarboncapturecenter.com/), which was the host for the project and provided space, flue gas, energy, and utilities to the Linde-BASF system. NCCC is located beside Alabama Power's E.C. Gaston power plant in Wilsonville, AL. In addition, the NCCC provided significant support for operations throughout the project. NCCC is sponsored by the US Department of Energy with a mission to accelerate the development of cost-effective CO_2 capture technologies.
- **Southern Company Services (SCS)** (http://www.southerncompany.com/), which is a division of Southern Company. SCS assisted with the coordination of site activities and training needed for site access as the NCCC testing facilities are located on part of the SCS site. SCS manages the NCCC.
- **The Linde Group** (http://www.linde.com/), which is a world-leading gases and engineering company. The Linde Group was the prime contractor to DOE on this project and was responsible for program management as well as process design, EPC, and operations for the pilot.
- **BASF** (http://www.basf.com/), which is a chemical developer and global supplier of chemicals. BASF developed, manufactured, and supplied the OASE® blue solvent technology used in the CO_2 capture pilot plant.
- **EPRI** (www.epri.com). EPRI was responsible for arranging and managing the performance test contractors (CB&I and TriTech), developing the test plan to perform independent performance testing, and documenting the results in this report. EPRI are also funding partners of the NCCC.
- **CB&I** (www.cbi.com), which was the principal contractor in charge of performing the on-site testing program of the Linde-BASF system.
- **TriTech Energy Research, LLC**, which is a consulting company that assisted in the development of the test plan, the on-site measurement program, and the analysis of the resulting measurements.

Report Structure

Following this Introduction, Section 2 presents key project events. Section 3 then gives an overall description of the Linde-BASF process and its associated equipment. Section 4 outlines the approach to testing undertaken by EPRI and its contractors. Section 5 describes how the testing was conducted and presents the campaign test results.

The appendices provide details on the Sampling and Analysis plan used, process performance calculations, detailed data reports for the test periods, data tables in SI units, and the CBI testing report. The following is a summary:

Appendix A. CB&I Sampling and Analysis Procedures

Appendix B. Supporting Calculations

Appendix C. Test Period Data Reports

Appendix D. Tables in SI Units

Appendix E. CB&I Test Report

2

PROJECT CHRONOLOGY

Linde-BASF Carbon Capture Pilot Plant Project Goals and Objectives

Key Project Events

Construction

The Linde-BASF project began with DOE award FE-0007453 in 2011 with a total project value of $22.7m. The project objectives were to design and build the pilot plant; conduct parametric testing to confirm that the pilot plant meets the performance targets and to obtain appropriate design information; perform a detailed data analysis to assess and develop the design basis for scale-up; and operate the pilot plant continuously under stable conditions to confirm the solvent stability and key material compatibility. The long-term test results will be used to update a techno-economic analysis for a 550 MWe coal-fired power plant incorporating the novel amine-based post-combustion CO_2 capture technology and confirm that it can meet the Department of Energy's carbon capture performance goals. Construction of the system modules commenced in July 2013 with field construction following in January 2014 at the NCCC Pilot Bay 2. Mechanical completion was achieved in July 2014.

Start-up

The process commissioning proceeded immediately after mechanical completion in July 2014, with the plant considered to be fully operational by August 2014. The plant was handed over to the site operations team for the commencement of the parametric testing.

Operations

The system has conducted two main phases of testing. The first phase was for parametric testing that began in January 2015 and continued throughout the entire year according to the NCCC PC4 operating schedule. Despite gaps in operations, the site achieved 2589 operating hours during the parametric testing phase. The second phase began in 2016 for long-term duration testing, starting in mid-May 2016 through the end of July 2016. EPRI testing was conducted in June 2016, near the midpoint of the long term testing phase, by which time the plant had achieved a further 560 hours of testing.

Decommissioning

Following the completion of the long term testing, the plant decommissioning phase was initiated to make the Pilot Bay 2 space available for future pilot testing activities. The plant was decommissioned between August 2016 and October 2016.

3

LINDE-BASF PILOT PLANT EQUIPMENT AND PROCESS DESCRIPTION

Process Overview

Carbon Capture Pilot Plant

The Linde-BASF carbon capture pilot plant project at the National Carbon Capture Center (NCCC) utilizes a 1 MWe equivalent slipstream from Alabama Power's E.C. Gaston Electric Generating Plant Unit 5 - an 880 MWe baseload pulverized coal-fired plant that burns a high sulfur bituminous coal. The host plant is equipped with a hot electrostatic precipitator (ESP) for initial dust removal, a selective catalytic reduction (SCR) unit for nitrogen oxide abatement, a baghouse for fine dust removal, and a Chiyoda flue gas desulfurization scrubber. The slipstream to the pilot plant is from a take-off downstream of the scrubber.

As part of the NCCC, the slipstream passes through a sulfur dioxide (SO_2) polishing scrubber and a booster fan before entering the carbon capture pilot plant. The treated flue gas exits the polishing scrubber with less than 1 ppmv SO_2, and enters the pilot plant (downstream of the booster fan) at a temperature around 155°F (68.3°C).

Situated at the NCCC Pilot Bay 2 location, the Linde-BASF carbon capture pilot plant is a Linde post combustion capture design that utilizes BASF's OASE® blue solvent technology. The design of the pilot plant consists of the following unit operations. The flue gas enters via a flue gas cooler (plate and frame design) which is used to control the incoming flue gas to a controlled temperature. The flue gas then enters an absorber tower that integrates CO_2 absorber sections and downstream water wash sections into a single column. The column also includes a novel 'gravity flow' interstage solvent cooler between the absorption sections. The emergent ‘depleted’ flue gas from the top of the tower is directed down to a booster fan that is strategically located downstream of the absorber column after the CO_2 in the flue gas has been removed. Use of the booster fan downstream of the absorber reduces the depleted gas volumetric flow because of the decreased CO_2 flow relative to the flue gas supply, and therefore reduces fan capacity and size requirements. The stripper column operates at a higher pressure than conventional monoethanolamine (MEA) systems, which reduces the downstream CO_2 compression requirement for sequestration and/or utilization and significantly lowers capital and operating costs for the PCC plant integrated with a power generation plant. A schematic of the Linde-BASF pilot plant is shown in Figure 3-1.

NCCC PSTU Pre-Scrubber

The NCCC Pilot Solvent Test Unit (PSTU) is capable of testing post combustion capture solvents at a 10 ton/day CO_2 capture quantity at 90% capture rate (based on MEA solvent).

Located next to the Linde-BASF facility, the PSTU was not employed for the Linde-BASF testing, however the pre-scrubber and booster fan of the PSTU were utilized to supply conditioned flue gas to the inlet of the Linde-BASF pilot plant. The pre-scrubber used sodium hydroxide to remove any remaining SO_2 in the flue gas that the main plant Chiyoda FGD scrubber did not capture.

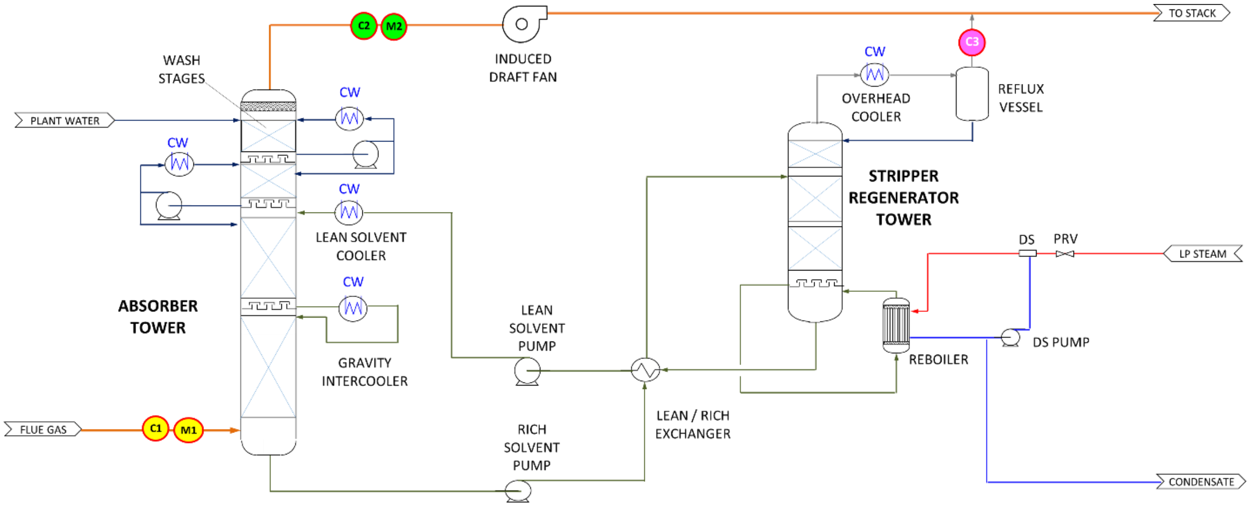


Figure 3-1
Process schematic of Linde-BASF carbon capture pilot plant

Pilot Plant Utilities

Electric Power

The major loads powered directly off the 480-VAC service include the:

- Booster Fan on PSTU Pre-Scrubber
- Booster Fan at Absorber Column Exit
- Rich and Lean Solution Pumps
- Water Wash (one of two in-service during testing) and Reflux Pumps
- Cooling Water Circulation Pump (not included in this design)

The power consumption from the two booster fans is estimated from measurements of the flow rate and pressure increase across the fan. Circulation pumping power is estimated from measured flow rates along with the pressure increase across the pump. Results from test runs are presented in Section 5.

4

PCC TESTING METHODOLOGY

Monitoring Program Description and Purpose

A series of tests were conducted over a four day period to assess the overall carbon capture performance of the Linde-BASF system. All tests were completed with the host Gaston Unit 5 plant operating in AGC (automatic generator control) with an output of either around 900 MW, or at a reduced level of 650 MW. At either load, the flow rate into the carbon capture pilot plant was kept relatively constant. As will be seen in the next section, there were differences in the performance of the carbon capture pilot plant due largely to changes in the flue gas inlet carbon dioxide concentration coming from the host plant.

For all tests, portable equipment was used to measure the temperature and volumetric flow rate on the flue gas inlet and outlet to and from the absorber column. Two continuous emissions monitoring (CEM) trailers were used to measure the flue gas stream for oxygen, carbon dioxide, SO_2, NO_x, and VOC's, at these locations. In addition, a continuous sample of the product CO_2 stream was analyzed with CEM's equipment for the same constituents.

Isokinetic sampling through impinger trains was performed at the absorber inlet and outlet locations to determine the following:

- H_2O concentration
- SO_2 and SO_3 emission levels
- Particulate emissions
- Total and vaporous fractions of HAPs metals and mercury
- Ammonia
- Aldehydes and Ketones

A total of twelve steady-state performance tests were completed during a four day span, with three tests for each of the constituents listed above. The moisture concentration of the flue gas sample was determined for all tests. Particulate and HAPs metals/mercury tests were two hours in duration each (3 total) to assist with achieving detectable levels of the metal species. All other tests were one hour in duration.

For a particular test run, either SO_2/SO_3, or HAPs metals and mercury, or ammonia, or aldehydes/ketones were measured, but not simultaneously since each involve different impinger train solutions and procedures. Also, during each day of testing, a single liquid sample was collected from the blowdown line on the PSTU pre-scrubber. The sample was analyzed for sulfate, sulfite, total solids residue, and HAP metals and mercury.

A summary of the location, parameter (i.e., SO_2/SO_3, HAPs metals, etc.), US EPA sampling and analysis method, and the duration of the tests completed is shown in Table 4-1.

Table 4-1
Summary of gas sampling and analysis plan

Description	Parameter	Sampling and Analysis Method[a]	No. and Duration of Tests
Flue Gas Absorber Inlet and Outlet Locations	Volumetric flow rate and gas composition	U.S. EPA 1, 2,3A, 4	With each test
	NOx	U.S. EPA 7E	Continuous - 24-hour
	SO_2	U.S. EPA Method 6C	Continuous - 24-hour
	THC	U.S EPA Method 25A	Continuous - 24-hour
	SO_2 and SO_3	U.S. EPA 8A	(3) 60-minute tests
	HAPs metals[b]	U.S. EPA 29	(3) 120-minute tests
	Particulate	U.S. EPA 5	(3) 120-minute tests, during HAPs metals
	Ammonia	U.S. EPA CTM 027	(3) 60-minute tests
	Aldehydes/Ketones	SW 846 Method 0011	(3) 60-minute tests
	Moisture	U.S. EPA 4	All Performance Tests (12)
	O_2/CO_2	U.S. EPA 3A[c]	Continuous - 24-hour
Product CO_2	O_2/CO_2	U.S. EPA 3A[c]	Continuous - 24-hour
	NO_x	U.S. EPA 7E	Continuous - 24-hour
	SO_2	U.S. EPA Method 6C	Continuous - 24-hour
	THC	U.S EPA Method 25A	Continuous - 24-hour
	Ammonia	U.S. EPA CTM 027	(3) 60-minute tests

[a] U.S. EPA Methods from 40 CFR 60 Appendix A; Method 8A (SO_3) from NCASI.

[b] HAPs metals: antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, and selenium.

[c] CO_2 CEMs using 0 to 100% scale; Oxygen CEM AMI Model 1000RS-T2 with 0- to 50 ppm range.

Flue Gas Temperature and Velocity Measurements

Flue gas temperature and velocity measurements were completed across multi-point traverse grids on the 10 inch (25.4 cm) duct leading into the absorber column, and on the 14 inch (35.6 cm) diameter duct at the outlet of the absorber column. A combined pitot tube and thermocouple assembly was used to traverse these ducts. A total of twelve sample points were completed in the horizontal plane at each test at these two locations; six points moving into the duct and 6 points moving back out of the duct. The traversing ports are installed in locations with sufficient upstream and downstream clearance to conform to U.S. Environmental Protection Agency (EPA) sampling requirements for flow measurement via pitot-tube traverses. Figure 4-1 also shows the locations of these two sample locations, along with the CEM's measurement point on the product CO_2 stream, and the location of the liquid sample on the PSTU blowdown line (red circles).

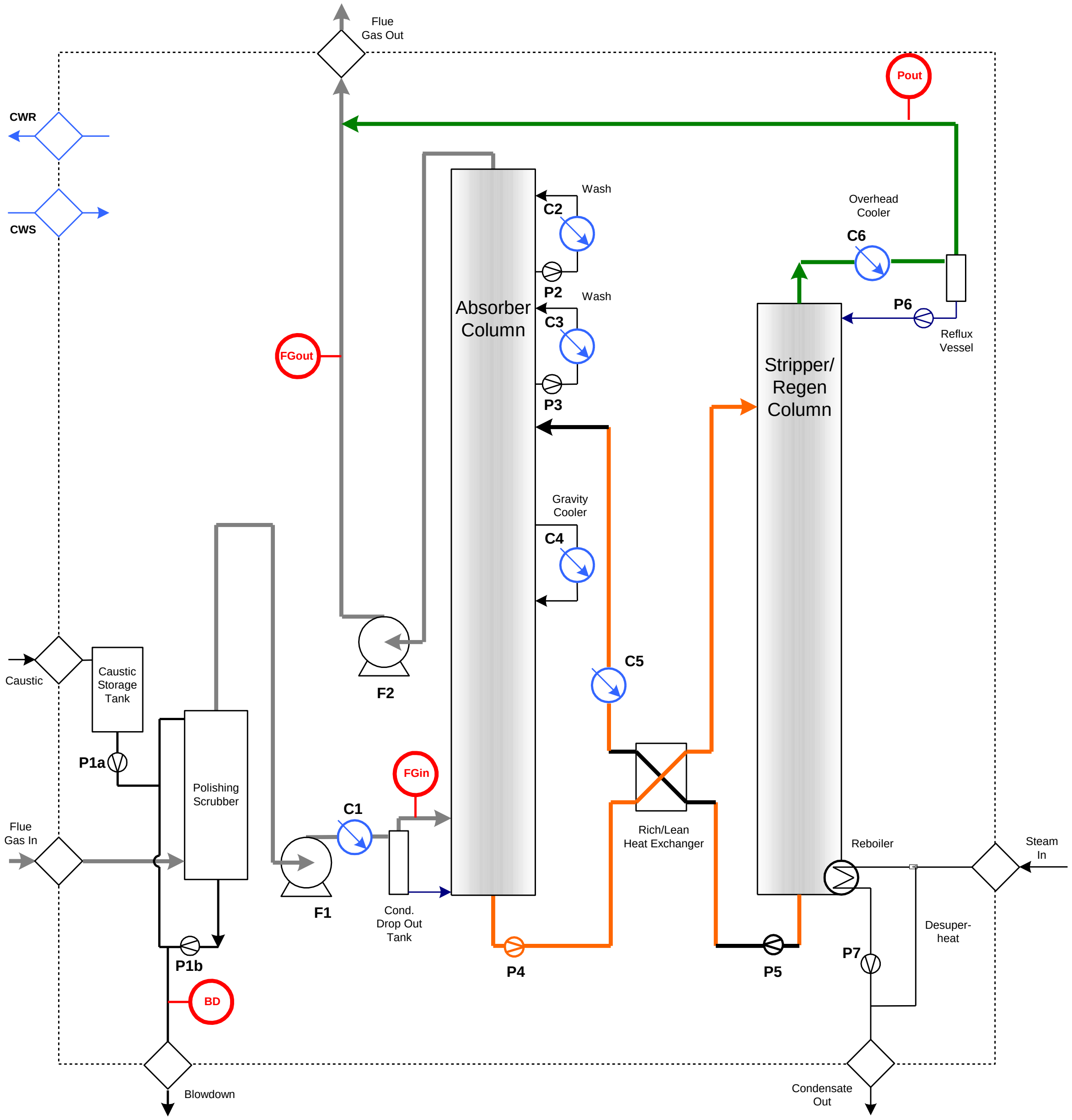


Figure 4-1
Linde-BASF PCC pilot plant – sample and measurement point locations

Flue Gas Sampling Locations and Procedures

The flue gas inlet to the absorber column consists of a circular fiberglass reinforced duct that is 12 inches (30.48 cm) internal diameter. The sample point for flue gas composition analysis by CB&I connected to a 12-inch section of the flue gas inlet pipe (shown in Figure 4-5), and the sample point for flue gas flowrate measurement was connected to a 10-inch section (shown in Figure 4-4). The outlet from the absorber column is a circular duct approximately 14 inches internal diameter. The bulk composition (O_2 and CO_2) of the flue gas inlet and outlet streams was measured continuously on these ducts via a fixed point sample probe situated on the centerline of each duct. NO_x, SO_2 and VOC emissions were also measured at these locations.

For VOC's, the flue gas sample passes through a long heat-traced sample line directly to the analyzer located in the CEMS trailer located on the ground floor. The remainder passes through a chiller located near the sample point for removal of moisture prior to being pumped through a heat-traced line to the analyzers. For all testing, the SO_2 and VOC concentrations at the absorber inlet and outlet locations were below the minimum detection limit of the analyzer. The CEM's trailers used during the testing are shown in Figure 4-2 and 4-3.

Figure 4-2
CB&I continuous monitoring trailer

Figure 4-3
CB&I continuous monitoring trailers and sample preparation truck

A 12 point sample grid (six points into the duct and 6 out of the duct) was used at the absorber inlet and outlet duct locations for H_2O and particulate/HAPs metals, SO_2/SO_3, ammonia and aldehyde/ketone measurements. Measurements were completed at port locations upstream of the CEM's sample port, and traversing was completed on the horizontal axis only.

Testing for SO_2/SO_3, particulate/HAPs metals, ammonia and aldehydes/ketones involved the use of impinger trains that followed U.S. EPA Methods 8/8A, 5/29, CTM 027, and SW846 Method 0011, respectively. Photographs of the sample locations are shown in Figures 4-3 through 4-7. A more detailed Sampling and Analysis Plan for the monitoring is presented in Appendix A.

Figure 4-4
Location of flue gas sampling point at the inlet to the absorber column

Figure 4-5
Location of CEM's flue gas sampling point at inlet to absorber column

Figure 4-6
Location of CEM's flue gas sample point at outlet from absorber column

Figure 4-7
Location of CEM's sample point on product CO_2 line

Liquid Sampling Locations and Methodology

The PSTU blowdown system was not in-use during any portion of the twelve performance tests that were conducted, thus no contemporaneous ‘blowdown’ sample could be collected during the testing periods. Liquid samples from the PSTU pre-scrubber blowdown line were therefore collected on a one-time basis during each day of testing. Each sample was analyzed for sulfate and sulfite, total solid residue, and HAPs metals and mercury.

Continuous Process Data

Continuous one-minute operating data pertaining to the PSTU pre-scrubber, including inlet and outlet flue gas information, were supplied by NCCC for the time periods associated with the twelve performance tests. Linde Group provided one-minute operating data related to the carbon capture pilot plant. This included flows, temperatures, and pressures on the inlet and outlet flue gas streams and on the cooling streams, CEM's data, and steam pressures, temperatures and flow rates. Auxiliary power use was determined from flow rates and manual measurements of the pressure rise across pumps. Calculations are detailed in Appendix B.

5

PERFORMANCE TEST OVERVIEW AND RESULTS

Summary

A total of twelve steady-state performance tests were completed over three days from June 16 to June 18, 2016. For the first two days of testing, the host plant was operating at baseload of approximately 880 MWe. For the last day of testing on Saturday, June 18, 2016, the host plant operated at a reduced output of 650 MWe. This is illustrated in Figure 5-1, which also shows the approximate times of each of the twelve steady-state tests that were completed. Two performance tests were completed on June 16, followed by four on June 17, and six on June 18.

