Flue Gas Aerosol Pretreatment Technologies to Minimize Post-Combustion CO$_2$ Capture (PCC) Solvent Losses

DOE funding award DE-FE0031592

Devin Bostick

2019 NETL CO$_2$ Capture Technology Meeting
August 26, 2019
Pittsburgh, PA

Making our world more productive
Acknowledgement and Disclaimer

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**Project Objectives**

**Overall Objective**

Demonstrate and evaluate two innovative flue gas aerosol pretreatment technologies identified to significantly reduce high aerosol particle concentrations (>10^7 particles/cm³) in the 70-200 nm particle size range:

1) A high velocity water spray-based system with unique design features
2) A novel electrostatic precipitator (ESP) device with optimized design and operating conditions.

In addition, a non-regenerative sorbent technology for SOₓ and NOₓ removal developed by InnoSepra will be evaluated for its aerosol removal potential.

**Specific Objectives**

— Complete an aerosol mechanism literature review and develop a mechanistic model characterizing aerosol formation and interaction with amine solvent in the absorber of a PCC plant

— Design, build, install, commission, and operate the three technologies for flue gas aerosol pretreatment at a coal-fired power plant host site providing the flue gas as a slipstream at a flow rate of 500-1000 scfm

— Complete parametric testing and analysis of each technology to demonstrate achievement of target performance

— Complete a benchmarking study to identify the optimal aerosol pretreatment system for commercial deployment and integration with solvent-based PCC technology
Abbott Power Plant Host Site
- 2 operating coal-fired boilers
- 15 MWe output

SUBAWARDEE
University of Illinois (UIUC)
*Dr. Kevin O’Brien*
- Aerosol mechanisms review
- Host site liaison
- Flue gas & liquid effluent analysis

SUBAWARDEE
InnoSepra
*Dr. Ravi Jain*
- Sorbent material validation tests
- Sorbent material procurement for pilot tests & test result analysis

SUBAWARDEE
Affiliated Construction Services (ACS)
*Greg Larson*
- Detailed engineering and procurement management for high-velocity water spray-based system and sorbent filter vessel
- Construction management for site modifications & module installation

SUBAWARDEE
Washington University in St. Louis (WUSTL)
*Dr. Pratim Biswas*
- Aerosol mechanisms modeling lead
- ESP pretreatment technology owner
- Aerosol particle characterization

PRIME CONTRACTOR
Linde Gas North America LLC
*PI: Devin Bostick*
- Prime contract
- Overall program management
- High velocity water spray-based aerosol pretreatment technology owner

U.S. Department of Energy Sponsorship
*Project Manager: Andy Aurelio*
## Project Timeline & Milestones

**BP1: Design & Engineering**
6/1/2018 - 2/28/2019

**BP2: Procurement, Fabrication & Installation**

**BP3: Testing & Analysis**
12/2/2019 - 11/30/2020

<table>
<thead>
<tr>
<th>Task ID</th>
<th>Milestone</th>
<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A</td>
<td>Updated PMP</td>
<td>06/29/18</td>
</tr>
<tr>
<td>1 B</td>
<td>Kick-Off Meeting</td>
<td>07/27/18</td>
</tr>
<tr>
<td>2 C</td>
<td>Mechanisms review &amp; modeling complete</td>
<td>10/31/18</td>
</tr>
<tr>
<td>3 D</td>
<td>Design &amp; engineering complete</td>
<td>01/31/19</td>
</tr>
<tr>
<td>3 E</td>
<td>Test plan complete</td>
<td>01/31/19</td>
</tr>
<tr>
<td>4 F</td>
<td>Fabrication &amp; procurement complete</td>
<td>08/26/19</td>
</tr>
<tr>
<td>5 G</td>
<td>Installation &amp; commissioning complete</td>
<td>11/29/19*</td>
</tr>
<tr>
<td>6 H</td>
<td>Parametric testing complete</td>
<td>5/1/20*</td>
</tr>
<tr>
<td>7 I</td>
<td>Benchmarking analysis complete</td>
<td>11/30/20*</td>
</tr>
<tr>
<td>8 J</td>
<td>Removal of equipment complete</td>
<td>11/30/20*</td>
</tr>
</tbody>
</table>

