Flue Gas Aerosol Pretreatment Technologies to Minimize Post-Combustion CO_2 Capture (PCC) Solvent Losses

DOE funding award DE-FE0031592

2018 NETL CO_2 Capture Technology Meeting

Devin Bostick, Linde LLC

August 16, 2018

Pittsburgh, PA

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Acknowledgement and Disclaimer

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Project Overview

Objectives, Scope, Timeline, Participants & Funding

Overview of The Linde Group

Founded	1879
Sales (2017)	$20 billion
Employees	64,000
Countries	>100
US Linde Gas HQ	Bridgewater, NJ
US Linde Engineering Facilities	Tulsa, OK Holly Springs, GA Houston, TX

Linde Engineering

Technology-focused

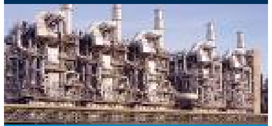
Air Separation

Global #1

Hydrogen/ Syn Gas

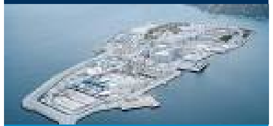
Global #2

Olefins



Global #2

Natural Gas



Global #3

Leveraging Synergies

Linde Gas - Tonnage

World-class operations

HyCO Tonnage Plants

>70 plants

ASU Tonnage Plants

>300 plants

CO2 Plants

>100 plants

ECOVAR Std Plants

>1,000 plants

Linde has extensive experience in CO_2 capture & handling

CO_2 Capture and Injection

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

CO_2 Wash Units

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

- Linde-Rectisol ®
- BASF Oase techn.®
- Benfield

CO_2 Food Grade Plants

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

CO_2 Transport and Distribution

Long experience in operation of CO_2 plants, transport & distribution

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

Project Objectives

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Overall Objective

Demonstrate and evaluate two innovative flue gas aerosol pretreatment technologies identified to significantly reduce high aerosol particle concentrations (>10^7 particles/cm^3) 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 an optimized design and operating conditions

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 two 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