The O_2 and CO_2 concentrations of the flue gas slipstream from the host plant into the carbon capture pilot plant also varied with the host plant capacity. This can be seen in Figure 5-2 for oxygen, and Figure 5-3 for carbon dioxide. However, for each steady-state performance test, the capacity of the host plant was relatively constant during the test period, as was the flow rate of flue gas into the carbon capture plant, as can be seen in Figure 5-4.

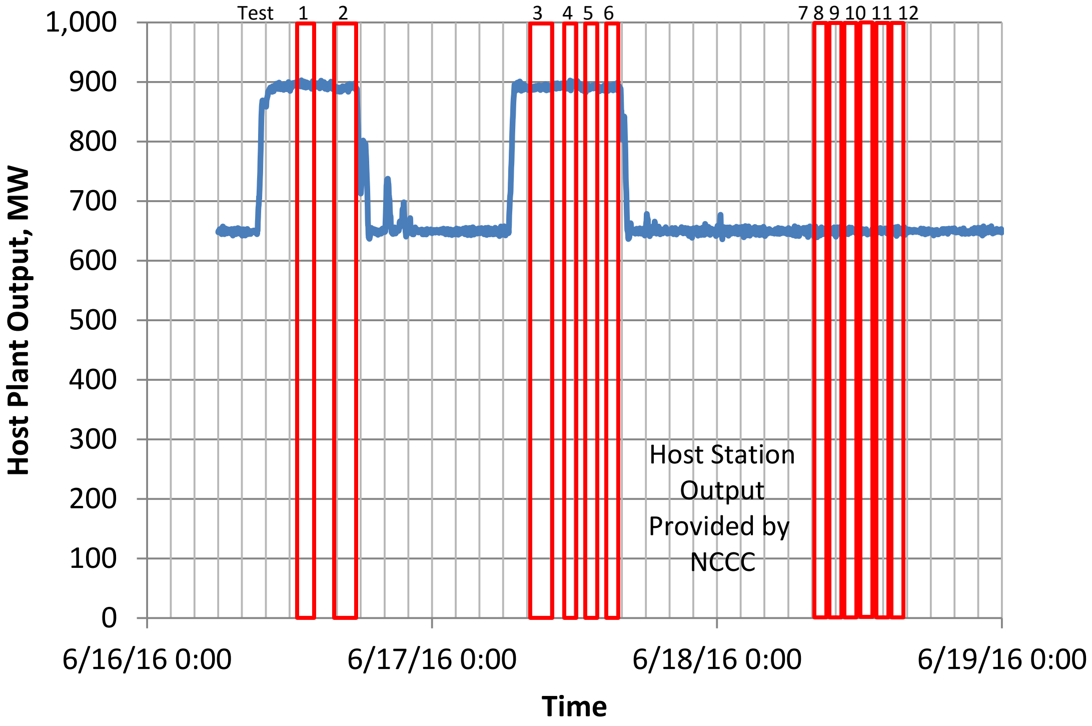


Figure 5-1
Host station capacity during the testing periods

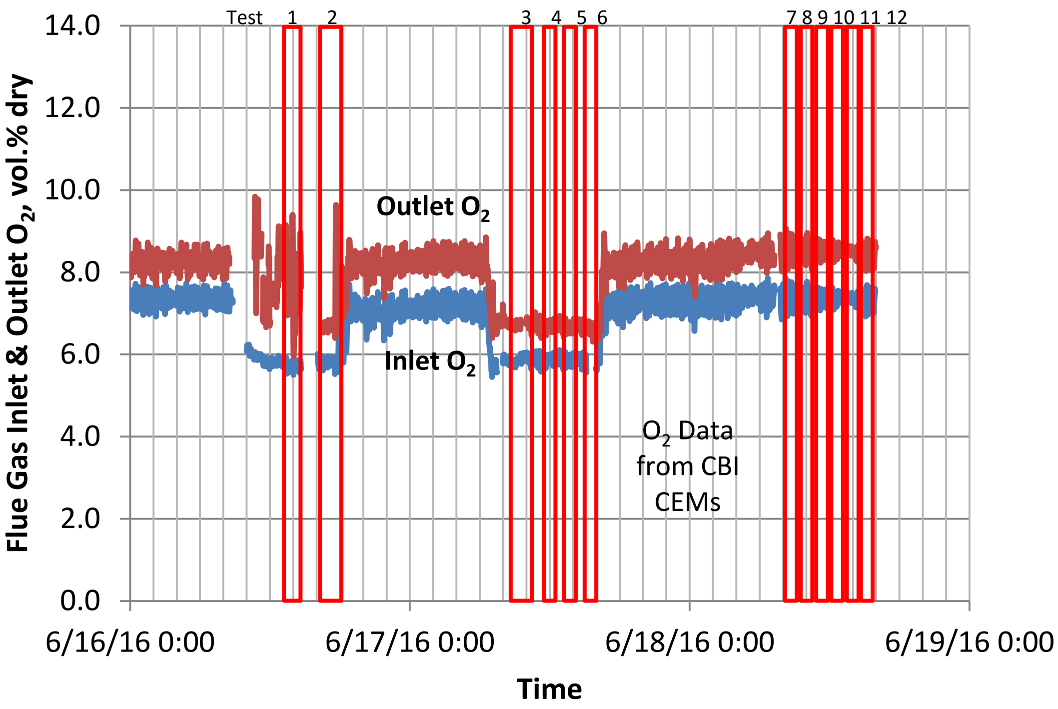


Figure 5-2
Flue gas inlet and outlet oxygen concentration during the testing periods

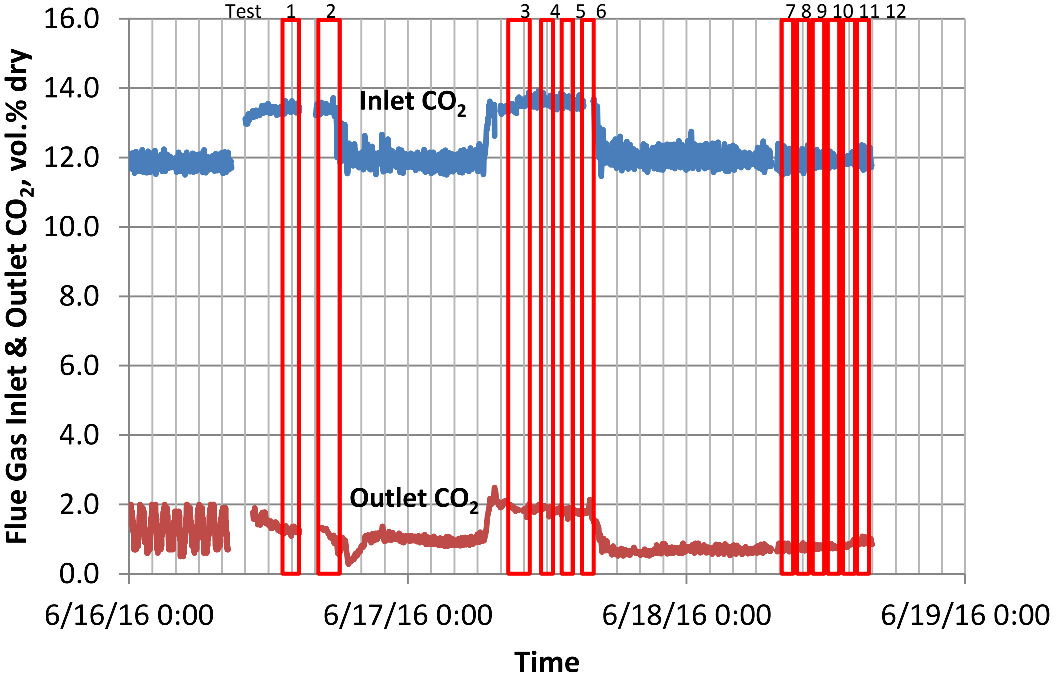


Figure 5-3
Flue gas inlet and outlet carbon dioxide concentration during the testing periods

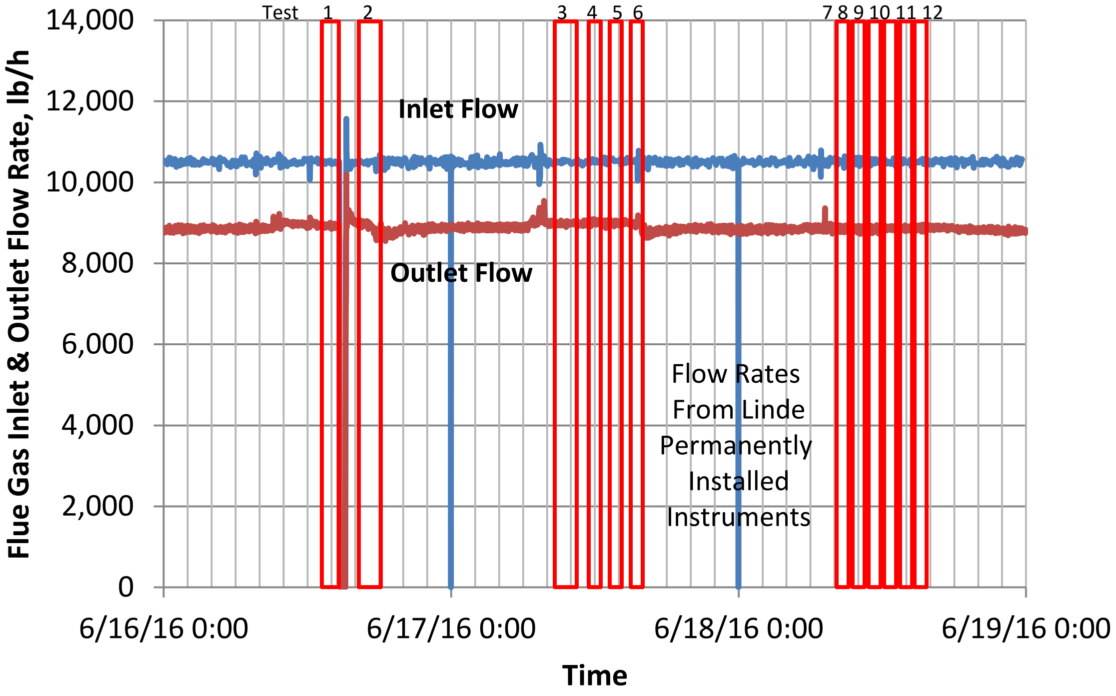


Figure 5-4
Flue gas inlet and outlet mass flow rates during the testing periods

The host station fired a high sulfur bituminous coal during the test week. Throughout the testing, the equivalent of a 1 MWe slipstream exits the duct work downstream of the scrubber and then enters the PSTU pre-scrubber situated adjacent to the carbon capture pilot plant. The 1 MWe slipstream represents between 10,000 and 12,000 lb/h of wet flue gas flow into the PSTU pre-scrubber.

Conditioned flue gas enters the CO_2 capture pilot plant at the battery limit with NCCC in a 14-inch internal diameter fiber glass reinforced plastic duct. It then flows through a plate and frame cooler, which lowers the temperature by approximately 35°F- 40°F to ~ 95°F indirectly using cooling water. Condensate generated from the flue gas cooling is removed from the flue gas stream and routed to the sump beneath the pilot skid. Following the cooler unit, the flue gas enters the lower portion of the absorber column. Gas sampling for each test was completed on the 12-inch diameter duct leading into the absorber column, and on the 14-inch diameter duct on the outlet of the absorber column. The captured CO_2 that exits the overhead cooler reflux drum at the outlet of the stripper column is also sampled.

The twelve tests that were completed as part of this campaign have been numbered 1 through 12 with an additional designation that identifies whether the test was a particulate/HAPs metals test, an SO_2/SO_3 test, an ammonia (NH_3) test, or an aldehyde(s) test. For example, the first particulate/HAPs metals test is identified as 'Test 1, PM-1'. For SO_2/SO_3, the fourth performance test completed in the sequence of twelve tests was the first SO_2/SO_3 test, and is identified as 'Test 4, SO3-1'. The seventh performance test was the first NH_3 test, and is designated as 'Test 7, NH3-1'. The tenth performance test was the first aldehyde(s) test, and is designated as 'Test 10, ALDH-1'. The last performance test was also the last aldehyde test, and is designated at 'Test 12, ALDH-3'.

Initially, all particulate/HAPs metals tests were planned for two hour durations in order to collect a sufficient sample size. All tests for gaseous constituents, i.e., SO_2/SO_3, ammonia, and aldehydes, were one hour duration. However, there were three anomalies that occurred during the test sequence. First, for Test 1, PM-1, the performance test was aborted after 78 minutes due to a sudden pressure spike at the absorber inlet. This was caused by a trip on the PSTU (pilot solvent test unit), which is situated on the flue gas slipstream leading into the carbon capture plant. This caused problems with the impinger train at this location and loss of representative particulate and moisture data. Second, for Test 2, a lightning storm moved into the area during the latter portion of the test period that required test personnel to leave the sample stations and seek shelter. As a result, the traversing sample probe remained in a fixed position for several of the sample points, the full two hour test was however completed. Third, for Test 4, SO3-1, the flue gas inlet sample pump failed at the 14 minute mark (target was 60 minutes) and the test was suspended. Following sample pump replacement, the test resumed for the remaining duration and was successfully completed.

For all performance tests, the inlet flue gas flow rate was held relatively uniform, with a high of 12,082 lb/h (wet), a low of 11,645 lb/h (wet), and an average for all 12 tests of 11,930 lb/h (wet). For each test, Linde personnel set steam flows and other process variables so as to optimize unit performance. EPRI's goal was to complete sampling on the flue gas inlet and outlet streams, and the product CO_2 stream, in order to calculate the CO_2 capture performance, measure the trace amounts of SO_2/SO_3, particulate, HAPs metals and mercury, ammonia, and aldehydes/ketones entering and leaving the process. In addition, data were collected to estimate auxiliary power consumption, steam energy usage, and cooling water requirements at test conditions.

Results from the 12 steady-state performance tests are presented below. Final summary sheet print-outs for each test are included in Appendix C. The metric values of all tables presented in this section are included in Appendix D. The raw data collected by CB&I are presented in Appendix E.

Overview of Operations

Performance testing of the Linde-BASF carbon capture pilot plant was conducted during the week of June 15-18, 2016. The first day was used by CB&I for equipment set-up, calibration and initial flow checks. The following is a summary of these four days of testing in chronological order, all times quoted are on the local time zone basis, central daylight time (CDT).

<u>June 15, 2016</u>

Gaston Unit 5 was brought back online in the afternoon of the previous day following a unit trip and achieved 680MWe prior to 19:00 that evening. Its operations were stable overnight and output was increased to maximum continuous output (MCR ~880MWe) at 09:00 without incident. The Linde-BASF carbon capture pilot plant was started at 06:00 (steam), with flue gas admission at 09:00. Since the unit takes at least 12 hours to reach stable operation, performance testing was delayed until the following day (June 16). CB&I therefore used this day to set up their equipment and carried out limited CEMS measurements, starting at 17:00.

During this set up process, it was discovered that the standoff spool-pieces on the absorber inlet and outlet duct are too long for the CB&I probes to traverse the duct cross-section. CB&I subsequently ordered new longer probes (8 ft. length) which were delivered early in the morning on June 16 so that the planned HAPs/PM tests (3 x 2 hour) tests could be completed.

Also, one of the CB&I CEMS NOx analyzers had blown fuses repeatedly (absorber outlet unit) – leaving two working analyzers. The plan was to monitor the CO_2 product for a half day (to verify that NOx is at trace levels in the CO_2 product) before moving it over to the absorber inlet.

June 16, 2016

The new, longer probes were onsite by 10:00 but there was considerable preparation work needed before the first PM/HAPs test could begin (i.e. flow checks, probe position markers etc.). CB&I started the first PM/HAPs test at 13:25. On the 10” and 14” ducts, CB&I sample at 6 discrete points (one traverse in and one traverse out for 12 total sample points) iso-kinetically in 10 minute intervals. The testing was proceeding without incident until, at 1 hour and 17 minutes into the planned 2 hour test, power to the PSTU was interrupted, thereby causing a shutdown of the PSTU gas blower and effectively starved the Linde-BASF plant of flue gas.

The Linde-BASF plant needed 2 hours to come back to stability. Subsequently, CB&I proceeded with the 2nd PM/HAPs test at 16:59. As before, everything was proceeding as planned until an intense thunderstorm rolled into the area around 17:30. CB&I personnel had to leave the sampling probes in place due to lightning risk. The probes therefore spent 30 minutes at a single point (close to centerline, point 4) before being traversed further (skipping points 5 and 6 on the way in). The remainder of the run was completed at 18:59 as scheduled (full 2 hours, but with an asterisk on the sampling locations as this can impact the representative nature of the sample).

For the next test day, the plan was to complete the 3rd PM/HAPs sample and three SO_2/SO_3 samples (1 hour duration), and complete the three ammonia and three aldehydes (1 hour duration each) on the following day (Saturday).

June 17, 2016

The third and final PM/HAPs test was started at 08:32 and concluded it at 10:32 without incident. During that test, pressure readings were collected from permanent and temporary gauges on the inlet and outlet of system pumps to allow an assessment to be made of the electrical power consumption of the process. There was no digital monitoring of pump or fan power, or overall system auxiliary power.

Following the completion of the last PM/HAPs test, CB&I switched over to SO_2/SO_3 extractive sampling, which use the same 6 traverse points but only with a total 1 hour duration (i.e. 5 minutes per point). The first test started at 11:32 and was interrupted due to failure of the sample gas extraction pump at 11:46. The test was suspended and CB&I swapped over to a spare pump, following which the test proceeded for an additional 23 minutes with the completion of the test at 12:55. The failure was thought to be heat related, as the surrounding air temperatures approached 95°F. The second SO_2/SO_3 test was started at 13:15 and ended at 14:15, and the third test was started at 14:29 and ended at 15:29. There were no reported issues with the last two tests.

Since CB&I hooked up the CO_2 product trace O_2 monitor (AMI 1000 RS), readings were consistently >2000 ppm. The Linde CEMS trace O_2 unit (which was practically the same module as the CB&I unit) was reading between 20-40ppm during the same testing period. CB&I had trouble with checking the zero gas (N_2, certified <1 ppmv O_2) with readings >1000ppm. Next, an 81 ppmv certified gas bottle was fed directly to the CB&I instrument and the level fell to 117 ppmv, and a direct zero check checked out at 7 ppmv. Hence, there was a problem with the sampling line on a negative gauge pressure system where even a tiny leakage rate results in high O_2 readings. CB&I then moved the sample point to a higher pressure source (33 psig), and the readings after this change were around 51 ppmv, which was a close match to the Linde number of 50 ppmv at the time. A span check with the Linde unit checked out well at 73 ppmv versus 81 ppmv span gas.

Again, thunderstorms and lightning moved into the area at 16:00 and testing was terminated for the day. The plan for the next test day was to conclude the testing with six 1 hour tests (3 ammonia tests and 3 tests aldehyde).

June 18, 2016

Unit 5 was operating at 650MWe gross (and not 880MWe gross) as the result of cooler weather and Saturday operation. The reduced load results in a lower inlet CO_2 concentration (11.8 vol.% dry vs. 13.2 vol.% dry) and capture rates averaging over 90%. The extractive sample times for the tests completed are shown below. There were no incidents to report during this testing

1st Ammonia	08:05 - 09:05
2nd Ammonia	09:18 - 10:18
3rd Ammonia	10:28 - 11:28
1st Aldehyde/Ketone	12:03 - 13:03
2nd Aldehyde/Ketone	13:26 - 14:26
3rd Aldehyde/Ketone	14:48 - 15:48

Throughout the testing, the CB&I product oxygen was initially 30ppmv, dropping to nearer 20 ppmv at the end. Linde measurements were around 15 ppmv. The Linde span gas (81 ppmv) was used to check the CB&I instrument at the end of the test day, and gave a reading of 40 ppmv. The CB&I instrument zeroed out at 9 ppmv.

The CB&I test report is included in Appendix E along with data summaries for the test periods.

Flue Gas Supply Conditions

Summaries of the flue gas inlet conditions to the absorber column are included in Tables 5-1 and 5-2. Table 5-1 shows the start and stop times for each test, the volumetric flow measured by CB&I on the absorber inlet duct, the temperature and pressure at this location, and the converted mass flow rate. The difference between the highest inlet flow rate (Test 10, ALDH-1) and the lowest flow rate (Test 11, ALDH-2) was only 437 lb/h, or 3.6%. Because the sample point location is downstream of the inlet cooler, the flue gas temperature was nearly constant, varying between 93°F and 95°F. The flue gas temperature at the inlet to the polishing scrubber was measured and recorded by NCCC, and varied between approximately 130°F to 135°F.

Table 5-2 summarizes the inlet flue gas composition for each of the twelve steady-state performance tests. The bulk gas composition (O_2 and CO_2) is based on measurements with portable CEM equipment in the straight section of duct at the inlet to the absorber column. The difference in the average O_2 and CO_2 values for the first six tests compared to the last six tests is apparent in Table 5-2, and results from capacity change on the host station. Also included with the CEM's measurements are the average SO_2, NO_x and THC (total hydrocarbon) emissions at this location. Both SO_2 and THC readings were below the detection limit of the analyzer for all tests. SO_2 measurements were also completed as part of SO_3 sampling during Tests 4 through 6 using impinger trains. Values were consistent at 0.5 ppmv dry for all three tests.