*expected completion date
## Project Budget: DOE Funding and Cost Share

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>DOE Funding</td>
<td>$457,822</td>
<td>$1,290,725</td>
<td>$1,078,826</td>
<td>$2,827,374</td>
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<td>Cost Share</td>
<td>$176,612</td>
<td>$260,949</td>
<td>$269,860</td>
<td>$707,421</td>
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<td>Total Project</td>
<td>$634,435</td>
<td>$1,551,674</td>
<td>$1,348,686</td>
<td>$3,534,795</td>
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</tbody>
</table>
Aerosol particle interaction with amine solvent inside PCC absorbers → leads to solvent losses in treated gas

**Phase I**
Aerosol growth and nucleation from water in absorber

**Phase II**
Aerosol growth from amine in absorber

**Phase III**
Buildup of captured CO₂ and amine bound to CO₂ in aerosols

**Phase IV**
Salt accumulation inside particles causing further amine and CO₂ diffusion into aerosols

The Kelvin equation gives the minimum particle diameter, $d^*$, of a liquid → supersaturation leads to nucleation of smaller particles:

$$d^* = \frac{4\sigma M}{\rho RT \ln(p/p_0)}$$

Problem: Amine compounds contained in aerosol particles are then emitted from PCC absorber in treated gas stream.
Benefits of aerosol particle reduction upstream of PCC plant (pretreatment)

- Manageable solvent supply and transport logistics
- Optimum power plant efficiency when integrated with PCC
- Improved PCC plant business case/lower cost
- Environmental sustainability and performance
- Reduces particulate that can unfavorably react with amine solvent
- Improved PCC plant specific energy performance

- Improved PCC plant specific energy performance
- Environmental sustainability and performance
- Reduced particulate that can unfavorably react with amine solvent
- Optimum power plant efficiency when integrated with PCC
- Manageable solvent supply and transport logistics
- Improved PCC plant business case/lower cost
Methods to reduce aerosol-driven solvent losses: Flue gas aerosol pretreatment provides optimum solution

- For power plants integrated with solvent-based PCC **without an existing baghouse**, optimized flue gas aerosol pretreatment is the only viable option to reduce aerosol concentrations from $>10^9$ particles/cm$^3$ to manageable levels near $10^4$-$10^6$ particles/cm$^3$ for particles with diameters in the range of 70-200 nm.

- Pretreatment has traditionally been performed using simple ESPs and Brownian filters.

- Few systematic studies have been conducted to evaluate performance of different technologies over a full range of conditions.

1. Based on single point experience, some options e.g. dry bed conf. may handle higher particle concentrations than others
High velocity water spray-based aerosol pretreatment technology
Developed by RWE & tested in Niederaussem, Germany at lignite-fired coal power plant

Mechanism of action
Water circulates in loop at high velocity and contacts aerosol particles using a spray nozzle comprised of very small holes. Contacting spray causes condensation and growth of particles that are then captured in loop and removed from vapor phase.

Performance
High velocity spray-based pretreatment reduced amine losses ~15-18 times during testing at 0.45 MWₑ PCC pilot in Niederaussum that began in 2009.

Typical inlet flue gas conditions at Abbott Power Plant:
~190 °F
~1 bar
~9.2 mol% CO₂ (dry), ~100-200 ppmv SO₂

Tests
Planned tests will evaluate new nozzle & perforated tray designs and the impact of several operating conditions (flows, temperatures, etc.) on performance.
Advanced ESP-based aerosol pretreatment technology
Developed by Washington University in St. Louis (WUSTL) and tested at NCCC in Wilsonville, AL on 6.5 slpm flue gas sample

Mechanism of action
ESP applies high voltage between plate and wire that ionizes flue gas aerosols. Ionized particles are diverted towards collecting plates for removal. WUSTL’s system will incorporate a patented photo-ionizer technology that enhances particle capture efficiency.

Performance
Based on flue gas testing at the Linde-BASF 1.5 MW_e pilot at NCCC in 2016, WUSTL’s ESP is expected to provide 98-99% removal efficiency for 1000 scfm gas flow and a specific collection area (SCA) of 95 m²/(m³/s), which can be increased to remove more particles in the size range of 10-500 nm.