Project Scope, Timeline & Milestones

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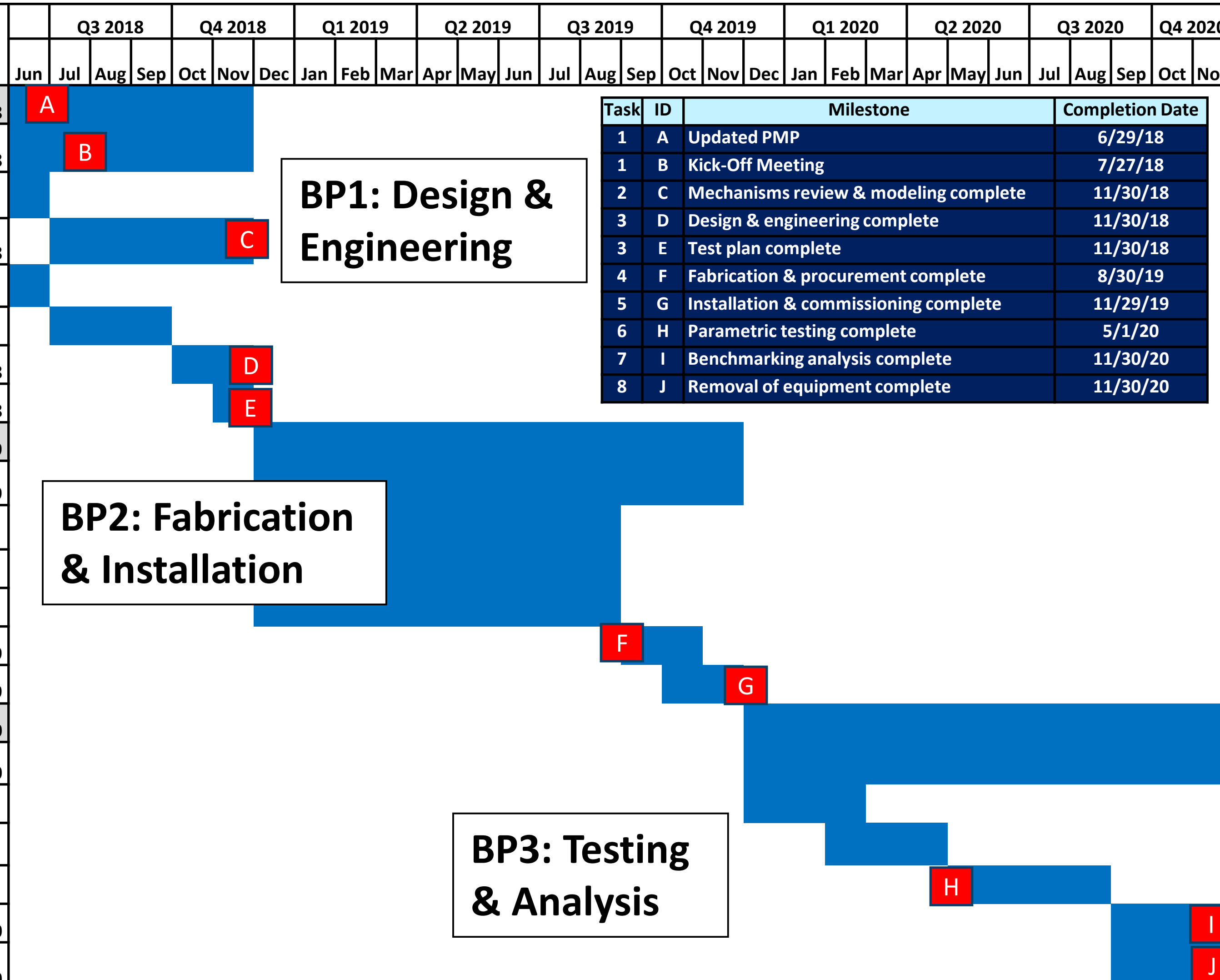
	Start	Finish
Budget Period 1	6/1/2018	11/30/2018
1.0: Project management	6/1/2018	11/30/2018
2.1: Mechanism review	6/1/2018	6/29/2018
2.2: Mechanism modeling	7/2/2018	11/28/2018
3.1: Design basis dev.	6/1/2018	6/29/2018
3.2: Basic engineering	7/2/2018	10/5/2018
3.3: Detailed engineering	10/8/2018	11/28/2018
3.4: Test planning	10/29/2018	11/28/2018
Budget Period 2	12/3/2018	11/29/2019
1.0: Project management	12/3/2018	11/29/2019
4.1: ESP system fabrication	12/3/2018	8/30/2019
4.2: Spray system fabrication	12/3/2018	8/30/2019
4.3: Procurement for install	12/3/2018	8/30/2019
5.1: Site installation	9/2/2019	10/18/2019
5.2: Commission & start-up	10/21/2019	11/29/2019
Budget Period 3	12/2/2019	11/30/2020
1.0: Project management	12/2/2019	11/30/2020
6.1: ESP system tests	12/2/2019	2/24/2020
6.2: Spray system tests	2/17/2020	4/30/2020
6.3: Test analysis	5/4/2020	8/28/2020
7.0: Benchmarking analysis	8/31/2020	11/27/2020
8.0: Removal of equipment	8/31/2020	11/27/2020



Task	ID	Milestone	Completion Date
1	A	Updated PMP	6/29/18
1	B	Kick-Off Meeting	7/27/18
2	C	Mechanisms review & modeling complete	11/30/18
3	D	Design & engineering complete	11/30/18
3	E	Test plan complete	11/30/18
4	F	Fabrication & procurement complete	8/30/19
5	G	Installation & commissioning complete	11/29/19
6	H	Parametric testing complete	5/1/20
7	I	Benchmarking analysis complete	11/30/20
8	J	Removal of equipment complete	11/30/20

Project Participants

Partner/ Organization	Lead contact(s)	Key Role(s)
DOE-NETL	Andy Aurelio, *Project Manager*	-Funding & sponsorship
Linde LLC	Devin Bostick, *Principal Investigator* Krish Krishnamurthy, *Technology Director*	-Prime contract -Overall program management -High velocity water spray-based aerosol pretreatment technology owner
University of Illinois Urbana-Champaign (UIUC)	Kevin O'Brien, *Project Lead*	-Aerosol mechanisms review -Host site liaison -Flue gas and liquid effluent composition measurement & analysis
Washington University in St. Louis (WUSTL)	Pratim Biswas, *Project Lead*	-Aerosol mechanisms modeling lead -ESP-based aerosol pretreatment technology owner -Characterization of aerosols in flue gas
Affiliated Construction Services (ACS)	Greg Larson, *Project Lead*	-Procurement management for high velocity water spray-based system -Construction management for site modifications & module installation

Project Budget: DOE Funding and Cost Share

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Source	Budget Period 1 Jun 2018 – Nov 2018	Budget Period 2 Dec 2018 – Nov 2019	Budget Period 3 Dec 2019 – Nov 2020	Total
DOE Funding	$457,822	$1,290,725	$1,078,826	$2,827,834
Cost Share	$176,612	$260,949	$269,860	$707,421
Total Project	$634,435	$1,551,674	$1,348,686	$3,534,795