Table 5-1
Summary of flue gas inlet conditions for 12 performance tests

	Date	Start Time	End Time	Flow acfm	Flow lb/h	Temp. °F	Pressure psig
Test 1, PM-1	6/16/2016	13:25	14:43	2,649	11,955	94.0	0.46
Test 2, PM-2	6/16/2016	16:59	18:59	2,670	12,007	93.0	0.43
Test 3, PM-3	6/17/2016	8:32	10:32	2,674	12,044	94.0	0.45
Test 4, SO3-1	6/17/2016	11:32	12:54	2,653	11,947	95.0	0.45
Test 5, SO3-2	6/17/2016	13:15	14:15	2,653	11,953	94.0	0.45
Test 6, SO3-3	6/17/2016	14:29	15:29	2,644	11,891	94.0	0.44
Test 7, NH3-1	6/18/2016	8:05	9:05	2,621	11,832	93.0	0.51
Test 8, NH3-2	6/18/2016	9:18	10:18	2,592	11,718	94.0	0.51
Test 9, NH3-3	6/18/2016	10:28	11:28	2,664	12,063	93.0	0.51
Test 10, ALDH-1	6/18/2016	12:03	13:03	2,661	12,082	93.0	0.52
Test 11, ALDH-2	6/18/2016	13:26	14:26	2,567	11,645	93.0	0.52
Test 12, ALDH-3	6/18/2016	14:48	15:48	2,646	12,013	93.0	0.52

Table 5-2
Summary of flue gas inlet composition for 12 performance tests

	Date	O_2 vol.% dry	CO_2 vol.% dry	SO_2[3] ppmv, dry	NO_x ppmv, dry	THC[4] ppmv dry	H_2O [2] vol.%
Test 1, PM-1	6/16/2016	5.7	13.4	<1	33.3	<2	5.3
Test 2, PM-2	6/16/2016	6.3	12.8	<1	39.5	<2	5.1
Test 3, PM-3	6/17/2016	5.9	13.5	<1	38.1	<2	5.3
Test 4, SO3-1	6/17/2016	5.9	13.6	0.5 [1]	38.3	<2	5.4
Test 5, SO3-2	6/17/2016	5.9	13.6	0.5 [1]	39.7	<2	5.3
Test 6, SO3-3	6/17/2016	5.9	13.6	0.5 [1]	39.5	<2	5.3
Test 7, NH3-1	6/18/2016	7.3	11.9	<1	38.9	<2	5.1
Test 8, NH3-2	6/18/2016	7.4	11.9	<1	37.6	<2	5.2
Test 9, NH3-3	6/18/2016	7.4	11.9	<1	39.1	<2	5.1
Test 10, ALDH-1	6/18/2016	7.4	11.9	<1	38.4	<2	5.1
Test 11, ALDH-2	6/18/2016	7.4	11.9	<1	36.4	<2	5.1
Test 12, ALDH-3	6/18/2016	7.3	12.0	<1	37.0	<2	5.1

1. SO_2 Values from Impinger Train Measurements
2. Calculated Based on Saturated Flue Gas Inlet Conditions
3. Low Detection Limit for CEMs SO_2 is 2% of scale
4. Low Detection Limit for CEMs THC is 2% of scale

CO_2 Removal Efficiency/Recovery

CO_2 capture performance of the Linde-BASF carbon capture pilot plant is defined by these measured mass flows:

- **CO_2 Entering in the Flue Gas Supply (S) –** determined by bulk composition of the flue gas supply (oxygen, CO_2, H_2O, and nitrogen by difference) and the volumetric flow measured by traverse
- **CO_2 Leaving in the Depleted Flue Gas (D) –** determined by bulk composition of the depleted flue gas (oxygen, CO_2, H_2O, and nitrogen by difference) and the volumetric flow measured by traverse
- **CO_2 in the Product Leaving the Carbon Capture Plant (P) –** determined by Linde-BASF instrumentation located at the outlet of the reflux vessel on the stripper column overhead cooler.

The CO_2 capture efficiency can be quantified in four ways and the recovery in two ways, as indicated in **Error! Reference source not found.**, using the massflow data (S, D and P) determined above.

Table 5-3
CO_2 capture rate and recovery methodologies

Term	Description	Formula
CO_2 Capture Efficiency: Method 1	CO_2 product flow as a ratio to the CO_2 flow in the flue gas supply	$=\frac{P}{S}$
CO_2 Capture Efficiency: Method 2	CO_2 product flow as a ratio to the sum of the CO_2 product flow and the CO_2 flow in the depleted flue gas	$=\frac{P}{P+D}$
CO_2 Capture Efficiency: Method 3	Ratio of the difference between the CO_2 flow in the flue gas supply and the CO_2 in the depleted flue gas to the CO_2 flow in the flue gas supply	$=\frac{S-D}{S}$
CO_2 Capture Efficiency: Method 4	100% less the ratio of the depleted flue gas CO_2 per unit O_2+N_2 to the flue gas supply CO_2 per unit O_2+N_2 (all calculated on a dry basis)	$=1-\frac{O_{CO_c}}{(1-O_{CO_2})}\frac{(1-I_{CO_2})}{I_{CO_2}}$ O_{CO2} = Depleted flue gas CO_2 v/v I_{CO2} = Flue gas supply CO_2, v/v
CO_2 Recovery: Method 1	Ratio of the sum of the CO_2 flow in depleted flue gas and the product CO_2 flow divided by the CO_2 flow in the flue gas supply	$=\frac{P+D}{S}$
CO_2 Recovery: Method 2	Ratio of CO_2 released from the process divided by the CO_2 absorbed by the process	$=\frac{P}{S-D}$

The CO_2 recovery rate is a measure of three factors: the accuracy of the respective CO_2 mass flow determinations, the degree to which CO_2 leaks to atmosphere inside the carbon capture pilot plant control volume, and the degree to which CO_2 is stored in or released from the solvent inventory during the test period (note that no sampling is undertaken during the test campaigns to assess the CO_2 content of the solvent).

The flue gas supply (in) and depleted flue gas (out) CO_2 concentrations from the continuous emission monitors (CEMs) are displayed in Figure 5-3 and a summary of average flue gas inlet and outlet values collected by CB&I during each of the 12 performance tests is shown in Figure 5-4. These values are averaged over the test period, as shown in Table 5-4, and are used to determine the flue gas input and output CO_2 mass flows. The CO_2 inlet concentration varied with the output capacity of the host boiler, which was at a lower load during tests 7-12. For all twelve test runs, the CO_2 concentration in the depleted flue gas stream varied between 0.7 and 1.9 vol.% dry.

Table 5-4
Summary of average flue gas inlet and outlet data collected by CB&I

	Flue Gas Inlet				**Flue Gas Outlet**			
	acfm	**°F**	**psig**	**CO_2 vol.% dry**	**acfm**	**°F**	**psig**	**CO_2 vol.% dry**
Test 1, PM-1	2,649	94.0	0.4620	13.4	2,576	102.0	0.1191	1.3
Test 2, PM-2	2,670	93.0	0.4295	12.8	2,643	105.0	0.0974	0.9
Test 3, PM-3	2,674	94.0	0.4475	13.5	2,467	106.0	0.1371	1.9
Test 4, SO3-1	2,653	95.0	0.4475	13.6	2,414	104.0	0.1191	1.9
Test 5, SO3-2	2,653	94.0	0.4475	13.6	2,484	103.0	0.1119	1.8
Test 6, SO3-3	2,644	94.0	0.4367	13.6	2,605	103.0	0.1083	1.8
Test 7, NH3-1	2,621	93.0	0.5053	11.9	2,472	101.0	0.1732	0.8
Test 8, NH3-2	2,592	94.0	0.5053	11.9	2,377	101.0	0.1877	0.7
Test 9, NH3-3	2,664	93.0	0.5089	11.9	2,449	100.0	0.1877	0.8
Test 10, ALDH-1	2,661	93.0	0.5233	11.9	2,422	102.0	0.1913	0.8
Test 11, ALDH-2	2,567	93.0	0.5197	11.9	2,430	101.0	0.1949	0.9
Test 12, ALDH-3	2,646	93.0	0.5233	12.0	2,398	101.0	0.2057	1.0

Table 5-5 summarizes the CO_2 flows for each of the twelve steady-state performance tests and Table 5-6 shows the calculated capture values, using the methods detailed in **Error! Reference source not found.** . Using the gas side measurements (Method 3) the values ranged from 87.7% to a high of 94.2%. Overall, higher capture rates were achieved during tests with a lower inlet flue gas CO_2 concentration, i.e., during the last six tests where the capacity of the host station was reduced from 880 MWe to around 650 MWe. For the tests with the host station at full capacity, the CO_2 inlet averaged 13.4 vol.% dry, and for the reduced load tests, the average was 11.9 vol.% dry. The results can be seen graphically in Figure 5-5 which shows the percentage CO_2 capture versus the inlet flue gas CO_2 concentration. However, there were other operating variables influencing the capture performance, including the regenerator steam flow.

The last two columns of Table 5-6 also list a value called the CO_2 recovery. The classic determination of this performance indicator is the percentage of CO_2 measured with Linde instrumentation at the outlet of the stripper overhead cooler reflux vessel plus the mass flow rate of CO_2 in the depleted flue gas stream measured by CB&I divided by the mass flow rate of CO_2 in the flue gas inlet stream measured by CB&I (Method 1 CO_2 Recovery). An alternative method is also presented, comparing the quantity of CO_2 released from the process against the quantity absorbed by the process (Method 2 CO_2 Recovery). Both methods of CO_2 recovery show good agreement, but are consistently around 85%, which is lower than a value of unity needed for complete CO_2 mass balance closure.

It is important to note that the flue gas and depleted gas flowrates measured using Linde's installed equipment are lower than those determined using CB&I's measurement equipment and calculations. CB&I measured the flue gas and depleted gas flowrates in line with EPA standard test methods 1, 2 and 4. However, the discrepancy between CB&I and Linde measured flowrates accounts for the significantly lower CO_2 capture rate shown in Table 5-6 for Method 1 CO_2 captured % as only the Linde in-situ plant measurement was available for CO_2 product flowrate determination. For comparison, Table 5-6 shows the Method 1 CO_2 captured % determination for both the combination of CB&I flue gas measurements and the Linde product gas as well as the determination using only the Linde measurements, to quantify this discrepancy and its impact on overall CO_2 capture rate. Additionally, Table 5-6 shows the Method 2 CO_2 recovery based on both the CB&I flue gas measurements and on only the Linde measurements to demonstrate the closeness to unity of the mass balance when determined using data measured by Linde plant in-situ instrumentation.

Table 5-5
Summary of flue gas capture and recovery flow rates

	Flue Gas Supply Flow Rate lb/h wet	Depleted Flue Gas Flow Rate lb/h wet	Flue Gas Supply CO_2 Flow Rate (S) lb/h	Depleted Flue Gas CO_2 Flow Rate (D) lb/h	Captured CO_2 Flow Rate (S-D) lb/h	Linde Measured CO_2 Product (P) lb/h	Recovered CO_2 Flow Rate (P+D) lb/h
Test 1, PM-1	11,955	10,462	2,247	200	2,047	1,736	1,936
Test 2, PM-2	12,007	10,614	2,163	140	2,023	1,706	1,846
Test 3, PM-3	12,044	9,959	2,278	277	2,001	1,617	1,894
Test 4, SO3-1	11,947	9,767	2,275	272	2,003	1,670	1,942
Test 5, SO3-2	11,953	10,051	2,277	266	2,011	1,671	1,937
Test 6, SO3-3	11,891	10,542	2,263	279	1,984	1,655	1,934
Test 7, NH3-1	11,832	10,119	1,990	120	1,870	1,615	1,735
Test 8, NH3-2	11,718	9,746	1,968	101	1,867	1,613	1,714
Test 9, NH3-3	12,063	10,072	2,026	119	1,907	1,610	1,729
Test 10, ALDH-1	12,082	9,937	2,030	118	1,912	1,615	1,733
Test 11, ALDH-2	11,645	10,010	1,956	133	1,823	1,593	1,726
Test 12, ALDH-3	12,013	9,883	2,034	146	1,888	1,589	1,735

Table 5-6
Summary of flue gas capture and recovery percentages

	S CO_2 Flow Rate (CB&I) lb/h	D CO_2 Flow Rate (CB&I) lb/h	P CO_2 Flow Rate (Linde) lb/h	Method 1 CO_2 Captured		Method 2 CO_2 Captured	Method 3 CO_2 Captured	Method 4 CO_2 Captured	Method 1 CO_2 Recovery	Method 2 CO_2 Recovery	
				% *	% †	% *	%	%	%*	% *	% †
Test 1, PM-1	2,247	200	1,736	77.3	87.8	89.7	91.1	91.5	86.2	84.8	95.6
Test 2, PM-2	2,163	140	1,706	78.9	91.7	92.4	93.5	93.8	85.3	84.3	97.0
Test 3, PM-3	2,278	277	1,617	71.0	86.1	85.4	87.8	87.6	83.1	80.8	98.1
Test 4, SO3-1	2,275	272	1,670	73.4	89.6	86.0	88.0	87.7	85.3	83.4	101.9
Test 5, SO3-2	2,277	266	1,671	73.4	89.9	86.3	88.3	88.4	85.0	83.1	101.9
Test 6, SO3-3	2,263	279	1,655	73.1	89.7	85.6	87.7	88.4	85.4	83.4	101.5
Test 7, NH3-1	1,990	120	1,615	81.2	93.9	93.1	94.0	94.0	87.2	86.4	98.6
Test 8, NH3-2	1,968	101	1,613	82.0	93.5	94.1	94.9	94.8	87.1	86.4	98.1
Test 9, NH3-3	2,026	119	1,610	79.5	93.4	93.1	94.1	94.0	85.3	84.4	98.2
Test 10, ALDH-1	2,030	118	1,615	79.6	94.2	93.2	94.2	94.0	85.4	84.5	99.0
Test 11, ALDH-2	1,956	133	1,593	81.4	90.8	92.3	93.2	93.3	88.3	87.4	95.4
Test 12, ALDH-3	2,034	146	1,589	78.1	93.0	91.6	92.8	92.6	85.3	84.2	98.4

*** Based on CB&I measured CO_2 in flue gas supply and depleted flue gas streams using Linde measured CO_2 product flowrate**

† Based on Linde in-situ plant measurements of flue gas supply, depleted flue gas and CO_2 product flowrate

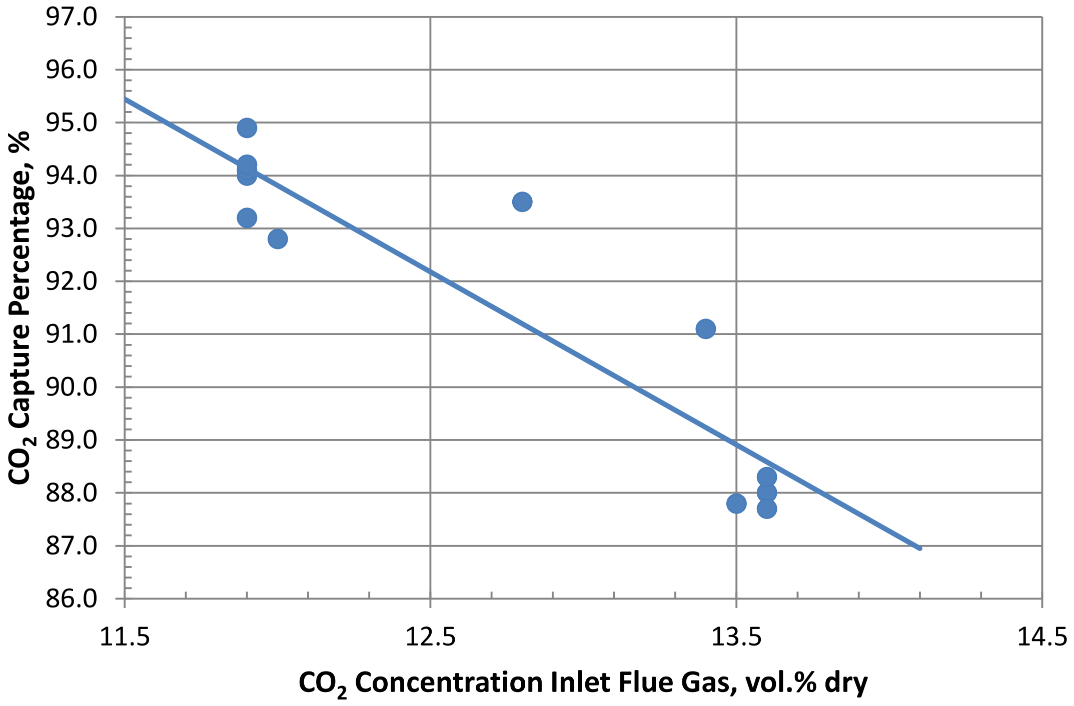


Figure 5-5
CO_2 capture percentage versus inlet flue gas CO_2 concentration

CO_2 Purity

The product CO_2 stream was sampled with CEM's equipment on the outlet pipe downstream of the stripper overhead cooler. The flue gas sample was sent through a chiller to remove moisture, and then to CO_2, trace O_2, SO_2, and THC analyzers. NOx measurements were not completed due to equipment problems, although this value is expected to be negligible. Descriptions of the equipment and various analyzers are included in Appendix E.

In general, the CO_2 analyzer read 100 vol.% dry for all tests. SO_2 and THC measurements were completed for the first 3 tests only. As shown in Table 5-7, SO_2 could not be detected within the accuracy of the instrument. THC levels were below 1 ppmv dry. For the first six performance tests, measurements of trace O_2 levels were in error due to suspected in-leakage within the sample line manifold. However, values collected by Linde using a similar instrument are shown in the 4th column of the first six tests, and averaged 35 ppmv dry. For the next six performance tests that were completed at the lower CO_2 flue gas inlet concentration, this same instrument averaged 15 ppmv dry.

Table 5-7
Composition of captured product CO_2 stream

	CO_2 vol.% dry	O_2 [1] ppmv dry	O_2 [2] ppmv dry	SO_2 ppmv dry	NOx ppmv dry	THC ppmv dry	H_2O [3] vol.%
Test 1, PM-1	100	n/a	26.7	0	n/a	0.9	5.36
Test 2, PM-2	100	n/a	31.3	0	n/a	0.8	4.81
Test 3, PM-3	100	n/a	25.2	0	n/a	0.5	3.75
Test 4, SO3-1	100	n/a	38.0	n/a	n/a	n/a	4.70
Test 5, SO3-2	100	n/a	38.4	n/a	n/a	n/a	4.99
Test 6, SO3-3	100	n/a	50.4	n/a	n/a	n/a	5.05
Test 7, NH3-1	100	30.4	15.0	n/a	n/a	n/a	2.96
Test 8, NH3-2	100	29.6	15.0	n/a	n/a	n/a	2.98
Test 9, NH3-3	100	28.7	15.0	n/a	n/a	n/a	2.99
Test 10, ALDH-1	100	22.4	15.0	n/a	n/a	n/a	3.03
Test 11, ALDH-2	100	21.0	14.9	n/a	n/a	n/a	3.08
Test 12, ALDH-3	100	20.3	15.1	n/a	n/a	n/a	3.11

1. Average Data Collected with CB&I Trace Oxygen Analyzer
2. Average Data Collected with Linde Trace Oxygen Analyzer
3. Based on Linde Pressure Reading and Assuming Saturated Product CO_2

n/a = not measured during test

The leakage problem that affected the CB&I O_2 analyzer was addressed for the final day of testing when six steady state performance tests were completed. The average for these tests was slightly higher at 25.4 ppmv dry, which is approximately 10 ppmv higher than the average of the Linde measurements. However, as reported earlier, a span gas (81 ppmv) was used to check the CB&I instrument at the end of the last test day, and gave a reading of 40 ppmv. The instrument zeroed out at 9 ppmv, creating uncertainty as to the accuracy of the reading.

Utilities Used

Import Steam

Steam from the host plant is used in the regenerator reboiler. The energy use is calculated by determining the enthalpy of the inlet steam and outlet condensate and multiplying this by the measured steam flow rate. Steam pressure, temperature and flow rate are measured with permanently installed Linde-BASF instrumentation. The results are shown in Table 5-8. The specific energy use is calculated by dividing the thermal usage by the CO_2 captured. The latter is based on measurements completed by CB&I.

Table 5-8
Summary of steam temperatures, pressures, flows and energy usage

	Flue Gas Supply Flow Rate lb/h	Captured CO_2 Flow Rate lb/h	Steam Flow Rate lb/h	Steam Temp. °F	Steam Pressure psig	Steam Energy Use MMBtu/h	Specific Steam Energy Use MMBtu/ton CO_2
Test 1, PM-1	11,955	2,047	2,292	352	109.9	2.17	2.12
Test 2, PM-2	12,007	2,023	2,340	345	109.7	2.21	2.18
Test 3, PM-3	12,044	2,001	2,195	344	110.1	2.08	2.08
Test 4, SO3-1	11,947	2,003	2,186	344	110.0	2.07	2.06
Test 5, SO3-2	11,953	2,011	2,201	345	110.1	2.08	2.07
Test 6, SO3-3	11,891	1,984	2,202	345	110.0	2.08	2.10
Test 7, NH3-1	11,832	1,870	2,178	344	110.0	2.06	2.20
Test 8, NH3-2	11,718	1,867	2,189	345	110.0	2.07	2.22
Test 9, NH3-3	12,063	1,907	2,182	345	110.0	2.06	2.16
Test 10, ALDH-1	12,082	1,912	2,181	345	110.0	2.06	2.16
Test 11, ALDH-2	11,645	1,823	2,155	345	110.1	2.04	2.24
Test 12, ALDH-3	12,013	1,888	2,151	345	110.1	2.04	2.16

Figure 5-6 shows the percentage CO_2 capture versus the specific steam energy use. The latter is defined as the MMBtu/h of net steam energy usage divided by the tons per hour of CO_2 removal. Comparing figures, the performance tests with the lowest CO_2 capture corresponded with tests with both the highest flue gas inlet CO_2 composition and the lowest specific steam energy usage.