Tests
Planned tests will evaluate voltage & current effects and the impact of the photo-ionizer on ESP performance. The effect of reduced SO_x from the InnoSepra sorbent filter and the filter’s own aerosol removal performance will also be evaluated.
InnoSepra sorbent filter technology for NO\textsubscript{x} and SO\textsubscript{x} removal
Developed by InnoSepra LLC and tested in Middlesex, NJ lab and at NCCC

Mechanism of action
Cost-effective, sorbent-filter based removal of residual SO\textsubscript{3}, SO\textsubscript{2}, NO\textsubscript{2}, HCl, and HF from PCC flue gas after the FGD and potential for aerosol particle reduction

Performance
Sorbent material validation tests show:
• >99% SO\textsubscript{2} and SO\textsubscript{3} removal for both impregnated and non-impregnated sorbents
• Very high capacities (20-30 wt%) for feed SO\textsubscript{2} & SO\textsubscript{3} concentrations of 5-15 ppmv
• Low material production costs (<$0.20-0.75/lb)
• Best results achieved with impregnated materials → 30 wt% SO\textsubscript{2} capacity for feeds containing 12-30 ppmv SO\textsubscript{2}

Tests
Planned tests will further evaluate the SO\textsubscript{x} and NO\textsubscript{x} reduction & aerosol particle removal capabilities of the InnoSepra sorbent material
Technical Approach

Host Site Setup, Innovation Targets & Success Criteria
Pilot host site: Abbott Power Plant at UIUC in Champaign, IL

Abbott chosen as optimal host site for testing since aerosol concentrations were measured to be among the highest found in scientific literature.
Pilot skid layout at Abbott Host Site

Abbott building wall

Exhaust flue gas duct from boiler after reheat burner

Abbott stack

12’W X 20’L Aerosol pretreatment pilot skid

Movable Analytical Container 34’L X12’W

(1) High velocity spray-based system
(2) ESP system
(3) InnoSepra filter system

To Abbott’s onsite water pretreatment system

Legend
- 8” flue gas piping
- 2” cooling water piping
- ½” potable water piping
- 480V power supply
- 2” process condensate piping
- ½” Instrument air line

Abbott electrostatic precipitators building
Abbott tractor house
Abbott external pollution control building
Abbott external caustic tank
Abbott brine tank
## Pilot test innovation targets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rationale</th>
<th>Expected target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle removal efficiency* for 500-1000 scfm flue gas slipstream (%)</td>
<td>Flue gas aerosol particles in size range 70-200 nm lead to amine losses in the treated gas of amine-based PCC plants</td>
<td>&gt;98%</td>
</tr>
<tr>
<td>Cost competitiveness** (COE = cost of electricity)</td>
<td>Reduced capital and operating costs are required for commercial application of enabling technologies for PCC</td>
<td>COE &lt; $133.20/MWh and cost of CO₂ captured &lt; $58/tonne when compared to DOE-NETL reference case B12B</td>
</tr>
<tr>
<td>Energy efficiency**</td>
<td>Low electricity consumption reduces parasitic load for enabling technologies</td>
<td>Energy consumption &lt; 14 MWe (threshold above which energy consumption greatly impacts COE and cost of CO₂ captured)</td>
</tr>
<tr>
<td>Environmental sustainability when integrated with PCC technology for supercritical coal-fired power plants without a baghouse</td>
<td>Minimal environmental impact is required to meet process safety &amp; regulatory requirements for customers</td>
<td>Process condensate adequately removed &amp; treated as needed; ESP solids removed and treated as needed.</td>
</tr>
</tbody>
</table>

*Particle removal efficiency = \((\text{Particle concentration before aerosol pretreatment (#/cm}^3) - \text{Particle concentration after aerosol pretreatment (#/cm}^3) \)/\((\text{Particle concentration before aerosol pretreatment (#/cm}^3)\) * 100

** when integrated with PCC technology for a 550 MWe supercritical coal-fired power plant without a baghouse
## Decision points and success criteria

<table>
<thead>
<tr>
<th>Decision Point</th>
<th>Date</th>
<th>Success Criteria</th>
</tr>
</thead>
</table>
| Equipment procurement and fabrication of both aerosol pretreatment systems and components for installation | 2/28/2019 | • Successful completion of designs, HAZOP/safety reviews and engineering documents that have been accepted by host site and reviewed by NETL  
• Update of costs based on vendor quotes and cost proposal within budget  
• Preliminary parametric test matrix in accordance with FOA guidelines and agreement with NETL |
| Installation of aerosol pretreatment systems on site                          | 08/30/2019 | • Host site is prepared and ready to receive aerosol pretreatment systems for installation |
| Handover to testing team                                                      | 11/29/2019 | • Successful completion of commissioning activities  
• Close-out of action items related to construction and installation from HAZOPS and safety reviews. |
| Start of testing phase                                                        | 12/02/2019 | • Finalization of a test matrix for the parametric testing campaign with minimal changes from preliminary test plan and agreement with NETL  
• Coal flue gas availability from host site |
| Project closeout                                                              | 11/30/2020 | • Successful demonstration of test objectives |
Technical risks and mitigation strategies