If the CO_2 removal is plotted against the actual steam energy use (MMBtu/h), the result is the plot in Figure 5-7. In this figure, two data trends are evident; one for each of the two conditions set by the host station. The first of these at MCR host station output averaged 13.4 vol.% CO_2 dry for the first six performance tests, and 11.9 vol.% dry for the final six performance tests at 650 MWe output, or approximately 75% MCR. Figure 5-8 is a graphical representation of the steam energy rate in MMBtu/h versus the amount of CO_2 captured in lb/h for the 12 performance tests.

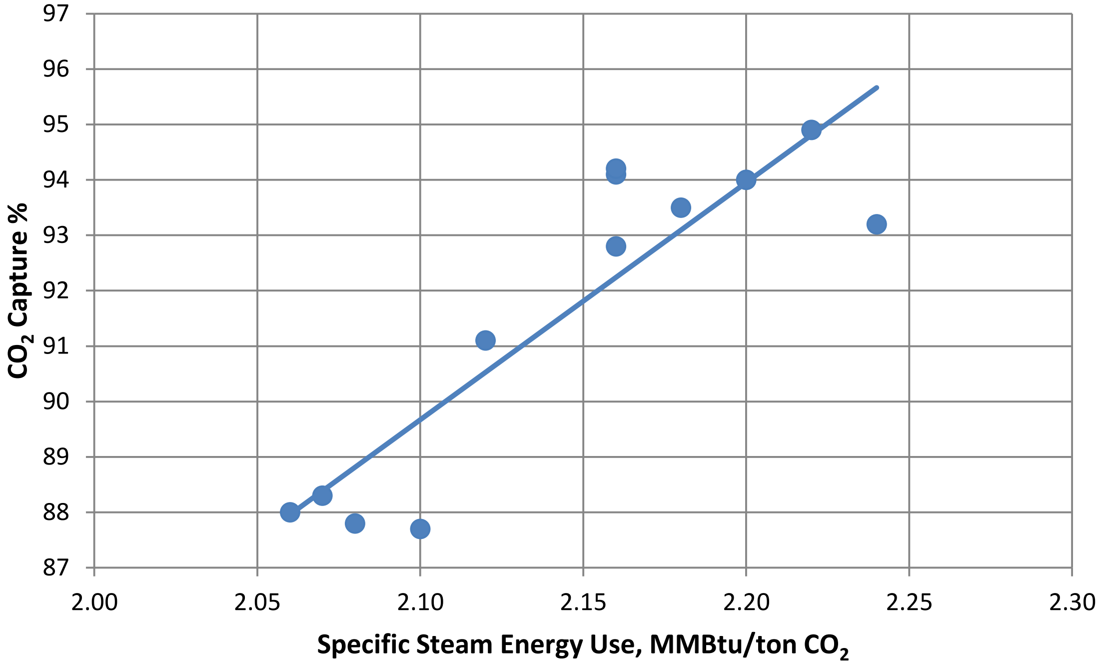


Figure 5-6
CO_2 capture percentage versus specific steam energy use, MMBtu/ton CO_2

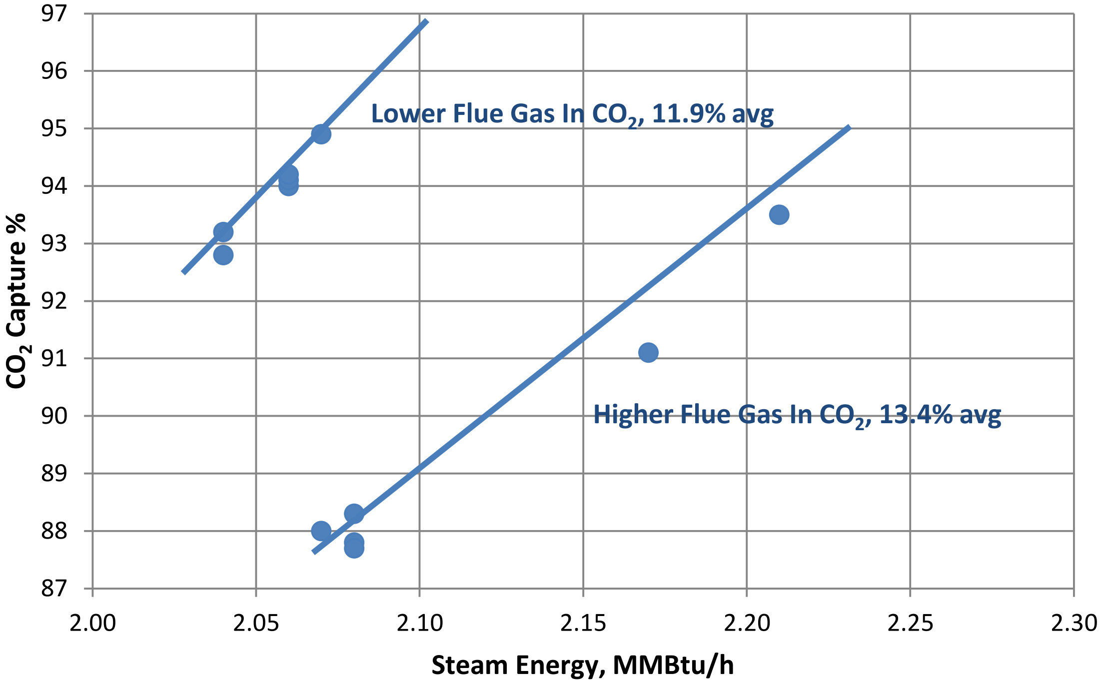


Figure 5-7
CO_2 capture percentage versus actual net steam energy use, MMBtu/h

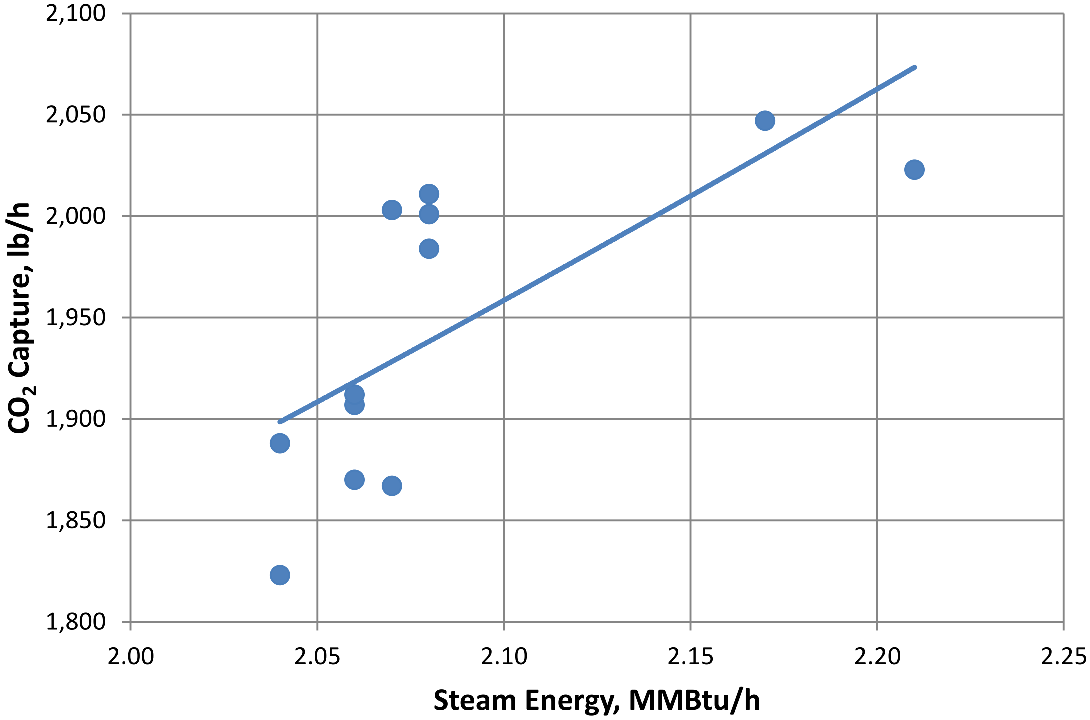


Figure 5-8
CO_2 capture quantity versus actual net steam energy use, MMBtu/h

Electrical Power

The major electrical loads required to operate the Linde-BASF carbon capture pilot plant are:

- Booster fan(s) - with testing configuration, there is a booster fan at the outlet of the PSTU scrubber, and at the outlet of the absorber column.
- Pumps - rich solution, lean solution, water wash pump, and reflux pump.

For a standalone, fully operating plant, there would be additional power requirements to compress and pump the product CO_2, to circulate (pump) cooling water through the various heat exchangers in the plant and to operate the forced draft fans on the cooling tower, and perhaps to operate a condensate forwarding pump depending on the plant configuration. There would also be a small power load for lighting, instrumentation, and control systems, and for operation of various pumps on the PSTU pre-scrubber, that were not accounted for during these tests.

For the PSTU and CO_2 capture pilot plant booster fans, the electrical power was estimated based on measurements of the pressure rise across the fan, the flow, and assuming a fan efficiency of 90% and a motor efficiency of 70%. The equation used to calculate the electrical power requirements of the two fans is shown below.

$$\mathrm{kW}_{\mathrm{fan}} = \left[\frac{\mathrm{dP}\left(\frac{\mathrm{lb}}{\mathrm{in}^2}\right) * \mathrm{flow}\left(\frac{\mathrm{ft}^3}{\mathrm{min}}\right) * 144\left(\frac{\mathrm{in}^2}{\mathrm{ft}^2}\right) * \frac{1}{60}\left(\frac{\mathrm{min}}{\mathrm{sec}}\right) * \frac{1}{550}\left(\frac{\mathrm{hp}}{\mathrm{ft\ lb}/\mathrm{sec}}\right)}{{}^{\eta_{\mathrm{fan}}}/_{100} * {}^{\eta_{\mathrm{motor}}}/_{100}}\right] * \frac{1\ \mathrm{kW}}{1.341\ \mathrm{hp}}$$

For the pumps outlined above, manual one-time pressure readings were taken on the inlet and outlet of the pump during the 2nd day of testing. Using the pressure increase across the pump, the measured flow rate determined with Linde instrumentation, the density of the fluid (reported by Linde for solvent), and assuming a pump efficiency of 90% and a motor efficiency of 70%, the electrical power was calculated for each pump (4 total). The equation used to calculate the electrical power requirements of the pumps is shown below.

$$\mathrm{kW_{pump}} = \left[\frac{\mathrm{dP}\left(\frac{\mathrm{lb}}{\mathrm{in}^2}\right) * \mathrm{flow}\left(\frac{\mathrm{lb}}{\mathrm{hr}}\right) * 144\left(\frac{\mathrm{in}^2}{\mathrm{ft}^2}\right) * \frac{1}{3600}\left(\frac{\mathrm{hr}}{\mathrm{sec}}\right) * \frac{1}{550}\left(\frac{\mathrm{hp}}{\mathrm{ft\,lb}/_{\mathrm{sec}}}\right)}{\mathrm{density}\left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right) * {}^{\eta_{\mathrm{pump}}}/_{100} * {}^{\eta_{\mathrm{motor}}}/_{100}}\right] * \frac{1\ \mathrm{kW}}{1.341\ \mathrm{hp}}$$

Table 5-9 summarizes the electrical power requirements that were estimated for the Linde-BASF pilot plant. Also shown in the last column is the estimated specific auxiliary power requirement, which is the estimated auxiliary power divided by the CO_2 capture rate.

Table 5-9
Summary of estimated auxiliary electrical power use

	Flue Gas Supply Flow Rate lb/h	Captured CO_2 Flow Rate lb/h		Estimated Auxiliary Power kW		Specific Auxiliary Power Use kWh/ton CO_2
Test 1, PM-1	11,955	2,047		41.1		40.1
Test 2, PM-2	12,007	2,023		43.1		42.6
Test 3, PM-3	12,044	2,001		41.9		41.9
Test 4, SO3-1	11,947	2,003		42.1		42.0
Test 5, SO3-2	11,953	2,011		42.3		42.1
Test 6, SO3-3	11,891	1,984		42.3		42.7
Test 7, NH3-1	11,832	1,870		43.9		47.0
Test 8, NH3-2	11,718	1,867		44.1		47.3
Test 9, NH3-3	12,063	1,907		44.0		46.2
Test 10, ALDH-1	12,082	1,912		44.0		46.0
Test 11, ALDH-2	11,645	1,823		43.9		48.2
Test 12, ALDH-3	12,013	1,888		44.2		46.9

Cooling Duty

All of these heat exchangers are located on the second level of the Linde-BASF carbon capture pilot plant. Cooling water is routed to each cooler from supply and return headers. Each cooler includes permanent instrumentation for measurement of the inlet and outlet temperatures, and inlet flow rate. The cooling duty is then calculated for each cooler using the following equation:

$$\mathrm{Btu/h_{cooling}} = \mathrm{flow}\left(\frac{\mathrm{lb}}{\mathrm{hr}}\right) * \left(\mathrm{Enthalpy\ In}\left(\frac{\mathrm{Btu}}{\mathrm{lb}}\right) - \mathrm{Enthalpy\ Out}\left(\frac{\mathrm{Btu}}{\mathrm{lb}}\right)\right)$$

The specific cooling load is calculated by dividing the total cooling load by the CO_2 captured. The overall cooling load varies with the inlet flue gas flow rate. Reporting of the cooling load provides an indication of the cooling water supply requirements and size of the cooling tower for full-scale applications of this technology.

Total cooling duty for the 12 performance tests is summarized in Table 5-10. The values listed for the total cooling load represent the aggregate cooling load from six coolers that are part of the overall process. These coolers are as follows:

- Feed Gas Cooler - located on the flue gas inlet duct between the PSTU and the absorber column.
- 2nd Water Wash Cooler - located at the top of the absorber column.
- 1st Water Wash Cooler - located below the upper water wash column. This cooler was not in use during these performance tests.
- Absorber Intermediate Cooler - located below the 1st water wash cooler.
- Lean Solution Cooler - located prior to lean solution entry into the absorber column.
- Overhead Condenser Cooler - located at the outlet of the stripper column.

Table 5-10
Summary of cooling duty during performance testing

	Flue Gas Supply Flow Rate lb/h	Captured CO_2 Flow Rate lb/h		Total Cooling Load MMBtu/h		Specific Cooling Load MMBtu/ton CO_2
Test 1, PM-1	11,955	2,047		2.94		2.87
Test 2, PM-2	12,007	2,023		2.71		2.68
Test 3, PM-3	12,044	2,001		2.70		2.70
Test 4, SO3-1	11,947	2,003		2.92		2.92
Test 5, SO3-2	11,953	2,011		2.89		2.87
Test 6, SO3-3	11,891	1,984		2.87		2.89
Test 7, NH3-1	11,832	1,870		2.65		2.83
Test 8, NH3-2	11,718	1,867		2.62		2.81
Test 9, NH3-3	12,063	1,907		2.60		2.73
Test 10, ALDH-1	12,082	1,912		2.53		2.65
Test 11, ALDH-2	11,645	1,823		2.61		2.86
Test 12, ALDH-3	12,013	1,888		2.55		2.70

Process Contaminants

SO_2/SO_3 Emissions

Although SO_2 emissions were measured with the CEM's system at the absorber inlet and outlet (downstream of the PSTU scrubber), values were below the measurement accuracy of the instrument for all test runs. However, during three of the performance tests, SO_2 emissions were measured (along with SO_3) with impinger trains which provided greater accuracy. The results are summarized in Table 5-11. The values reported at the PSTU scrubber inlet were measured with instrumentation installed by NCCC. The overall removal values shown in the last column represent the difference between the NCCC value at the PSTU inlet, and the value measured with impinger trains by CB&I at the absorber outlet. In general, values at the absorber inlet and outlet varied between 0.5 and 0.7 ppmv for the three tests.

Table 5-11
Summary of SO_2 emissions during performance tests

Test No.	SO_2 Emissions						
	Scrubber Inlet ppmv dry	Scrubber Inlet lb/h	Absorber Inlet ppmv dry	Absorber Inlet lb/h	Absorber Outlet ppmv dry	Absorber Outlet lb/h	% Overall Removal
Test 4, SO3-1	43.8	1.174	0.5	0.013	0.7	0.015	98.7
Test 5, SO3-2	45.0	1.209	0.5	0.013	0.7	0.015	98.8
Test 6, SO3-3	43.7	1.182	0.5	0.012	0.7	0.015	98.7

SO_3 emissions were also measured at the absorber inlet and outlet current with SO_2 with the same impinger train. Results are shown in Table 5-12. Values were below the detection limit of the method at both locations, with the exception of the inlet measurement during Test 5, SO3-3. A value of 0.4 ppmv was measured on the inlet during this run. SO_3 measurements were not completed upstream of the PSTU.

Table 5-12
Summary of SO_3 emissions during performance tests

Test No.	SO_3 Emissions						
	Scrubber Inlet ppmv dry	Scrubber Inlet lb/h	Absorber Inlet ppmv dry	Absorber Inlet lb/h	Absorber Outlet ppmv dry	Absorber Outlet lb/h	% Overall Removal
Test 4, SO3-1			<0.12	<0.0044	<0.12	<0.0037	
Test 5, SO3-2			0.4	0.100	<0.12	<0.0037	
Test 6, SO3-3			<0.12	<0.0044	<0.12	<0.0037	

Note: Mass emissions in lb/h reported as H_2SO_4

NOx Emissions

NOx concentrations were measured by CB&I with CEM's equipment on the inlet and outlet of the absorber column for all tests. In addition, values were measured and recorded by NCCC at the inlet to the PSTU scrubber. Average results from each run are shown in Table 5-13. Some of the increase in the concentration levels between the three locations results from the removal of CO_2 in the flue gas. The table also shows the mass flow rates at each of the three locations. For all tests, the percentage of overall removal showed a slight gain that averaged 4.2% between the absorber outlet and the PSTU inlet. This value likely reflects measurement uncertainty, as it is unlikely that NOx is created or released by the capture process. The most likely scenario, and one supported by the similarity of data between the three locations, is that NOx passes through the system largely unchanged and without absorption by the scrubber spray or into the capture plant solvent.

Table 5-13
Summary of NOx emissions during performance tests

Test No.	NOx Emissions						
	Scrubber Inlet ppmv dry	Scrubber Inlet lb/h	Absorber Inlet ppmv dry	Absorber Inlet lb/h	Absorber Outlet ppmv dry	Absorber Outlet lb/h	% Overall Removal
Test 1, PM-1	28.6	0.55	33.3	0.65	35.7	0.58	-4.7
Test 2, PM-2	37.4	0.73	39.5	0.77	47.4	0.77	-6.1
Test 3, PM-3	34.9	0.68	38.1	0.75	46.1	0.70	-3.7
Test 4, SO3-1	33.0	0.64	38.3	0.75	45.1	0.68	-6.9
Test 5, SO3-2	33.4	0.64	39.7	0.77	44.5	0.69	-7.3
Test 6, SO3-3	33.2	0.64	39.5	0.77	46.7	0.76	-18.0
Test 7, NH3-1	35.8	0.70	38.9	0.75	46.3	0.72	-3.3
Test 8, NH3-2	34.2	0.67	37.6	0.72	43.7	0.66	1.2
Test 9, NH3-3	36.0	0.70	39.1	0.77	45.4	0.71	-1.4
Test 10, ALDH-1	34.9	0.68	38.4	0.76	44.3	0.68	-0.3
Test 11, ALDH-2	33.2	0.65	36.4	0.69	41.9	0.65	-0.6
Test 12, ALDH-3	33.5	0.65	37.0	0.73	42.7	0.65	0.6

Particulate Emissions

Total filterable PM emissions were measured on the flue gas absorber inlet and outlet sampling locations during the first three performance tests. The measurements employ a heated sample probe and filter assembly that is installed on the front end of an impinger train. The latter is used (along with the filter catch) to determine HAPs metal and mercury concentrations which are discussed in the next section.

Results are shown in Table 5-14 for the three tests. Total particulate measurements were completed at the absorber inlet and outlet locations, but not at the inlet to the PSTU pre-scrubber. For Test 1, PM-1, a system trip resulted in a compromised flue gas sample at the absorber inlet location, and data were not available for this test run. In general, particulate levels were extremely low at the absorber inlet location, and were below the detection limit of the sample method of Test 3, PM-3. Higher concentrations were measured at the absorber outlet location for Test 2, PM-2 and Test 3, PM-3.

Table 5-14
Summary of particulate emissions during performance tests

Test No.	Particulate Emissions					
	Scrubber Inlet ppmv dry	Scrubber Inlet lb/h	Absorber Inlet grains/dscf	Absorber Inlet lb/h	Absorber Outlet grains/dscf	Absorber Outlet lb/h
Test 1, PM-1			n/a	n/a	0.0030	0.057
Test 2, PM-2			0.0005	0.010	0.0017	0.032
Test 3, PM-3			<0.000081	<0.0017	0.0024	0.044

HAPs Metals and Mercury

HAPs metals and mercury concentrations were measured at the absorber inlet and outlet locations concurrent with the particulate tests discussed above. The results are summarized in Table 5-15. Cells in this table that are shaded represent values for particular HAPs metals that were below the detection limit of the method. However, in this table, the values below the detection limit are used in the average columns for the absorber inlet and outlet locations.