<table>
<thead>
<tr>
<th>Description of Risk</th>
<th>Probability</th>
<th>Impact</th>
<th>Risk Management Mitigation and Response Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical Risks:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material Compatibility</td>
<td>Low</td>
<td>Medium</td>
<td>• Flue gas composition and analysis will be used as part of the design basis. Material compatibility with corrosive contaminants in the flue gas can be addressed by host site and Linde Engineering experience with flue gas handling.</td>
</tr>
<tr>
<td>Waste Handling</td>
<td>Low</td>
<td>Medium</td>
<td>• Batch analysis of flue gas condensate and other liquid waste streams for regulatory compliance before disposal.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Treated flue gas will be sent back to the Abbott power plant stack for monitoring before exhaust.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Solid waste (flue gas particles) is expected to be low.</td>
</tr>
<tr>
<td>Flue gas aerosol variability</td>
<td>Medium</td>
<td>Medium</td>
<td>• The aerosol control methods being tested are expected to work over wide ranges of aerosol particle concentrations and size distributions.</td>
</tr>
<tr>
<td>Plugging process equipment</td>
<td>Low</td>
<td>Medium</td>
<td>• The aerosol particle concentration in the Abbott flue gas has been measured. The design and operation of all equipment components for each aerosol control module will be sufficient to prevent plugging based on these measurements and Linde Engineering experience with similar systems.</td>
</tr>
<tr>
<td>Flue gas condition variability affecting aerosol measurements</td>
<td>Low</td>
<td>Medium</td>
<td>• Online flue gas analysis (temperature, composition, pressure, humidity, etc.) during testing; team experience handling various flue gas qualities.</td>
</tr>
</tbody>
</table>
Progress and Current Project Status

Budget Period 1 & Budget Period 2
## Milestone status through August 26\textsuperscript{th}, 2019

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Number</th>
<th>Description</th>
<th>Planned Completion Date</th>
<th>Actual Completion Date</th>
<th>Verification Method</th>
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<tr>
<td>a</td>
<td>1</td>
<td>Updated Project Management Plan</td>
<td>06/29/2018</td>
<td>06/29/2018</td>
<td>Project Management Plan file</td>
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<tr>
<td>b</td>
<td>1</td>
<td>Kickoff Meeting</td>
<td>07/31/2018</td>
<td>07/27/2018</td>
<td>Presentation file</td>
</tr>
<tr>
<td>c</td>
<td>2</td>
<td>Review and modeling effort of aerosol-driven amine loss mechanisms complete</td>
<td>11/30/2018</td>
<td>10/31/2018</td>
<td>Report to DOE</td>
</tr>
<tr>
<td>d</td>
<td>3</td>
<td>Design, Engineering and Cost Analysis Complete</td>
<td>11/30/2018</td>
<td>01/31/2019</td>
<td>Report to DOE (Review Meeting)</td>
</tr>
<tr>
<td>e</td>
<td>3</td>
<td>Complete preliminary test plan</td>
<td>11/30/2018</td>
<td>01/31/2019</td>
<td>Test Plan Document</td>
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<tr>
<td>f</td>
<td>1</td>
<td>Completion of statement of host site acceptance of HAZOP and safety reviews</td>
<td>10/31/2018</td>
<td>12/20/2018</td>
<td>Host Site Statement Document</td>
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<tr>
<td>g</td>
<td>1</td>
<td>Submission of an Executed Host Site Agreement</td>
<td>11/30/2018</td>
<td>01/16/2019</td>
<td>Host Site Agreement Document</td>
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<tr>
<td>h</td>
<td>4</td>
<td>Fabrication and procurement complete</td>
<td>08/30/2019</td>
<td>08/26/2019</td>
<td>Report to DOE</td>
</tr>
<tr>
<td>i</td>
<td>5</td>
<td>Site Installation and Commissioning complete/Both ACMs ready for testing</td>
<td>11/29/2019</td>
<td>On Track</td>
<td>Presentation file</td>
</tr>
</tbody>
</table>
Successful completion of design, engineering and cost estimate in Budget Period 1 (Jun 2018 – Feb 2019)