Table 5-15
Summary of HAPs metals and mercury concentrations during performance tests

	Absorber Inlet Concentration µg/dscm				Absorber Outlet Concentration µg/dscm			
	Test 1 PM-1	Test 2 PM-2	Test 3 PM-3	Avg.	Test 1 PM-1	Test 2 PM-2	Test 3 PM-3	Avg.
Antimony	1.44	0.88	0.96	1.09	5.67	1.13	1.19	2.66
Arsenic	1.64	0.88	1.02	1.18	2.75	1.54	1.62	1.97
Beryllium	0.07	0.05	0.05	0.06	0.09	0.06	0.06	0.07
Cadmium	0.72	0.44	0.48	0.55	0.91	0.56	0.60	0.69
Chromium	8.58	3.60	1.26	4.48	1.53	8.91	7.50	5.98
Cobalt	0.72	0.44	0.48	0.55	0.91	0.83	0.60	0.78
Lead	1.44	2.00	1.49	1.64	4.27	3.09	4.14	3.83
Manganese	18.90	8.50	8.70	12.03	28.50	15.00	n/a	21.75
Nickel	13.00	6.50	2.10	7.20	2.75	4.76	7.59	5.03
Selenium	9.20	2.50	8.80	6.83	4.49	16.10	5.24	8.61
Mercury	0.54	0.47	0.24	0.42	0.64	0.77	0.32	0.58

▨ values below detection limit of method

n/a = not applicable, possible sample contamination

In general, concentrations of antimony, arsenic, beryllium, cadmium and cobalt are negligible at both locations. Lead is also negligible except for one low reading that was above the minimum detection limit during Test 2, PM-2 at the absorber inlet location. For the remaining HAPs, including chromium, manganese, nickel, selenium and mercury, there is no significant change in concentration levels between the absorber inlet and outlet locations. The same is true when comparing to the total mass flow of these constituents. Mass flows are summarized in Table 5-16, and are obtained by multiplying the concentration times the measured inlet or outlet absorber volumetric flow rate.

The values shown in Tables 5-15 and 5-16 are also included in the performance test overview pages that are included in Attachment C. In these tables, the mass flow is calculated and shown only if the concentration level of a particular analyte was greater than the value of the minimum detection limit.

Table 5-16
Summary of HAPs metals and mercury mass flows during performance tests

	Absorber Inlet Mass Flow mg/hr				Absorber Outlet Mass Flow mg/hr			
	Test 1 PM-1	Test 2 PM-2	Test 3 PM-3	Avg.	Test 1PM-1	Test 2 PM-2	Test 3 PM-3	Avg.
Antimony	5.99	3.69	4.02	4.56	21.68	4.37	4.30	10.12
Arsenic	6.82	3.69	4.27	4.92	10.51	5.96	5.86	7.44
Beryllium	0.30	0.20	0.21	0.23	0.36	0.22	0.22	0.27
Cadmium	2.99	1.84	2.01	2.28	3.48	2.17	2.17	2.61
Chromium	35.67	15.08	5.27	18.67	5.85	34.48	27.12	22.48
Cobalt	2.99	1.84	2.01	2.28	3.48	3.21	2.17	2.95
Lead	5.99	8.38	6.24	6.87	16.32	11.96	14.97	14.42
Manganese	78.58	35.60	36.41	50.19	108.95	58.06	n/a	83.50
Nickel	54.05	27.22	8.79	30.02	10.51	18.42	27.44	18.79
Selenium	38.25	10.47	36.83	28.51	17.16	62.31	18.95	32.81
Mercury	2.25	1.97	1.00	1.74	2.45	2.98	1.16	2.19

▨ values below detection limit of method

n/a = not applicable, possible sample contamination

Figures 5-9 through 5-11 graphically summarize the average solid and vapor fractions of each of the eleven HAPs metals and mercury that were measured during the first three performance tests. The values represent the total mass flow measured at the inlet and outlet of the absorber column. The averages include values that were below the minimum detection limit of the method. Any value below the minimum detection limit of the method is outlined in black in these figures.

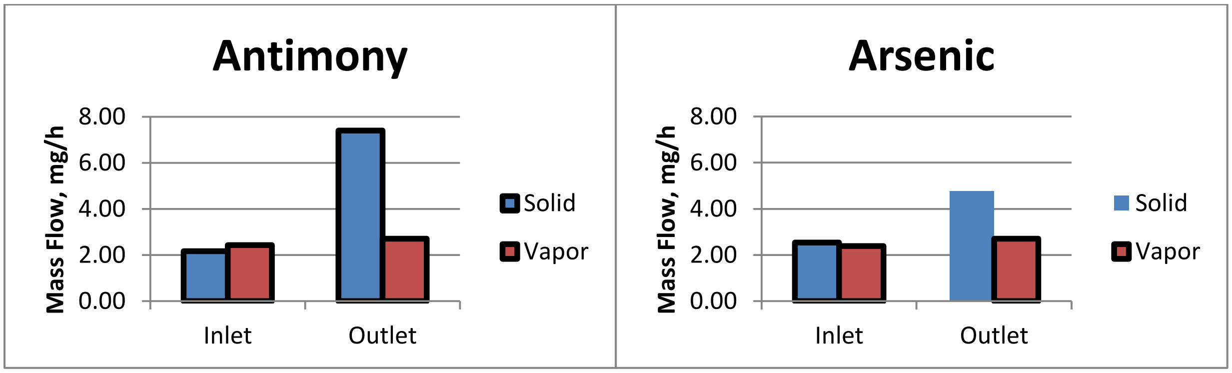


Figure 5-9
Distribution of antimony and arsenic

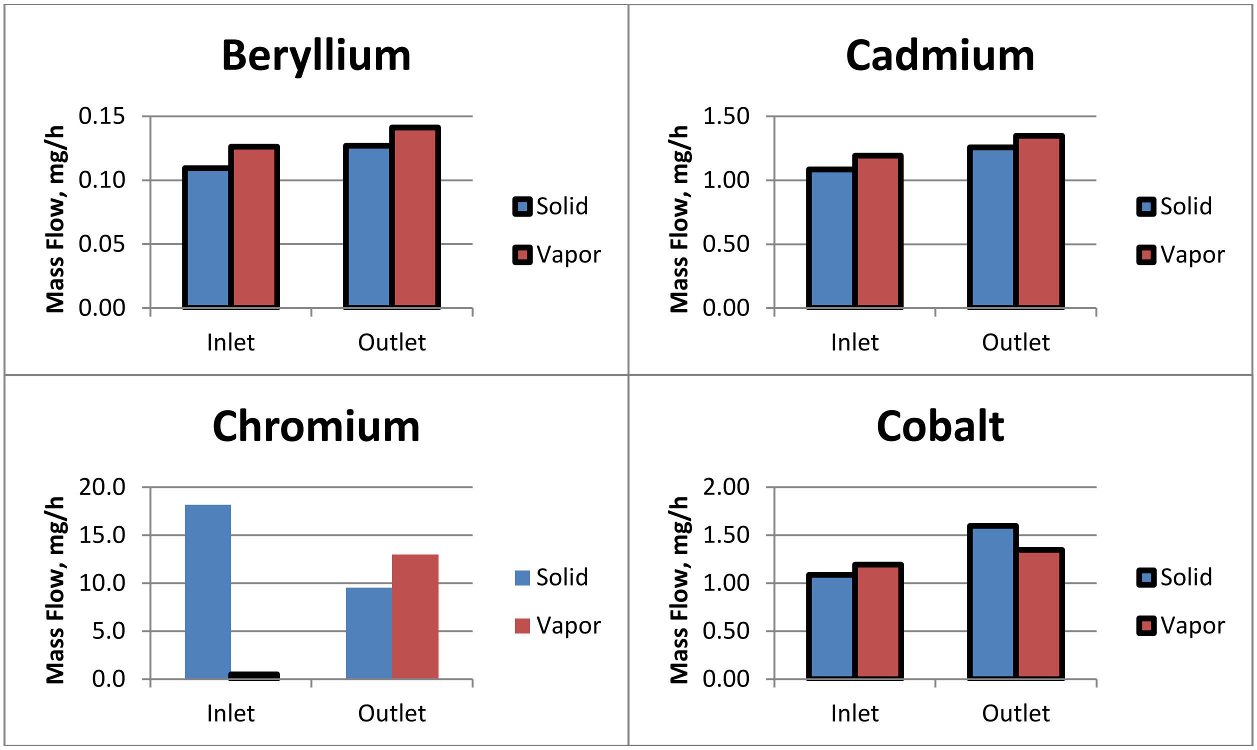


Figure 5-10
Distribution of beryllium, cadmium, chromium and cobalt

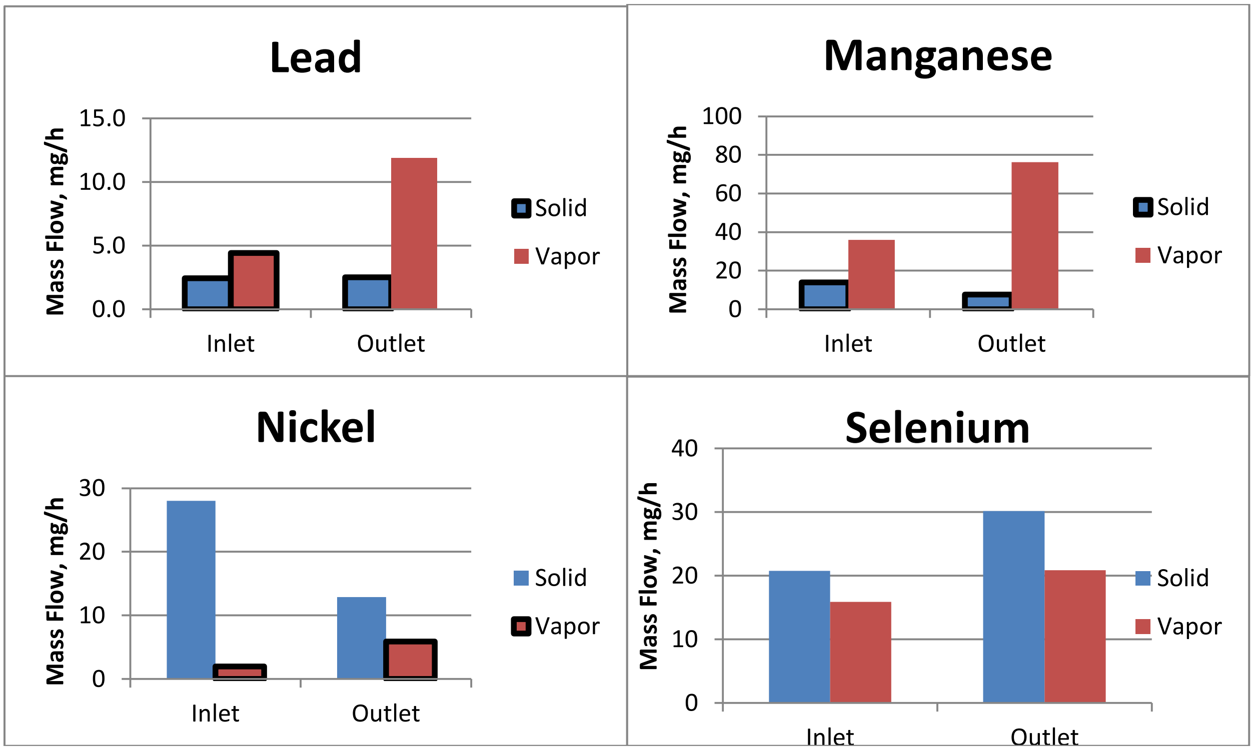


Figure 5-11
Distribution of lead, manganese, nickel and selenium

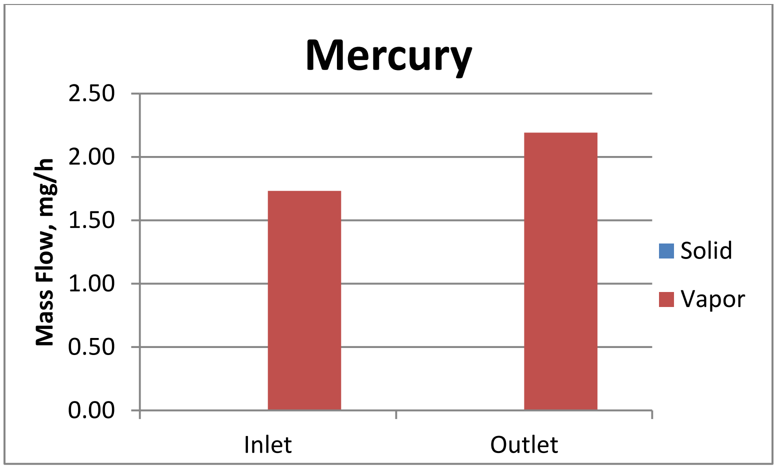


Figure 5-12
Distribution of mercury

Ammonia

Ammonia concentrations were measured at the absorber inlet and outlet, and on the product CO_2 stream during three performance tests identified at Test 7, NH3-1, Test 8, NH3-2, and Test 9, NH3-3. Results are summarized in Table 5-17. Concentrations of ammonia at the absorber inlet were below the detection limit of the method for all three tests. At the absorber outlet, concentrations for the three tests averaged around 1 ppmv dry, indicating some solvent carry-over past the spray cooler. Trace amounts were also measured in the product CO_2 stream, averaging around 0.3 ppmv for the three tests. The mass flows of these constituents at each location is also shown in Table 5-17.

Table 5-17
Summary of NH_3 concentrations and mass flows during three performance tests

	NH_3 Emissions					
Test No.	Absorber Inlet ppmv dry	Absorber Inlet lb/h	Absorber Outlet ppmv dry	Absorber Outlet lb/h	Captured CO_2 Stream ppmv dry	Captured CO_2 Stream lb/h
Test 7, NH3-1	<0.017	<0.0001	1.000	0.0060	0.150	0.000
Test 8, NH3-2	<0.017	<0.0001	0.720	0.0040	0.320	0.000
Test 9, NH3-3	<0.017	<0.0001	1.200	0.0070	0.380	0.000

Aldehydes/Ketones

Aldehyde and ketone compounds were collected at the absorber inlet and outlet using impinger trains, and were analyzed using the procedures of SW 846 Method 0011 (Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, Third Edition). The results are summarized in Table 5-18, which shows the concentrations for the three performance tests at the absorber inlet and outlet. Two of the ketones, (acetophenone and isophorone) and one of the aldehydes (proponaldehyde) had concentrations below the detection limit of the method at both locations. Formaldehyde showed a slight increase in concentration level between the inlet and outlet, while acetaldehyde showed a substantial increase. It is uncertain what the source of the formaldehyde and acetaldehyde are on the absorber inlet. Formaldehyde and acetaldehyde are organic chemical compounds with the formulas CH_2O and CH_3CHO respectively.

Table 5-18
Summary of aldehyde concentrations during three performance tests

	Absorber Inlet Concentration, µg/dscm				Absorber Outlet Concentration, µg/dscm			
	Test 10 ALDH-1	Test 11 ALDH-2	Test 12 ALDH-3	Avg.	Test 10 ALDH-1	Test 11 ALDH-2	Test 12 ALDH-3	Avg.
Formaldehyde	41.0	50.9	42.9	44.9	60.9	56.8	60.7	59.5
Acetaldehyde	8.4	14.6	10.9	11.3	220.4	260.3	245.9	242.2
Acetophenone	<0.71	<1.7	<1.6	<1.3	<1.5	<2.7	<2.5	<2.2
Isophorone	<0.71	<1.7	<1.6	<1.3	<1.5	<2.7	<2.5	<2.2
Propionaldehyde	<0.71	<1.7	<1.6	<1.3	<1.5	<2.7	<2.5	<2.2

< Indicates measured value below the detection limit of the method

Table 5-19 converts these concentrations into mass flows. Again, the increase in the quantity of acetaldehyde at the absorber outlet is obvious in all three performance tests, with relatively consistent results on the inlet and outlet locations for all three performance tests.

Table 5-19
Summary of aldehyde mass flows during three performance tests

	Absorber Inlet Mass Flow, mg/hr				Absorber Outlet Mass Flow, mg/hr			
	Test 10 ALDH-1	Test 11 ALDH-2	Test 12 ALDH-3	Avg.	Test 10 ALDH-1	Test 11 ALDH-2	Test 12 ALDH-3	Avg.
Formaldehyde	172.36	208.65	181.44	185.97	232.81	219.84	219.46	224.03
Acetaldehyde	35.83	58.97	45.36	45.36	842.54	1,007.45	889.05	913.01
Acetophenone	<3.175	<7.257	<6.804	<5.443	<5.443	<9.979	<9.072	<8.165
Isophorone	<3.175	<7.257	<6.804	<5.443	<5.443	<9.979	<9.072	<8.165
Propionaldehyde	<3.175	<7.257	<6.804	<5.443	<5.443	<9.979	<9.072	<8.165

< Indicates measured value below the detection limit of the method

It can be noted here that formaldehyde and acetaldehyde are known degradation products of alkanolamine solvents in an oxidative environment, such as that brought about by exposing solvent to flue gases containing a significant oxygen component due to excess air requirements of combustion and air ingress.

PSTU Pre-Scrubber Blowdown

Samples were collected from the PSTU pre-scrubber blowdown sample line during each day of testing, and were analyzed for sulfite, sulfate, ammonium ion, HAPs metals and mercury. The results for sulfite, sulfate, and ammonium ion are shown in Table 5-20. HAPs metals and mercury concentrations are shown in Table 5-21.

Ideally, the scrubber blowdown sulfur, ammonia and HAPs metals concentrations, combined with the blowdown flow rate, would be used as part of a material balance, provided that flue gas sampling is done at the inlet to the scrubber. However, the PSTU pre-scrubber flue gas outlet duct enters a common header which serves other test facilities. As a result, flue gas sampling was performed downstream of the scrubber (upstream of the absorber column). In addition, there was no pre-scrubber blowdown flow during any of the performance testing periods. As such, the data in Tables 5-20 and 5-21 are presented here for completeness.

Table 5-20
Summary of pre-scrubber blowdown sulfur and ammonia concentrations

Date (2016)	Parameter[a]			
	Sulfite (mg/L)	Sulfate (mg/L)	Ammonium Ion (mg/L)	Gravimetric Residue (g/mL)
6/16	333.6	104,650	Not detected (<50)	0.1497
6/17	938.2	114,040	95.1	0.1488
6/18	448.6	128,330	Not detected (<50)	0.1521

[a] mg/mL = Milligrams per milliliter; g = grams.

Table 5-21
Summary of pre-scrubber blowdown HAPs metals and mercury concentrations

Date (2016)	6/16	6/17	6/18
Analyte	Test 1 (µg/mL)[a]	Test 2 (µg/mL)	Test 3 (µg/mL)
Arsenic	0.460	0.253	0.160
Antimony	0.391	ND	ND
Beryllium	ND	ND	ND
Cadmium	ND	0.321	0.297
Chromium	0.471	0.028	ND
Cobalt	ND	0.435	0.360
Lead	0.718	ND	ND
Manganese	ND	0.081	ND
Mercury	4.14E-05	1.17E-05	1.93E-05
Nickel	0.347	0.510	0.466
Selenium	0.694	0.552	0.356

[a] µg/mL = Micrograms per milliliter; ND = not detected.

A

SAMPLING AND ANALYSIS PROCEDURES PLAN

Procedures for the sampling and analysis of gas and liquid samples collected during campaign testing were drawn up by CB&I – the test contractor selected by EPRI for the Linde-BASF pilot plant testing. CB&I's plan included the development of a project team for testing at the site along with safety procedures and quality assurance/quality control for all sampling and analysis methods. The procedures of gas and liquid sampling and analysis are summarized below.

Gas Sampling and Analysis

Table A-1 summarizes the Linde-BASF pilot plant sampling locations, required measurement parameters for each gas stream, the sampling and analytical methods, and number of tests for each location.

Sampling Locations

Sampling of the flue gas inlet stream to the pilot plant absorber column for SO_2/SO_3, particulates, ammonia and aldehyde/ketones is conducted on a 10-inch (25.4 cm) diameter, horizontal duct. A single sample port is located on the side of this duct 17.7 ft. (538.5 cm) downstream of a 90° bend, and 17 inches (43.2 cm) upstream of an expansion in the duct from a diameter of 10 to 12 inches (25.4 to 30.48 cm). Traverses are made with 6 measurement points moving into the duct, and six points moving out of the duct. The CEM's sample probe is located in the 12-inch (25.4 cm) section of the duct just downstream of the traversing port identified above. The sample probe is in a fixed vertical position along the centerline of the duct.

Sampling of the flue gas outlet stream from the absorber column for SO_2/SO_3, particulates, ammonia and aldehyde/ketones is conducted on a 14-inch (35.6 cm) diameter, horizontal duct. A single sample port is located on the side of this duct approximately 40 ft. (12.2 m) downstream of a flow disturbance, and 2 ft. (61 cm) upstream of a 90° bend in the duct. Traverses are made with 6 measurement points moving into the duct, and six points moving out of the duct. The CEM's sample probe is located in the 14 inch (35.6 cm) section of the duct downstream of the traversing port identified above. The sample probe is in a fixed vertical position along the centerline of the duct.

A complete cross-sectional traverse was conducted before each test at the absorber inlet and outlet locations to measure gas velocity, static pressure and temperature. The nominal precision of EPA flow measurements using S-type pitot tubes is +5 percent.

A heated CEM's sample line is also installed in a fixed position on the centerline of the 6 inch (15.2 cm) product CO_2 stream. A sample is pulled from this off-take for measurement of the ammonia concentration during three of the performance tests.