— Task 2: Review of aerosol-driven amine loss mechanisms for PCC plants
  ● Review and modeling work completed, report submitted & presentation made to DOE-NETL
  ● Pilot plant operating conditions informed from modeling study

— Task 3: Pilot plant design and engineering
  ● Design basis completed with Abbott Power Plant (UIUC)
  ● Basic design & engineering for spray-based system completed by Linde
  ● Basic design & engineering for ESP system completed by WUSTL. Sorbent filter system designed by InnoSepra.
  ● Detailed engineering completed:
    1) ACS: spray-based system & sorbent filter vessel
    2) WUSTL: ESP system
  ● Hazard and operability study (HAZOP) completed with project team in Oct 2018 and host site in Dec 2018
  ● Host site agreement executed in Jan 2019
  ● Pilot plant cost estimation completed and budget updated
Successful completion of procurement & fabrication in Budget Period 2 (Mar 2019 – Nov 2019)

— Task 4: Pilot equipment procurement and fabrication
  • All inside battery limit (ISBL) pilot equipment & raw materials procured
  • Spray system, ESP system, and sorbent filter vessel fabrication complete. Spray tower system factory acceptance test will be completed by 8/30/19.
  • Local contractors selected for outside battery limit (OSBL) piping fabrication. OSBL piping installation to begin after module installation in September 2019.
  • Contract executed with local construction firm to install flue gas supply & return ports in Abbott plant duct; port fabrication work in progress
  • Aerosol measurement equipment and gas composition analysis system procured
  • Vendor packages prepared for shipment & installation at Abbott host site
  • Control logic and safety matrix developed based on HAZOP review and action items
  • Control system signals from ESP, InnoSepra filter, and gas analyzer rack incorporated into final design

— Task 5: Pilot plant installation planned to begin on 9/3/2019
Fabricated aerosol pretreatment skid – High velocity spray system

- Perforated plate change-out flange
- Aerosol measurement port for spray tower
- Controls box
- Automated flow-switching valve
- Process water heat exchanger
- Column demister
- Spray nozzle insert
- Aerosol measurement ports for ESP and filter
Gas sample probes designed and fabricated by UIUC

SO\textsubscript{2} dilution system procured and calibrated by UIUC based on host site conditions

Other completed items:
- Unneeded equipment removed from analytical trailer
- SO\textsubscript{2} analyzer calibrated and ready for testing
- Calibration gas cylinders and related equipment delivered to host site
- Analytical trailer transport plan coordinated with shipping vendors
Aerosol measurement equipment - WUSTL

Aerosol particle profile for inlet and outlet of each process component will be measured.

**Scanning mobility particle sizer (SMPS)** characterizes particles in the 1-450 nm size range

**Aerodynamic particle sizer (APS)** characterizes particles in the 0.5-20 µm size range
Detailed installation and commissioning plan developed

<table>
<thead>
<tr>
<th>Activity</th>
<th>Start</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Installation phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pour equipment pad, pad curing, set analytical trailer</td>
<td>9/3/19</td>
<td>9/11/19</td>
</tr>
<tr>
<td>OSBL electrical work (run 200 A feeder from tractor house,</td>
<td>9/3/19</td>
<td>9/23/19</td>
</tr>
<tr>
<td>run power to trailer &amp; skid)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSBL mechanical piping (install process water, potable water, flue</td>
<td>9/3/19</td>
<td>9/30/19</td>
</tr>
<tr>
<td>gas piping)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISBL installation (set fabricated equipment, install interconnecting</td>
<td>9/11/19</td>
<td>11/11/19</td>
</tr>
<tr>
<td>piping, leak check piping, install instrumentation, heat tracing, and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>insulation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Commissioning phase</strong></td>
<td>10/17/19</td>
<td>11/29/19</td>
</tr>
<tr>
<td>Spray tower, sorbent filter, and ESP I/O checkout</td>
<td>10/17/19</td>
<td>11/29/19</td>
</tr>
<tr>
<td>Operations &amp; safety training</td>
<td>11/25/19</td>
<td>11/29/19</td>
</tr>
</tbody>
</table>

*On track to complete BP2 on schedule (11/29/19)*
Plans for future development

Project team plans to use constructed aerosol pretreatment equipment in future government-funded CO₂ capture demonstration projects

Processes can easily be scaled up 10-100 times for demonstration and/or commercial application based on existing designs

Team will continue to identify technology component improvements (e.g. better performing spray nozzle designs & optimized operating conditions, ESP photo-ionizer design optimization, etc.)
Thank you for your attention

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