Table A-1
Gas sampling and analysis plan

Description	Parameter	Sampling and Analysis Method[a]	No. and Duration of Tests
Flue Gas Absorber Inlet and Outlet Locations	Volumetric flow rate and gas composition	U.S. EPA 1, 2,3A, 4	With each test
	NOx	U.S. EPA 7E	Continuous - 24-hour
	SO_2	U.S. EPA Method 6C	Continuous - 24-hour
	THC	U.S EPA Method 25A	Continuous - 24-hour
	SO_2 and SO_3	U.S. EPA 8A	(3) 60-minute tests
	HAPs metals[b]	U.S. EPA 29	(3) 120-minute tests
	Particulate	U.S. EPA 5	(3) 120-minute tests, during HAPs metals
	Ammonia	U.S. EPA CTM 027	(3) 60-minute tests
	Aldehydes/Ketones	SW 846 Method 0011	(3) 60-minute tests
	Moisture	U.S. EPA 4	All Performance Tests (12)
	O_2/CO_2	U.S. EPA 3A[c]	Continuous - 24-hour
Product CO_2	O_2/CO_2	U.S. EPA 3A[c]	Continuous - 24-hour
	NO_x	U.S. EPA 7E	Continuous - 24-hour
	SO_2	U.S. EPA Method 6C	Continuous - 24-hour
	THC	U.S EPA Method 25A	Continuous - 24-hour
	Ammonia	U.S. EPA CTM 027	(3) 60-minute tests

[a] U.S. EPA Methods from 40 CFR 60 Appendix A; Method 8A (SO_3) from NCASI.

[b] HAPs metals: antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, and selenium.

[c] CO_2 CEMs using 0 to 100% scale; Oxygen CEM AMI Model 1000RS-T2 with 0- to 50 ppm range.

Flue gas moisture content was determined two ways, as required by U.S. EPA Method 4. The first calculation uses psychometric data (gas temperature, stack pressure and barometric pressure) to calculate the saturation percent moisture. The second calculation uses the actual water condensate collected in the impinger section of the sampling trains coupled with the metered sample volume, to determine the as-measured moisture value. As required by Method 4, the lower of the two values is used in all flow rate and emission rate calculations. The nominal precision of Method 4 is +5 %. The measured flue gas, CO_2, and moisture mass flow rates were calculated in pounds per hour using the measured volumetric gas flow rate at stack conditions (temperature and pressure) and measured gas composition.

CEMs Data

At each of the three gas sampling locations, CEMs were used to measure the real-time concentrations of oxygen, CO_2, NOx, SO_2 and THC. Procedures detailed in EPA Methods 3A, 6C, 7E, and 25A were used. The EPA instrumental methods measure pollutant concentrations on a dry basis, except for THC which is measured on a wet basis. Wet-basis concentrations were calculated using the average measured moisture content in the inlet and outlet flue gas streams. Wet and dry mass emission rates were calculated using the average flue gas flow rate measured during each test day. For the test campaign, levels of SO_2 and THC at the inlet were below the 2% accuracy range of the analyzer.

H_2SO_4 (including SO_3) and SO_2

Procedures outlined in Method 8A developed by the National Council for Air and Stream Improvement (NCASI) were used to collect and analyze samples. Before each test, a velocity and temperature traverse was conducted to determine flue gas flow rate.

Filterable Particulate and HAPs Metals

Filterable PM and metals data were collected using the procedures of U.S. EPA Methods 5 and 29. In addition to the Method 29 metals analyses, the front-half fraction of the sampling train (sample nozzle rinse, probe rinse, front filter holder glassware rinse, and tared quartz filter) were analyzed for filterable particulate before this fraction was analyzed for metals. Filterable particulate is defined as that material, uncombined with water, collected in the front half of the Method 5 sampling train (sample nozzle, glass-lined probe, and tared quartz-fiber filter) and analyzed gravimetrically using U.S. EPA Method 5 procedures. The sample probe and filter are heated to 248° ±25°F (120° ±13.9°C).

Ammonia

Modified procedures detailed in U.S. EPA's Conditional Test Method 027 (CTM-027) were used to measure NH_3 concentrations and mass emission rates at the flue gas absorber inlet and outlet locations. The modification consisted of eliminating the filter system (either in-stack or out-of-stack) before the impinger section of the sample train. The sampling probe was maintained at or slightly above the stack temperature, as required by the method, and all samples were collected using isokinetic sampling techniques.

Aldehydes and Ketones

Aldehyde and ketone compounds were collected at the absorber inlet and outlet sample locations and analyzed using the procedures of SW-846 Method 0011 (Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, Third Edition). Gaseous and particulate pollutants were withdrawn isokinetically from the source and collected in aqueous acidic 2,4-dinitrophenylhydrazine (DNPH). Aldehyde and ketone compounds react with the DNPH solution to form specific derivatives. The derivatives were extracted, solvent-exchanged, concentrated, and analyzed by high-performance liquid chromatography in accordance with SW-846 Method 8315 procedures.

Process Liquid Sampling and Analysis

Liquid samples are collected on a one-time basis from the scrubber blowdown stream during each of the three days of testing. Continuous or intermittent blowdown was not used by the process during the performance testing. However, three total samples (one from each day) were collected and analyzed for sulfate, sulfite, ash (total residue), and HAPs metals as indicated in Table A-2. Sulfite is determined on-site while all other constituents are tested at an off-site laboratory.

Table A-2
Routine liquid sampling and analysis requirements

Stream	Nominal Stream Conditions		SO_3^{2-} [a]	SO_4^{2-} [b]	Ash	HAPs metals[b]
	Temperature	Pressure				
PSTU SO_2 scrubber blowdown	87°F 31°C	10 psig 1.7 bar	X	X	X	X

All streams are aqueous liquids.

Analyte	Result	Collection and Analysis Procedure
SO_3^{2-}	Total sulfite, per unit liquid volume	EPRI Method M2, sulfite titration in iodine using thiosulfate, performed on site
SO_4^{2-}	Total sulfate, per unit liquid volume	EPA 300.0, performed off site (modified to exclude sulfite)
HAPs	Heavy metals focusing on total mercury	SW 6010B for major metals, SW 7470 for mercury, performed off site
Ash	Total insoluble material, per unit liquid volume	Gravimetric

[a] SO_3^{-2} = Sulfur trioxide; SO_4^{-2} = sulfate; liquid samples are collected for individual analysis contemporaneously with gas sampling runs.

[b] For HAPs, a single daily liquid sample is prepared as a composite of equal volumes of the three samples collected contemporaneously with the gas sampling runs.

B

SUPPORTING CALCULATIONS

Heat Duty Calculations

The primary continuous heat duty in the Linde-BASF pilot plant is the regenerator reboiler. The reboiler load is served by superheated steam imported from the host plant as indicated in Figure B-1. The regenerator reboiler is designed to use saturated steam. The imported steam is metered and reduced in pressure to that required by the reboiler heat load. The reduced pressure steam is then sprayed to vapor saturation with saturated condensate.

Additional heat could be recovered to the process from warm condensate leaving the regenerator reboiler. As a result, the plant heat duty is calculated based on the condensate temperature (T_c) downstream of the heat recovery.

The overall heat duty is calculated as:

$$Q = F_i\left(h\left(T_i, P_i\right) - h\left(T_c\ , P_c\right)\right)$$

Where:

Q	= component heat duty	Btu/h	kW_{th}
F_i	= measured steam flow	lb/h	kg/sec
$h(T_i,P_i)$	= superheated steam enthalpy	Btu/lb	kJ/kg
$h(T_c,P_c)$	= saturated liquid enthalpy	Btu/lb	kJ/kg
T_i	= measured steam temperature	ºF	ºC
P_i	= measured steam pressure	psia	MPa
P_c	= measured condensate pressure	psia	MPa
T_c	= measured condensate temperature	psia	MPa

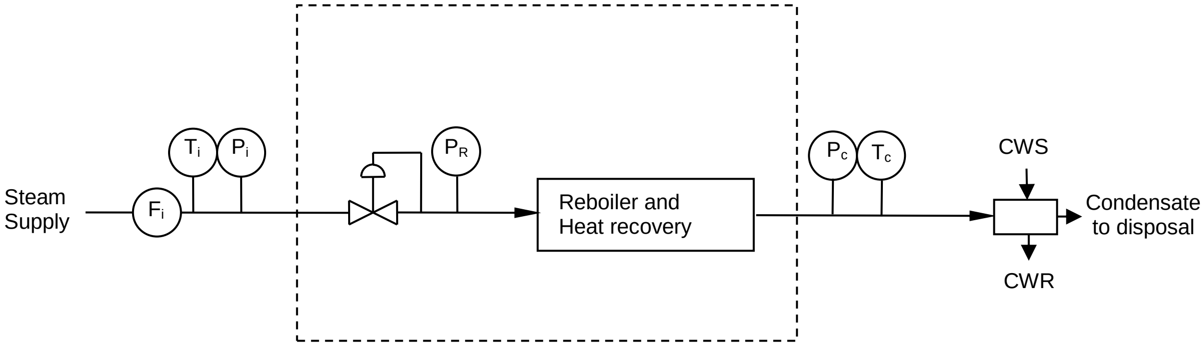
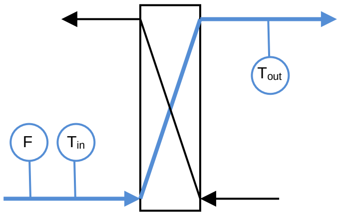


Figure B-1
Regenerator reboiler flow diagram for calculation of heat duty

Cooling Duty Calculations

A total of six heat exchangers are located on the second level of the Linde-BASF carbon capture pilot plant. One of these, the lower water wash cooler, was not used during the current test campaign. Cooling water is routed to each cooler from supply and return headers. Each cooler includes permanent instrumentation for measurement of the inlet and outlet temperatures, and inlet flow rate. The cooling duty is then calculated for each cooler using the following equation:

$$\text{Btu/h}_{\text{cooling}} = \text{flow (F)} \left(\frac{\text{lb}}{\text{hr}}\right) * \left(\text{Enthalpy In } (\text{T}_{\text{in}}) \left(\frac{\text{Btu}}{\text{lb}}\right) - \text{Enthalpy Out } (\text{T}_{\text{out}}) \left(\frac{\text{Btu}}{\text{lb}}\right)\right)$$



Cooling duty was calculated for the following:

- Feed Gas Cooler - located on the flue gas inlet duct between the PSTU and the absorber column.
- 2nd Water Wash Cooler - located at the top of the absorber column.
- Absorber Intermediate Cooler - located below the 1st water wash cooler.
- Lean Solution Cooler - located prior to lean solution entry into the absorber column.
- Overhead Condenser Cooler - located at the outlet of the stripper column.

Electrical Duty Calculations

For pumps, the electrical power requirements were calculated according to the following equation:

$$\text{kW}_{\text{pump}} = \left[\frac{\text{dP}\left(\frac{\text{lb}}{\text{in}^2}\right) * \text{flow}\left(\frac{\text{lb}}{\text{hr}}\right) * 144\left(\frac{\text{in}^2}{\text{ft}^2}\right) * \frac{1}{3600}\left(\frac{\text{hr}}{\text{sec}}\right) * \frac{1}{550}\left(\frac{\text{hp}}{\text{ft lb}/\text{sec}}\right)}{\text{density}\left(\frac{\text{lb}}{\text{ft}^3}\right) * {}^{\eta_{\text{pump}}}/_{100} * {}^{\eta_{\text{motor}}}/_{100}}\right] * \frac{1\text{ kW}}{1.341\text{ hp}}$$

For the pump calculations, manual one-time pressure readings were taken on the inlet and outlet of the pump. Using the pressure increase across the pump, the measured flow rate determined with Linde instrumentation, the density of the fluid (reported by Linde for solvent), and assuming a pump efficiency of 90% and a motor efficiency of 70%, the electrical power was calculated for each pump (4 total). Included in this calculation were the rich solution, lean solution, water wash, and reflux pumps.

For the PSTU and CO_2 capture pilot plant booster fans, the electrical power was estimated based on measurements of the pressure rise across the fan, the flow, and assuming a fan efficiency of 90% and a motor efficiency of 70%. The equation used to calculate the electrical power requirements of the two fans is shown below.

$$\mathrm{kW_{fan}} = \left[\frac{\mathrm{dP}\ \left(\frac{\mathrm{lb}}{\mathrm{in^2}}\right) * \mathrm{flow}\ \left(\frac{\mathrm{ft^3}}{\mathrm{min}}\right) * 144\ \left(\frac{\mathrm{in^2}}{\mathrm{ft^2}}\right) * \frac{1}{60}\left(\frac{\mathrm{min}}{\mathrm{sec}}\right) * \frac{1}{550}\left(\frac{\mathrm{hp}}{\mathrm{ft\,lb}/\mathrm{sec}}\right)}{\eta_{\mathrm{fan}}/100 * \eta_{\mathrm{motor}}/100}\right] * \frac{1\ \mathrm{kW}}{1.341\ \mathrm{hp}}$$

C
CAMPAIGN TEST PERIOD DATA REPORTS

Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 1, PM-1

Start **6/16/16 13:25**
Stop **6/16/16 14:43**

Summary			
Inlet Flue Gas Flow Rate	lb/h	11,955	*isokinetically*
CO_2 Captured	%	91.1	*(supply-return)/supply*
CO_2 Recovery	%	86.2	*produced/captured*
Specific Thermal Use	MMBtu/ton CO_2	2.12	*per CO_2 captured*
Specific Electrical Use	kWh/ton CO_2	40.13	*per CO_2 captured*
Total Cooling Load	MMBtu/ton CO_2	2.87	*per CO2 captured*

Captured CO_2 Composition		
O_2	ppmv dry	🟦
CO_2	vol. % (dry)	100.0

Stream Data		**Flue Gas Supply (Absorber In)**	**Depleted Flue Gas (Absorber Out)**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	^oF	94.0	102.0		90.6	
Pressure	psig	0.46	0.12		-1.12	
Total Flow	acfm	2,649	2,576			
Total Flow	lb/hr	11,955	10,462		2,047	
H_2O	vol. %, wet	5.3	6.9			
CO_2	vol. %, dry	13.4	1.3		100.0	
O_2	vol. %, dry	5.7	7.7		🟦	ppmv dry
N_2	vol. %, dry	80.9	91.0			
MW	lb/lb-mol, wet	29.7	27.8		🟦	
Sulfite	mg/l					333.7
Sulfate	mg/l					104,650
Total Solids	mg/l					149,700
SO_2 (cem's)	ppmv, dry	0.2	0.4		🟦	
H_2SO_4	ppmv, dry	🟦	🟦			
NOx	ppmv, dry	33.3	35.7		🟦	
THC	ppmv, dry	0.0	0.0		0.9	wet
Total Filterable Particulate	gr/dscf	🟦	0.0030			
Hg	µg/dscm	🟦	0.64			
H_2O Flow	lb/h	381	470	-89	*	0
SO_2 Flow	lb/h	0.01	0.01	0.00	🟦	
H_2SO_4 Flow	lb/h	🟦	🟦	🟦		
NOx Flow	lb/h	0.65	0.58	0.07	🟦	
THC Flow	lb/h	0.00	0.00	0.00	🟦	
Total Filterable Particulate	lb/h	🟦	0.06	🟦		
Hg	mg/h	🟦	2.45	🟦		🟦
CO_2 Flow	lb/h	2,247	200	2,047	1,736	
	metric tonne/h	1.02	0.09	0.93	0.79	

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.17	**Avg. Electrical Use**	41.1	**Total Cooling Duty**	2.94
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.47	**Specific Electrical Use**	44.2	**Specific Cooling Duty**	3.34
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.12		40.1		2.87

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**		**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**		**Removed (Supply-Return) mg/h**
Antimony	<1.44			<5.67			
Arsenic	<1.64			<2.75			
Barium							
Beryllium	<0.071			<0.093			
Cadmium	<0.72			<0.91			
Chromium	<8.58			1.53	5.85		
Cobalt	<0.72			<0.91			
Lead	<1.44			<4.27			
Manganese	18.90	78.58		28.5	108.95		-30.37
Nickel	<13.0			2.75	10.51		
Selenium	9.20	38.25		4.49	17.16		21.08
Silver							
Thallium							
Mercury	0.54	2.25		0.64	2.45		-0.20

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▨ Gray Cell Indicates No Measurement. < Indicates Value Below Instrument or Method Accuracy.

Indicates Value Is Below Instrument Detection Limit

Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 2, PM-2

Start 6/16/16 16:59
Stop 6/16/16 18:59

Summary				**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	12,007	*isokinetically*			
CO_2 Captured	%	93.5	*(supply-return)/supply*	O_2	ppmv dry	🟦
CO_2 Recovery	%	85.3	*produced/captured*	CO_2	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO_2	2.18	*per CO_2 captured*			
Specific Electrical Use	kWh/ton CO_2	42.57	*per CO_2 captured*			
Total Cooling Load	MMBtu/ton CO_2	2.68	*per CO2 captured*			

Stream Data		**Flue Gas Supply (Absorber In)**	**Depleted Flue Gas (Absorber Out)**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**	
Temperature	^oF	93.0	105.0		87.6		
Pressure	psig	0.43	0.10		-0.93		
Total Flow	acfm	2,670	2,643				
Total Flow	lb/hr	12,007	10,614		2,023		
H_2O	vol. %, wet	5.1	7.5				
CO_2	vol. %, dry	12.8	0.9		100.0		
O_2	vol. %, dry	6.3	7.4		🟦		ppmv dry
N_2	vol. %, dry	80.9	91.7				
MW	lb/lb-mol, wet	29.7	27.7		🟦		
Sulfite	mg/l					333.7	
Sulfate	mg/l					104,650	
Total Solids	mg/l					149,700	
SO_2 (cem's)	ppmv, dry	0.1	0.6		🟦		
H_2SO_4	ppmv, dry	🟦	🟦				
NOx	ppmv, dry	39.5	47.4		🟦		
THC	ppmv, dry	0.1	0.0		0.8		wet
Total Filterable Particulate	gr/dscf	0.0005	0.0017				
Hg	µg/dscm	0.47	0.77				
H_2O Flow	lb/h	372	515	-143	*	0	
SO_2 Flow	lb/h	0.00	0.01	-0.01	🟦		
H_2SO_4 Flow	lb/h	🟦	🟦	🟦			
NOx Flow	lb/h	0.77	0.77	0.00	🟦		
THC Flow	lb/h	0.00	0.00	0.00	🟦		
Total Filterable Particulate	lb/h	0.01	0.03	-0.02			
Hg	mg/h	1.97	2.98	-1.01		🟦	
CO_2 Flow	lb/h	2,163	140	2,023	1,706		
	metric tonne/h	0.98	0.06	0.92	0.77		

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.21	**Avg. Electrical Use**	43.1	**Total Cooling Duty**	2.71
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.54	**Specific Electrical Use**	46.9	**Specific Cooling Duty**	3.12
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.18		42.6		2.68

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**		**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**		**Removed (Supply-Return) mg/h**
Antimony	<0.88			<1.13			
Arsenic	<0.88			<1.54			
Barium							
Beryllium	<0.048			<0.058			
Cadmium	<0.44			<0.56			
Chromium	<3.60			8.91	34.48		
Cobalt	<0.44			<0.83			
Lead	2.00	8.38		<3.09			
Manganese	8.50	35.60		<15.00			
Nickel	6.50	27.22		4.76	18.42		8.80
Selenium	2.50	10.47		16.1	62.31		-51.84
Silver							
Thallium							
Mercury	0.47	1.97		0.77	2.98		-1.01

🟦 Blue Cell Indicates Samples or Analysis Not Collected During the Test, or Sample Not Representative.
⬜ Gray Cell Indicates No Measurement.   < Indicates Value Below Instrument or Method Accuracy.
🟧 Indicates Value Is Below Instrument Detection Limit

Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 3, PM-3

Start **6/17/16 8:32**
Stop **6/17/16 10:32**

Summary					**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	12,044	*isokinetically*				
CO_2 Captured	%	87.8	*(supply-return)/supply*		O_2	ppmv dry	
CO_2 Recovery	%	83.1	*produced/captured*		CO_2	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO_2	2.08	*per CO_2 captured*				
Specific Electrical Use	kWh/ton CO_2	41.90	*per CO_2 captured*				
Total Cooling Load	MMBtu/ton CO_2	2.70	*per CO2 captured*				

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	^oF	94.0	106.0		79.5	
Pressure	psig	0.45	0.14		-1.11	
Total Flow	acfm	2,674	2,467			
Total Flow	lb/hr	12,044	9,959		2,001	
H_2O	vol. %, wet	5.3	7.6			
CO_2	vol. %, dry	13.5	1.9		100.0	
O_2	vol. %, dry	5.9	6.7			ppmv dry
N_2	vol. %, dry	80.6	91.4			
MW	lb/lb-mol, wet	29.7	27.8			
Sulfite	mg/l					938.2
Sulfate	mg/l					114,040
Total Solids	mg/l					148,800
SO_2 (cem's)	ppmv, dry	0.3	0.3			
H_2SO_4	ppmv, dry					
NOx	ppmv, dry	38.1	46.1			
THC	ppmv, dry	0.1	0.0		0.5	wet
Total Filterable Particulate	gr/dscf	<0.000081	0.0024			
Hg	µg/dscm	0.24	0.32			
H_2O Flow	lb/h	388	492	-104	*	0
SO_2 Flow	lb/h	0.01	0.01	0.00		
H_2SO_4 Flow	lb/h					
NOx Flow	lb/h	0.75	0.70	0.05		
THC Flow	lb/h	0.00	0.00	0.00		
Total Filterable Particulate	lb/h	<0.0017	0.04			
Hg	mg/h	1.00	1.16	-0.15		
CO_2 Flow	lb/h	2,278	277	2,001	1,617	
	metric tonne/h	1.03	0.13	0.91	0.73	

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.08	**Avg. Electrical Use**	41.9	**Total Cooling Duty**	2.70
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.41	**Specific Electrical Use**	46.2	**Specific Cooling Duty**	3.14
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.08		41.9		2.70

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**	**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**	**Removed (Supply-Return) mg/h**
Antimony	<0.96		<1.19		
Arsenic	<1.02		<1.62		
Barium					
Beryllium	<0.049		<0.062		
Cadmium	<0.48		<0.60		
Chromium	<1.26		7.5	27.12	
Cobalt	<0.48		<0.60		
Lead	<1.49		<4.14		
Manganese	<8.70				
Nickel	<2.10		7.59	27.44	
Selenium	8.80	36.83	5.24	18.95	17.88
Silver					
Thallium					
Mercury	0.24	1.00	0.32	1.16	-0.15

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▩ Gray Cell Indicates No Measurement. < Indicates Value Below Instrument or Method Accuracy.
🟧 Indicates Value Is Below Instrument Detection Limit

Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 4, SO3-1

Start	**6/17/16 11:32**
Stop	**6/17/16 12:55**

Summary			
Inlet Flue Gas Flow Rate	lb/h	11,947	*isokinetically*
CO_2 Captured	%	88.0	*(supply-return)/supply*
CO_2 Recovery	%	85.3	*produced/captured*
Specific Thermal Use	MMBtu/ton CO_2	2.06	*per CO_2 captured*
Specific Electrical Use	kWh/ton CO_2	42.03	*per CO_2 captured*
Total Cooling Load	MMBtu/ton CO_2	2.92	*per CO2 captured*

Captured CO_2 Composition		
O_2	ppmv dry	
CO_2	vol. % dry	100.0

Stream Data		Flue Gas Supply	Depleted Flue Gas	Removed (Supply - Return)	Captured CO_2	Scrubber Blowdown
Temperature	°F	95.0	104.0		86.4	
Pressure	psig	0.45	0.12		-1.14	
Total Flow	acfm	2,653	2,414			
Total Flow	lb/hr	11,947	9,767		2,003	
H_2O	vol. %, wet	5.4	7.3			
CO_2	vol. %, dry	13.6	1.9		100.0	
O_2	vol. %, dry	5.9	6.7			ppmv dry
N_2	vol. %, dry	80.5	91.4			
MW	lb/lb-mol, wet	29.7	27.8			
Sulfite	mg/l					938.2
Sulfate	mg/l					114,040
Total Solids	mg/l					148,800
SO_2	ppmv, dry	0.5	0.7			
H_2SO_4	ppmv, dry	<0.12	<0.12			
NOx	ppmv, dry	38.3	45.1			
THC	ppmv, dry	0.1	0.0			wet
Total Filterable Particulate	gr/dscf	n/a	n/a			
Hg	µg/dscm	0.00	0.00			
H_2O Flow	lb/h	387	463	-76	*	0
SO_2 Flow	lb/h	0.013	0.015	-0.002		
H_2SO_4 Flow	lb/h	<0.0044	<0.0037			
NOx Flow	lb/h	0.75	0.68	0.07		
THC Flow	lb/h	0.00	0.00	0.00		
Total Filterable Particulate	lb/h					
Hg	mg/h					
CO_2 Flow	lb/h	2,275	272	2,003	1,670	
	metric tonne/h	1.03	0.12	0.91	0.76	

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.07	**Avg. Electrical Use**	42.1	**Total Cooling Duty**	2.92
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.40	**Specific Electrical Use**	46.3	**Specific Cooling Duty**	3.40
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.06		42.0		2.92

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**	**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**	**Removed (Supply-Return) mg/h**
Antimony					
Arsenic					
Barium					
Beryllium					
Cadmium					
Chromium					
Cobalt					
Lead					
Manganese					
Nickel					
Selenium					
Silver					
Thallium					
Mercury					

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□ Indicates Value Is Below Instrument Detection Limit

Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 5, SO3-2

Start	**6/17/16 13:15**
Stop	**6/17/16 14:15**

Summary					**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	11,953	*isokinetically*				
CO_2 Captured	%	88.3	*(supply-return)/supply*		O_2	ppmv dry	🟦
CO_2 Recovery	%	85.0	*produced/captured*		CO_2	vol. % dry	99.7
Specific Thermal Use	MMBtu/ton CO_2	2.07	*per CO_2 captured*				
Specific Electrical Use	kWh/ton CO_2	42.06	*per CO_2 captured*				
Total Cooling Load	MMBtu/ton CO_2	2.87	*per CO2 captured*				

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**	
Temperature	°F	94.0	103.0		88.4		
#NAME?	psig	0.45	0.11		-1.12		
Total Flow	acfm	2,653	2,484				
Total Flow	lb/hr	11,953	10,051		2,011		
H_2O	vol. %, wet	5.3	7.2				
CO_2	vol. %, dry	13.6	1.8		99.7		
O_2	vol. %, dry	5.9	6.7		🟦	ppmv dry	
N_2	vol. %, dry	80.5	91.5				
MW	lb/lb-mol, wet	29.8	27.8		🟦		
Sulfite	mg/l					938.2	
Sulfate	mg/l					114,040	
Total Solids	mg/l					148,800	
SO_2	ppmv, dry	0.5	0.7		🟦		
H_2SO_4	ppmv, dry	0.4	<0.12				
NOx	ppmv, dry	39.7	44.5		🟦		
THC	ppmv, dry	0.2	0.0		🟦	wet	
Total Filterable Particulate	gr/dscf	n/a	n/a				
Hg	µg/dscm	0.00	0.00				
H_2O Flow	lb/h	381	467	-86	*	0	
SO_2 Flow	lb/h	0.013	0.015	-0.002	🟦		
H_2SO_4 Flow	lb/h	0.01	<0.0037				
NOx Flow	lb/h	0.77	0.69	0.09	🟦		
THC Flow	lb/h	0.00	0.00	0.00	🟦		
Total Filterable Particulate	lb/h	🟦	🟦	🟦			
Hg	mg/h	🟦	🟦	🟦		🟦	
CO_2 Flow	lb/h	2,277	266	2,011	1,671		
	metric tonne/h	1.03	0.12	0.91	0.76		

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.08	**Avg. Electrical Use**	42.3	**Total Cooling Duty**	2.89
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.41	**Specific Electrical Use**	46.4	**Specific Cooling Duty**	3.34
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.07		42.1		2.87

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**		**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**		**Removed (Supply-Return) mg/h**
Antimony	🟦	🟦		🟦	🟦		🟦
Arsenic	🟦	🟦		🟦	🟦		🟦
Barium							
Beryllium	🟦	🟦		🟦	🟦		🟦
Cadmium	🟦	🟦		🟦	🟦		🟦
Chromium	🟦	🟦		🟦	🟦		🟦
Cobalt	🟦	🟦		🟦	🟦		🟦
Lead	🟦	🟦		🟦	🟦		🟦
Manganese	🟦	🟦		🟦	🟦		🟦
Nickel	🟦	🟦		🟦	🟦		🟦
Selenium	🟦	🟦		🟦	🟦		🟦
Silver							
Thallium							
Mercury	🟦	🟦		🟦	🟦		🟦

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🟧 Indicates Value Is Below Instrument Detection Limit

Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 6, SO3-3

Start **6/17/16 14:29**
Stop **6/17/16 15:29**

Summary					**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	11,891	*isokinetically*				
CO_2 Captured	%	87.7	*(supply-return)/supply*		O_2	ppmv dry	
CO_2 Recovery	%	85.4	*produced/captured*		CO_2	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO_2	2.10	*per CO_2 captured*				
Specific Electrical Use	kWh/ton CO_2	42.66	*per CO_2 captured*				
Total Cooling Load	MMBtu/ton CO_2	2.89	*per CO2 captured*				

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	^oF	94.0	103.0		88.8	
Pressure	psig	0.44	0.11		-1.12	
Total Flow	acfm	2,644	2,605			
Total Flow	lb/hr	11,891	10,542		1,984	
H_2O	vol. %, wet	5.3	7.1			
CO_2	vol. %, dry	13.6	1.8		100.0	
O_2	vol. %, dry	5.9	6.7			ppmv dry
N_2	vol. %, dry	80.5	91.5			
MW	lb/lb-mol, wet	29.8	27.8			
Sulfite	mg/l					938.2
Sulfate	mg/l					114,040
Total Solids	mg/l					148,800
SO_2	ppmv, dry	0.5	0.7			
H_2SO_4	ppmv, dry	<0.12	<0.12			
NOx	ppmv, dry	39.5	46.7			
THC	ppmv, dry	0.2	0.0			wet
Total Filterable Particulate	gr/dscf	n/a	n/a			
Hg	µg/dscm	0.00	0.00			
H_2O Flow	lb/h	380	481	-101	*	0
SO_2 Flow	lb/h	0.012	0.015	-0.003		
H_2SO_4 Flow	lb/h	<0.0044	<0.0037			
NOx Flow	lb/h	0.77	0.76	0.01		
THC Flow	lb/h	0.00	0.00	0.00		
Total Filterable Particulate	lb/h					
Hg	mg/h					
CO_2 Flow	lb/h	2,263	279	1,984	1,655	
	metric tonne/h	1.03	0.13	0.90	0.75	

	MMBtu/h		kW		MMBtu/h	
Total Thermal Use	2.08	**Avg. Electrical Use**	42.3	**Total Cooling Duty**	2.87	
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2	
Specific Thermal Use	2.44	**Specific Electrical Use**	47.0	**Specific Cooling Duty**	3.37	
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2	
	2.10		42.7		2.89	

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**	**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**	**Removed (Supply-Return) mg/h**
Antimony					
Arsenic					
Barium					
Beryllium					
Cadmium					
Chromium					
Cobalt					
Lead					
Manganese					
Nickel					
Selenium					
Silver					
Thallium					
Mercury					

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Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 7, NH3-1

Start	**6/18/16 8:05**
Stop	**6/18/16 9:05**

Summary				**Captured CO$_2$ Composition**		
Inlet Flue Gas Flow Rate	lb/h	11,832	*isokinetically*			
CO$_2$ Captured	%	94.0	*(supply-return)/supply*	O$_2$	ppmv dry	30.4
CO$_2$ Recovery	%	87.2	*produced/captured*	CO$_2$	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO$_2$	2.20	*per CO$_2$ captured*			
Specific Electrical Use	kWh/ton CO$_2$	46.99	*per CO$_2$ captured*			
Total Cooling Load	MMBtu/ton CO$_2$	2.83	*per CO2 captured*			

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO$_2$**	**Scrubber Blowdown**
Temperature	°F	93.0	101.0		73.2	
Pressure	psig	0.51	0.17		-0.74	
Total Flow	acfm	2,621	2,472			
Total Flow	lb/hr	11,832	10,119		1,870	
H$_2$O	vol. %, wet	5.1	6.7			
CO$_2$	vol. %, dry	11.9	0.8		100.0	
O$_2$	vol. %, dry	7.3	8.5		30.4	ppmv dry
N$_2$	vol. %, dry	80.8	90.7			
MW	lb/lb-mol, wet	29.6	27.8		44.2	dry
Sulfite	mg/l					448.6
Sulfate	mg/l					128,330
Total Solids	mg/l					152,100
SO$_2$	ppmv, dry	0.2	0.9		🟦	
NH$_3$	ppmv, dry	<0.017	1.0		0.15	
NOx	ppmv, dry	38.9	46.3		🟦	
THC	ppmv, dry	0.2	0.0		🟦	wet
Total Filterable Particulate	gr/dscf	🟦	🟦			
Hg	µg/dscm	🟦	🟦			
H$_2$O Flow	lb/h	368	438	-70	*	0
SO$_2$ Flow	lb/h	0.00	0.02	-0.02	🟦	
NH$_3$ Flow	lb/h	n/a	0.006	n/a	0.000	
NOx Flow	lb/h	0.75	0.72	0.03	🟦	
THC Flow	lb/h	0.00	0.00	0.00	🟦	
Total Filterable Particulate	lb/h	🟦	🟦	🟦		
Hg	mg/h	🟦	🟦	🟦		🟦
CO$_2$ Flow	lb/h	1,990	120	1,870	1,615	
	metric tonne/h	0.90	0.05	0.85	0.73	

	MMBtu/h			kW			MMBtu/h
Total Thermal Use	2.06		**Avg. Electrical Use**	43.9		**Total Cooling Duty**	2.65
	GJ/tonne CO$_2$			kWh/tonne CO$_2$			GJ/ltonne CO$_2$
Specific Thermal Use	2.56		**Specific Electrical Use**	51.8		**Specific Cooling Duty**	3.30
	MMBtu/ton CO$_2$			kWh/ton CO$_2$			MMBtu/ton CO$_2$
	2.20			47.0			2.83

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**		**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**		**Removed (Supply-Return) mg/h**
Antimony	🟦	🟦		🟦	🟦		🟦
Arsenic	🟦	🟦		🟦	🟦		🟦
Barium							
Beryllium	🟦	🟦		🟦	🟦		🟦
Cadmium	🟦	🟦		🟦	🟦		🟦
Chromium	🟦	🟦		🟦	🟦		🟦
Cobalt	🟦	🟦		🟦	🟦		🟦
Lead	🟦	🟦		🟦	🟦		🟦
Manganese	🟦	🟦		🟦	🟦		🟦
Nickel	🟦	🟦		🟦	🟦		🟦
Selenium	🟦	🟦		🟦	🟦		🟦
Silver							
Thallium							
Mercury	🟦	🟦		🟦	🟦		🟦

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Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 8, NH3-2

Start **6/18/16 9:18**
Stop **6/18/16 10:18**

Summary			
Inlet Flue Gas Flow Rate	lb/h	11,718	*isokinetically*
CO_2 Captured	%	94.9	*(supply-return)/supply*
CO_2 Recovery	%	87.1	*produced/captured*
Specific Thermal Use	MMBtu/ton CO_2	2.22	*per CO_2 captured*
Specific Electrical Use	kWh/ton CO_2	47.26	*per CO_2 captured*
Total Cooling Load	MMBtu/ton CO_2	2.81	*per CO2 captured*

Captured CO_2 Composition		
O_2	ppmv dry	29.6
CO_2	vol. % dry	100.0

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	°F	94.0	101.0		73.4	
Pressure	psig	0.51	0.19		-0.74	
Total Flow	acfm	2,592	2,377			
Total Flow	lb/hr	11,718	9,746		1,867	
H_2O	vol. %, wet	5.2	6.5			
CO_2	vol. %, dry	11.9	0.7		100.0	
O_2	vol. %, dry	7.4	8.5		29.6	ppmv dry
N_2	vol. %, dry	80.7	90.8			
MW	lb/lb-mol, wet	29.6	27.8		44.3	dry
Sulfite	mg/l					448.6
Sulfate	mg/l					128,330
Total Solids	mg/l					152,100
SO_2 (CEM'S)	ppmv, dry	0.1	0.6		🟦	
NH_3	ppmv, dry	<0.017	0.7		0.32	
NOx	ppmv, dry	37.6	43.7		🟦	
THC	ppmv, dry	0.2	0.0		🟦	wet
Total Filterable Particulate	gr/dscf	🟦	🟦			
Hg	µg/dscm	🟦	🟦			
H_2O Flow	lb/h	367	412	-45	*	0
SO_2 Flow (CEM'S)	lb/h	0.00	0.01	-0.01	🟦	
NH_3 Flow	lb/h	n/a	0.004	n/a	0.000	
NOx Flow	lb/h	0.72	0.66	0.06	🟦	
THC Flow	lb/h	0.00	0.00	0.00	🟦	
Total Filterable Particulate	lb/h	🟦	🟦	🟦		
Hg	mg/h	🟦	🟦	🟦		🟦
CO_2 Flow	lb/h	1,968	101	1,867	1,613	
	metric tonne/h	0.89	0.05	0.85	0.73	

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.07	**Avg. Electrical Use**	44.1	**Total Cooling Duty**	2.62
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.58	**Specific Electrical Use**	52.1	**Specific Cooling Duty**	3.27
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.22		47.3		2.81

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**	**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**	**Removed (Supply-Return) mg/h**
Antimony	🟦	🟦	🟦	🟦	🟦
Arsenic	🟦	🟦	🟦	🟦	🟦
Barium					
Beryllium	🟦	🟦	🟦	🟦	🟦
Cadmium	🟦	🟦	🟦	🟦	🟦
Chromium	🟦	🟦	🟦	🟦	🟦
Cobalt	🟦	🟦	🟦	🟦	🟦
Lead	🟦	🟦	🟦	🟦	🟦
Manganese	🟦	🟦	🟦	🟦	🟦
Nickel	🟦	🟦	🟦	🟦	🟦
Selenium	🟦	🟦	🟦	🟦	🟦
Silver					
Thallium					
Mercury	🟦	🟦	🟦	🟦	🟦

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Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 9, NH3-3

Start	**6/18/16 10:28**
Stop	**6/18/16 11:28**

Summary				**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	12,063	*isokinetically*			
CO_2 Captured	%	94.1	*(supply-return)/supply*	O_2	ppmv dry	28.7
CO_2 Recovery	%	85.3	*produced/captured*	CO_2	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO_2	2.16	*per CO_2 captured*			
Specific Electrical Use	kWh/ton CO_2	46.16	*per CO_2 captured*			
Total Cooling Load	MMBtu/ton CO_2	2.73	*per CO2 captured*			

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	°F	93.0	100.0		73.5	
Pressure	psig	0.51	0.19		-0.74	
Total Flow	acfm	2,664	2,449			
Total Flow	lb/hr	12,063	10,072		1,907	
H_2O	vol. %, wet	5.1	6.5			
CO_2	vol. %, dry	11.9	0.8		100.0	
O_2	vol. %, dry	7.4	8.5		28.7	ppmv dry
N_2	vol. %, dry	80.7	90.7			
MW	lb/lb-mol, wet	29.6	27.8		44.3	dry
Sulfite	mg/l					448.6
Sulfate	mg/l					128,330
Total Solids	mg/l					152,100
SO_2 (CEM'S)	ppmv, dry	0.1	0.5			
NH_3	ppmv, dry	<0.017	1.2		0.38	
NOx	ppmv, dry	39.1	45.4			
THC	ppmv, dry	0.1	0.0			wet
Total Filterable Particulate	gr/dscf					
Hg	µg/dscm					
H_2O Flow	lb/h	377	422	-45	*	0
SO_2 Flow (CEM'S)	lb/h	0.00	0.01	-0.01		
NH_3 Flow	lb/h	n/a	0.007	n/a	0.000	
NOx Flow	lb/h	0.77	0.71	0.07		
THC Flow	lb/h	0.00	0.00	0.00		
Total Filterable Particulate	lb/h					
Hg	mg/h					
CO_2 Flow	lb/h	2,026	119	1,907	1,610	
	metric tonne/h	0.92	0.05	0.86	0.73	

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.06	**Avg. Electrical Use**	44.0	**Total Cooling Duty**	2.60
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.52	**Specific Electrical Use**	50.9	**Specific Cooling Duty**	3.18
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.16		46.2		2.73

	Flue Gas Supply, µg/dscm	**Flue Gas Supply, mg/h**	**Depleted Flue Gas, µg/dscm**	**Depleted Flue Gas, mg/h**	**Removed (Supply-Return) mg/h**
Antimony					
Arsenic					
Barium					
Beryllium					
Cadmium					
Chromium					
Cobalt					
Lead					
Manganese					
Nickel					
Selenium					
Silver					
Thallium					
Mercury					

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Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 10, ALDH-1

Start 6/18/16 12:03
Stop 6/18/16 13:03

Summary				**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	12,082	*isokinetically*			
CO_2 Captured	%	94.2	*(supply-return)/supply*	O_2	ppmv dry	22.4
CO_2 Recovery	%	85.4	*produced/captured*	CO_2	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO_2	2.16	*per CO_2 captured*			
Specific Electrical Use	kWh/ton CO_2	46.04	*per CO_2 captured*			
Total Cooling Load	MMBtu/ton CO_2	2.65	*per CO2 captured*			

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	°F	93.0	102.0		73.9	
Pressure	psig	0.52	0.19		-0.73	
Total Flow	acfm	2,661	2,422			
Total Flow	lb/hr	12,082	9,937		1,912	
H_2O	vol. %, wet	5.1	6.7			
CO_2	vol. %, dry	11.9	0.8		100.0	
O_2	vol. %, dry	7.4	8.5		22.4	ppmv dry
N_2	vol. %, dry	80.7	90.7			
MW	lb/lb-mol, wet	29.6	27.8		44.4	dry
Sulfite	mg/l					448.6
Sulfate	mg/l					128,330
Total Solids	mg/l					152,100
SO_2 (CEM'S)	ppmv, dry	0.1	0.5			
NH_3	ppmv, dry					
NOx	ppmv, dry	38.4	44.3			
THC	ppmv, dry	0.1	0.0			wet
Total Filterable Particulate	gr/dscf					
Hg	µg/dscm					
H_2O Flow	lb/h	373	434	-61	*	0
SO_2 Flow (CEM'S)	lb/h	0.00	0.01	-0.01		
NH_3 Flow	lb/h					
NOx Flow	lb/h	0.76	0.68	0.08		
THC Flow	lb/h	0.00	0.00	0.00		
Total Filterable Particulate	lb/h					
Hg	mg/h					
CO_2 Flow	lb/h	2,030	118	1,912	1,615	
	metric tonne/h	0.92	0.05	0.87	0.73	

	MMBtu/h			kW			MMBtu/h
Total Thermal Use	2.06		**Avg. Electrical Use**	44.0		**Total Cooling Duty**	2.53
	GJ/tonne CO_2			kWh/tonne CO_2			GJ/ltonne CO_2
Specific Thermal Use	2.51		**Specific Electrical Use**	50.7		**Specific Cooling Duty**	3.08
	MMBtu/ton CO_2			kWh/ton CO_2			MMBtu/ton CO_2
	2.16			46.0			2.65

	Absorber Inlet, µg/dscm	**Absorber Inlet, mg/h**		**Absorber Outlet, µg/dscm**	**Absorber Outlet, mg/h**		**Removed (Supply-Return) mg/h**
Formaldehyde	41.0	173.4		60.9	221.8		-48.5
Acetaldehyde	8.4	35.5		220.4	802.8		-767.3
Acetophenone	<0.71			<1.5			
Isophonone	<0.71			<1.5			
Propionaldehyde	<0.71			<1.5			

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Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 11, ALDH-2

Start	**6/18/16 13:26**
Stop	**6/18/16 14:26**

Summary					**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	11,645	*isokinetically*				
CO_2 Captured	%	93.2	*(supply-return)/supply*		O_2	ppmv dry	21.0
CO_2 Recovery	%	88.3	*produced/captured*		CO_2	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO_2	2.24	*per CO_2 captured*				
Specific Electrical Use	kWh/ton CO_2	48.16	*per CO_2 captured*				
Total Cooling Load	MMBtu/ton CO_2	2.86	*per CO2 captured*				

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	°F	93.0	101.0		74.4	
Pressure	psig	0.52	0.19		-0.74	
Total Flow	acfm	2,567	2,430			
Total Flow	lb/hr	11,645	10,010		1,823	
H_2O	vol. %, wet	5.1	6.6			
CO_2	vol. %, dry	11.9	0.9		100.0	
O_2	vol. %, dry	7.4	8.5		21.0	ppmv dry
N_2	vol. %, dry	80.7	90.6			
MW	lb/lb-mol, wet	29.6	27.8		44.5	dry
Sulfite	mg/l					448.6
Sulfate	mg/l					128,330
Total Solids	mg/l					152,100
SO_2 (CEM'S)	ppmv, dry	0.1	0.5		🟦	
NH_3	ppmv, dry	🟦	🟦		🟦	
NOx	ppmv, dry	36.4	41.9		🟦	
THC	ppmv, dry	0.0	0.0		🟦	wet
Total Filterable Particulate	gr/dscf	🟦	🟦			
Hg	µg/dscm	🟦	🟦			
H_2O Flow	lb/h	362	426	-64	*	0
SO_2 Flow (CEM'S)	lb/h	0.00	0.01	-0.01	🟦	
NH_3 Flow	lb/h	🟦	🟦	🟦	🟦	
NOx Flow	lb/h	0.69	0.65	0.05	🟦	
THC Flow	lb/h	0.00	0.00	0.00	🟦	
Total Filterable Particulate	lb/h	🟦	🟦	🟦		
Hg	mg/h	🟦	🟦	🟦		🟦
CO_2 Flow	lb/h	1,956	133	1,823	1,593	
	metric tonne/h	0.89	0.06	0.83	0.72	

	MMBtu/h			kW			MMBtu/h
Total Thermal Use	2.04		**Avg. Electrical Use**	43.9		**Total Cooling Duty**	2.61
	GJ/tonne CO_2			kWh/tonne CO_2			GJ/ltonne CO_2
Specific Thermal Use	2.60		**Specific Electrical Use**	53.1		**Specific Cooling Duty**	3.33
	MMBtu/ton CO_2			kWh/ton CO_2			MMBtu/ton CO_2
	2.24			48.2			2.86

	Absorber Inlet, µg/dscm	**Absorber Inlet, mg/h**		**Absorber Outlet, µg/dscm**	**Absorber Outlet, mg/h**		**Removed (Supply-Return) mg/h**
Formaldehyde	50.9	207.7		56.8	210.5		-2.8
Acetaldehyde	14.6	59.6		260.3	964.6		-905.0
Acetophenone	<1.7			<2.7			
Isophonone	<1.7			<2.7			
Propionaldehyde	<1.7			<2.7			

🟦 Blue Cell Indicates Samples or Analysis Not Collected During the Test, or Sample Not Representative.

▨ Gray Cell Indicates No Measurement. < Indicates Value Below Instrument or Method Accuracy.

🟧 Indicates Value Is Below Instrument Detection Limit

Southern Company Plant Gaston - National Carbon Capture Center (NCCC)
Linde-BASF Post Combustion CO2 Capture Plant
Campaign Test Results
Test 12, ALDH-3

Start 6/18/16 14:48
Stop 6/18/16 15:48

Summary				**Captured CO_2 Composition**		
Inlet Flue Gas Flow Rate	lb/h	12,013	*isokinetically*			
CO_2 Captured	%	92.8	*(supply-return)/supply*	O_2	ppmv dry	20.3
CO_2 Recovery	%	85.3	*produced/captured*	CO_2	vol. % dry	100.0
Specific Thermal Use	MMBtu/ton CO_2	2.16	*per CO_2 captured*			
Specific Electrical Use	kWh/ton CO_2	46.87	*per CO_2 captured*			
Total Cooling Load	MMBtu/ton CO_2	2.70	*per CO2 captured*			

Stream Data		**Flue Gas Supply**	**Depleted Flue Gas**	**Removed (Supply - Return)**	**Captured CO_2**	**Scrubber Blowdown**
Temperature	°F	93.0	101.0		74.8	
Pressure	psig	0.52	0.21		-0.73	
Total Flow	acfm	2,646	2,398			
Total Flow	lb/hr	12,013	9,883		1,888	
H_2O	vol. %, wet	5.1	6.5			
CO_2	vol. %, dry	12.0	1.0		100.0	
O_2	vol. %, dry	7.3	8.4		20.3	ppmv dry
N_2	vol. %, dry	80.7	90.6			
MW	lb/lb-mol, wet	29.6	27.8		44.5	dry
Sulfite	mg/l					448.6
Sulfate	mg/l					128,330
Total Solids	mg/l					152,100
SO_2 (CEM'S)	ppmv, dry	0.1	0.5			
NH_3	ppmv, dry					
NOx	ppmv, dry	37.0	42.7			
THC	ppmv, dry	0.1	0.0			wet
Total Filterable Particulate	gr/dscf					
Hg	µg/dscm					
H_2O Flow	lb/h	372	418	-46	*	0
SO_2 Flow (CEM'S)	lb/h	0.00	0.01	-0.01		
NH_3 Flow	lb/h					
NOx Flow	lb/h	0.73	0.65	0.08		
THC Flow	lb/h	0.00	0.00	0.00		
Total Filterable Particulate	lb/h					
Hg	mg/h					
CO_2 Flow	lb/h	2,034	146	1,888	1,589	
	metric tonne/h	0.92	0.07	0.86	0.72	

	MMBtu/h		kW		MMBtu/h
Total Thermal Use	2.04	**Avg. Electrical Use**	44.2	**Total Cooling Duty**	2.55
	GJ/tonne CO_2		kWh/tonne CO_2		GJ/ltonne CO_2
Specific Thermal Use	2.51	**Specific Electrical Use**	51.7	**Specific Cooling Duty**	3.14
	MMBtu/ton CO_2		kWh/ton CO_2		MMBtu/ton CO_2
	2.16		46.9		2.70

	Absorber Inlet, µg/dscm	**Absorber Inlet, mg/h**	**Absorber Outlet, µg/dscm**	**Absorber Outlet, mg/h**	**Removed (Supply-Return) mg/h**
Formaldehyde	42.9	181.0	60.7	222.1	-41.2
Acetaldehyde	10.9	46.0	245.9	899.9	-853.9
Acetophenone	<1.6		<2.5		
Isophonone	<1.6		<2.5		
Propionaldehyde	<1.6		<2.5		

🟦 Blue Cell Indicates Samples or Analysis Not Collected During the Test, or Sample Not Representative.
▒ Gray Cell Indicates No Measurement. < Indicates Value Below Instrument or Method Accuracy.
░ Indicates Value Is Below Instrument Detection Limit

D

SECTION 5 TABLES IN SI UNITS

Table 5-1

Summary of Flue Gas Inlet Conditions for 12 Performance Tests.

	Date	Start Time	End Time	Flow m^3/s	Flow kg/h	Temp. ºC	Pressure kPa
Test 1, PM-1	6/16/2016	13:25	14:43	1.2502	5,423	34.4	3.19
Test 2, PM-2	6/16/2016	16:59	18:59	1.2601	5,446	33.9	2.96
Test 3, PM-3	6/17/2016	8:32	10:32	1.2620	5,463	34.4	3.09
Test 4, SO3-1	6/17/2016	11:32	12:54	1.2521	5,419	35.0	3.09
Test 5, SO3-2	6/17/2016	13:15	14:15	1.2521	5,422	34.4	3.09
Test 6, SO3-3	6/17/2016	14:29	15:29	1.2478	5,394	34.4	3.01
Test 7, NH3-1	6/18/2016	8:05	9:05	1.2370	5,367	33.9	3.48
Test 8, NH3-2	6/18/2016	9:18	10:18	1.2233	5,315	34.4	3.48
Test 9, NH3-3	6/18/2016	10:28	11:28	1.2573	5,472	33.9	3.51
Test 10, ALDH-1	6/18/2016	12:03	13:03	1.2559	5,480	33.9	3.61
Test 11, ALDH-2	6/18/2016	13:26	14:26	1.2115	5,282	33.9	3.58
Test 12, ALDH-3	6/18/2016	14:48	15:48	1.2488	5,449	33.9	3.61

Table 5-3

Summary of Flue Gas Capture and Recovery Flow Rates and Percentages

	Flue Gas Supply Flow Rate kg/h wet	Depleted Flue Gas Flow Rate kg/h wet	CO_2 Flow Rate				CO_2 Capture Method*			
			Flue Gas Supply kg/h	Depleted Flue Gas kg/h	Captured kg/h	Product kg/h	1 %	2 %	3 %	4 %
Test 1, PM-1	5,423	4,745	1,019	91	929	788	77.3	89.7	91.1	91.5
Test 2, PM-2	5,446	4,814	981	64	918	774	78.9	92.4	93.5	93.8
Test 3, PM-3	5,463	4,517	1,033	126	908	734	71.0	85.4	87.8	87.6
Test 4, SO3-1	5,419	4,430	1,032	123	909	757	73.4	86.0	88.0	87.7
Test 5, SO3-2	5,422	4,559	1,033	121	912	758	73.4	86.3	88.3	88.4
Test 6, SO3-3	5,394	4,782	1,026	127	900	751	73.1	85.6	87.7	88.4
Test 7, NH3-1	5,367	4,590	903	54	848	733	81.2	93.1	94.0	94.0
Test 8, NH3-2	5,315	4,421	893	46	847	732	82.0	94.1	94.9	94.8
Test 9, NH3-3	5,472	4,569	919	54	865	730	79.4	93.1	94.1	94.0
Test 10, ALDH-1	5,480	4,507	921	54	867	732	79.5	93.2	94.2	94.0
Test 11, ALDH-2	5,282	4,540	887	60	827	723	81.5	92.3	93.2	93.3
Test 12, ALDH-3	5,449	4,483	923	66	856	721	78.1	91.6	92.8	92.6

* See **Error! Reference source not found.**

Table 5-4
Summary of Average Flue Gas Inlet and Outlet Data Collected by CB&I During Testing

	Flue Gas Inlet				Flue Gas Outlet			
	m^3/s	°C	kPa	CO_2 vol.% dry	m^3/s	°C	kPa	CO_2 vol.% dry
Test 1, PM-1	1.2502	34.4	3.1854	13.4	1.2157	38.9	0.8212	1.3
Test 2, PM-2	1.2601	33.9	2.9613	12.8	1.2474	40.6	0.6715	0.9
Test 3, PM-3	1.2620	34.4	3.0854	13.5	1.1643	41.1	0.9453	1.9
Test 4, SO3-1	1.2521	35.0	3.0854	13.6	1.1393	40.0	0.8212	1.9
Test 5, SO3-2	1.2521	34.4	3.0854	13.6	1.1723	39.4	0.7715	1.8
Test 6, SO3-3	1.2478	34.4	3.0109	13.6	1.2294	39.4	0.7467	1.8
Test 7, NH3-1	1.2370	33.9	3.4839	11.9	1.1667	38.3	1.1942	0.8
Test 8, NH3-2	1.2233	34.4	3.4839	11.9	1.1218	38.3	1.2941	0.7
Test 9, NH3-3	1.2573	33.9	3.5087	11.9	1.1558	37.8	1.2941	0.8
Test 10, ALDH-1	1.2559	33.9	3.6080	11.9	1.1431	38.9	1.3190	0.8
Test 11, ALDH-2	1.2115	33.9	3.5832	11.9	1.1468	38.3	1.3438	0.9
Test 12, ALDH-3	1.2488	33.9	3.6080	12.0	1.1317	38.3	1.4183	1.0

Table 5-5
Summary of Average Parameters Used to Calculate CO_2 Recovery

	Linde Measured Product CO_2 kg/h	CB&I Measured CO_2 Depleted Flue Gas kg/h	CB&I Measured CO_2 Supply Flue Gas kg/h	Method 1 CO_2 Recovery % *	Method 2 CO_2 Recovery % *
Test 1, PM-1	787.4	90.7	1,019.2	86.2	84.8
Test 2, PM-2	773.8	63.5	981.1	85.3	84.3
Test 3, PM-3	733.5	125.6	1,033.3	83.1	80.8
Test 4, SO3-1	757.5	123.4	1,031.9	85.3	83.4
Test 5, SO3-2	758.0	120.7	1,032.8	85.0	83.1
Test 6, SO3-3	750.7	126.6	1,026.5	85.4	83.4
Test 7, NH3-1	732.6	54.4	902.6	87.2	86.4
Test 8, NH3-2	731.6	45.8	892.7	87.1	86.4
Test 9, NH3-3	730.3	54.0	919.0	85.3	84.4
Test 10, ALDH-1	732.6	53.5	920.8	85.4	84.5
Test 11, ALDH-2	722.6	60.3	887.2	88.3	87.4
Test 12, ALDH-3	720.8	66.2	922.6	85.3	84.2

* See **Error! Reference source not found.**

Table 5-7
Summary of Steam Temperatures, Pressures, Flows and Energy Usage

	Flue Gas Supply Flow Rate kg/h	Captured CO_2 Flow Rate kg/h	Steam Flow Rate kg/h	Steam Temp. °C	Steam Pressure kPa	Steam Energy Use GJ/h	Specific Steam Energy Use GJ/tonne CO_2
Test 1, PM-1	5,423	929	1,040	178	757.7	2.29	2.46
Test 2, PM-2	5,446	918	1,061	174	756.4	2.33	2.53
Test 3, PM-3	5,463	908	996	173	759.1	2.19	2.42
Test 4, SO3-1	5,419	909	992	173	758.4	2.18	2.39
Test 5, SO3-2	5,422	912	998	174	759.1	2.19	2.41
Test 6, SO3-3	5,394	900	999	174	758.4	2.19	2.44
Test 7, NH3-1	5,367	848	988	173	758.4	2.17	2.56
Test 8, NH3-2	5,315	847	993	174	758.4	2.18	2.58
Test 9, NH3-3	5,472	865	990	174	758.4	2.17	2.51
Test 10, ALDH-1	5,480	867	989	174	758.4	2.17	2.51
Test 11, ALDH-2	5,282	827	977	174	759.1	2.15	2.60
Test 12, ALDH-3	5,449	856	976	174	759.1	2.15	2.51

Table 5-8
Summary of Estimated Auxiliary Electrical Power Use

	Flue Gas Supply Flow Rate kg/h	Captured CO_2 Flow Rate kg/h		Estimated Auxiliary Power kW		Specific Auxiliary Power Use kWh/tonne CO_2
Test 1, PM-1	5,423	929		41.1		44.2
Test 2, PM-2	5,446	918		43.1		47.0
Test 3, PM-3	5,463	908		41.9		46.2
Test 4, SO3-1	5,419	909		42.1		46.3
Test 5, SO3-2	5,422	912		42.3		46.4
Test 6, SO3-3	5,394	900		42.3		47.1
Test 7, NH3-1	5,367	848		43.9		51.8
Test 8, NH3-2	5,315	847		44.1		52.1
Test 9, NH3-3	5,472	865		44.0		50.9
Test 10, ALDH-1	5,480	867		44.0		50.7
Test 11, ALDH-2	5,282	827		43.9		53.1
Test 12, ALDH-3	5,449	856		44.2		51.7

Table 5-9
Summary of Cooling Duty During Performance Testing

	Flue Gas Supply Flow Rate kg/h	Captured CO_2 Flow Rate kg/h		Total Cooling Load GJ/h		Specific Cooling Load GJ/tonne CO_2
Test 1, PM-1	5,423	929		3.10		3.34
Test 2, PM-2	5,446	918		2.86		3.12
Test 3, PM-3	5,463	908		2.85		3.14
Test 4, SO3-1	5,419	909		3.08		3.39
Test 5, SO3-2	5,422	912		3.05		3.34
Test 6, SO3-3	5,394	900		3.03		3.36
Test 7, NH3-1	5,367	848		2.79		3.29
Test 8, NH3-2	5,315	847		2.76		3.27
Test 9, NH3-3	5,472	865		2.74		3.17
Test 10, ALDH-1	5,480	867		2.67		3.08
Test 11, ALDH-2	5,282	827		2.75		3.32
Test 12, ALDH-3	5,449	856		2.69		3.14

Table 5-10
Summary of SO_2 Emissions During Performance Tests

	SO_2 Emissions						
Test No.	**Scrubber Inlet ppmv dry**	**Scrubber Inlet kg/h**	**Absorber Inlet ppmv dry**	**Absorber Inlet kg/h**	**Absorber Outlet ppmv dry**	**Absorber Outlet kg/h**	**% Overall Removal**
Test 4, SO3-1	43.8	0.533	0.5	0.0059	0.7	0.0068	98.7
Test 5, SO3-2	45.0	0.548	0.5	0.0059	0.7	0.0068	98.8
Test 6, SO3-3	43.7	0.536	0.5	0.0054	0.7	0.0068	98.7

Table 5-11
Summary of SO_3 Emissions During Performance Tests

	SO_3 Emissions						
Test No.	**Scrubber Inlet ppmv dry**	**Scrubber Inlet kg/h**	**Absorber Inlet ppmv dry**	**Absorber Inlet kg/h**	**Absorber Outlet ppmv dry**	**Absorber Outlet kg/h**	**% Overall Removal**
Test 4, SO3-1			<0.12	<0.0020	<0.12	<0.0017	
Test 5, SO3-2			0.4	0.045	<0.12	<0.0017	
Test 6, SO3-3			<0.12	<0.0020	<0.12	<0.0017	

Note: Mass emissions in lb/h reported as H_2SO_4

Table 5-12
Summary of NOx Emissions During Performance Tests

Test No.	NOx Emissions						
	Scrubber Inlet ppmv dry	Scrubber Inlet kg/h	Absorber Inlet ppmv dry	Absorber Inlet kg/h	Absorber Outlet ppmv dry	Absorber Outlet kg/h	% Overall Removal
Test 1, PM-1	28.6	0.25	33.3	0.29	35.7	0.26	-4.7
Test 2, PM-2	37.4	0.33	39.5	0.35	47.4	0.35	-6.1
Test 3, PM-3	34.9	0.31	38.1	0.34	46.1	0.32	-3.7
Test 4, SO3-1	33.0	0.29	38.3	0.34	45.1	0.31	-6.9
Test 5, SO3-2	33.4	0.29	39.7	0.35	44.5	0.31	-7.3
Test 6, SO3-3	33.2	0.29	39.5	0.35	46.7	0.34	-18.0
Test 7, NH3-1	35.8	0.32	38.9	0.34	46.3	0.33	-3.3
Test 8, NH3-2	34.2	0.30	37.6	0.33	43.7	0.30	1.2
Test 9, NH3-3	36.0	0.32	39.1	0.35	45.4	0.32	-1.4
Test 10, ALDH-1	34.9	0.31	38.4	0.34	44.3	0.31	-0.3
Test 11, ALDH-2	33.2	0.29	36.4	0.31	41.9	0.29	-0.6
Test 12, ALDH-3	33.5	0.30	37.0	0.33	42.7	0.29	0.6

Table 5-16
Summary of Ammonia Concentrations and Mass Flows During Three Performance Tests

Test No.	NH_3 Emissions					
	Absorber Inlet ppmv dry	Absorber Inlet kg/h	Absorber Outlet ppmv dry	Absorber Outlet kg/h	Captured CO_2 Stream ppmv dry	Captured CO_2 Stream kg/h
Test 7, NH3-1	<0.017	<0.00005	1.000	0.0027	0.150	0.000
Test 8, NH3-2	<0.017	<0.00005	0.720	0.0018	0.320	0.000
Test 9, NH3-3	<0.017	<0.00005	1.200	0.0032	0.380	0.000

E

CB&I TEST REPORT

Emission Test Report

Post-Combustion Carbon Dioxide Capture Process Linde-BASF Pilot Plant at National Carbon Capture Center
Southern Company Plant Gaston
Wilsonville, Alabama

Prepared for
Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, California 94304

Prepared by
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