Cost share commitments:

Linde: $234,869

University of Illinois (UIUC): $231,339

Washington University in St. Louis (WUSTL): $191,213

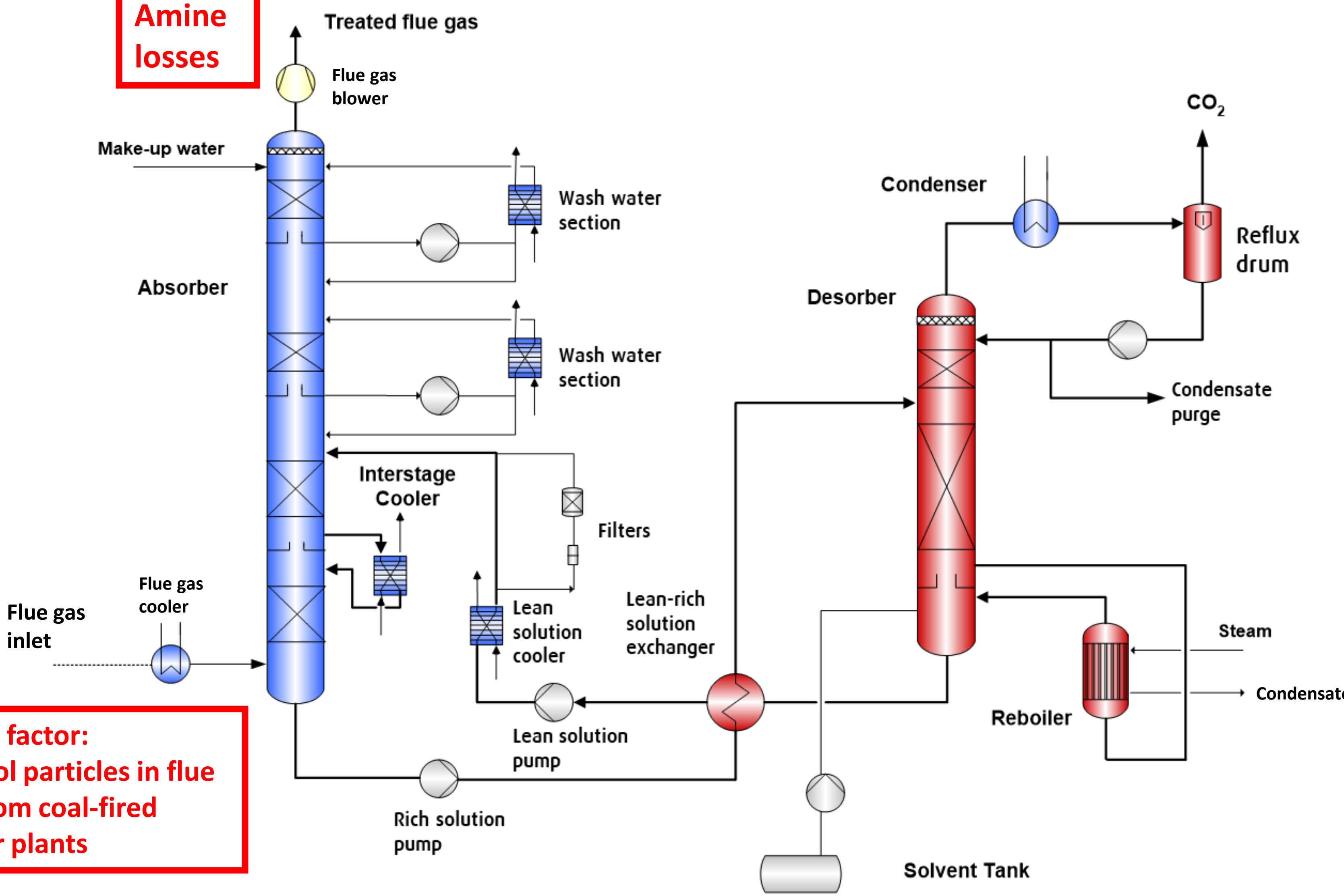
Affiliated Construction Services (ACS): $50,000

Technology Development

Rationale, Background & Previous Research

Rationale: reducing aerosol-driven amine losses from solvent-based PCC technology enables its broader commercial deployment

Amine losses



Major factor: aerosol particles in flue gas from coal-fired power plants

Aerosol particle formation during coal combustion

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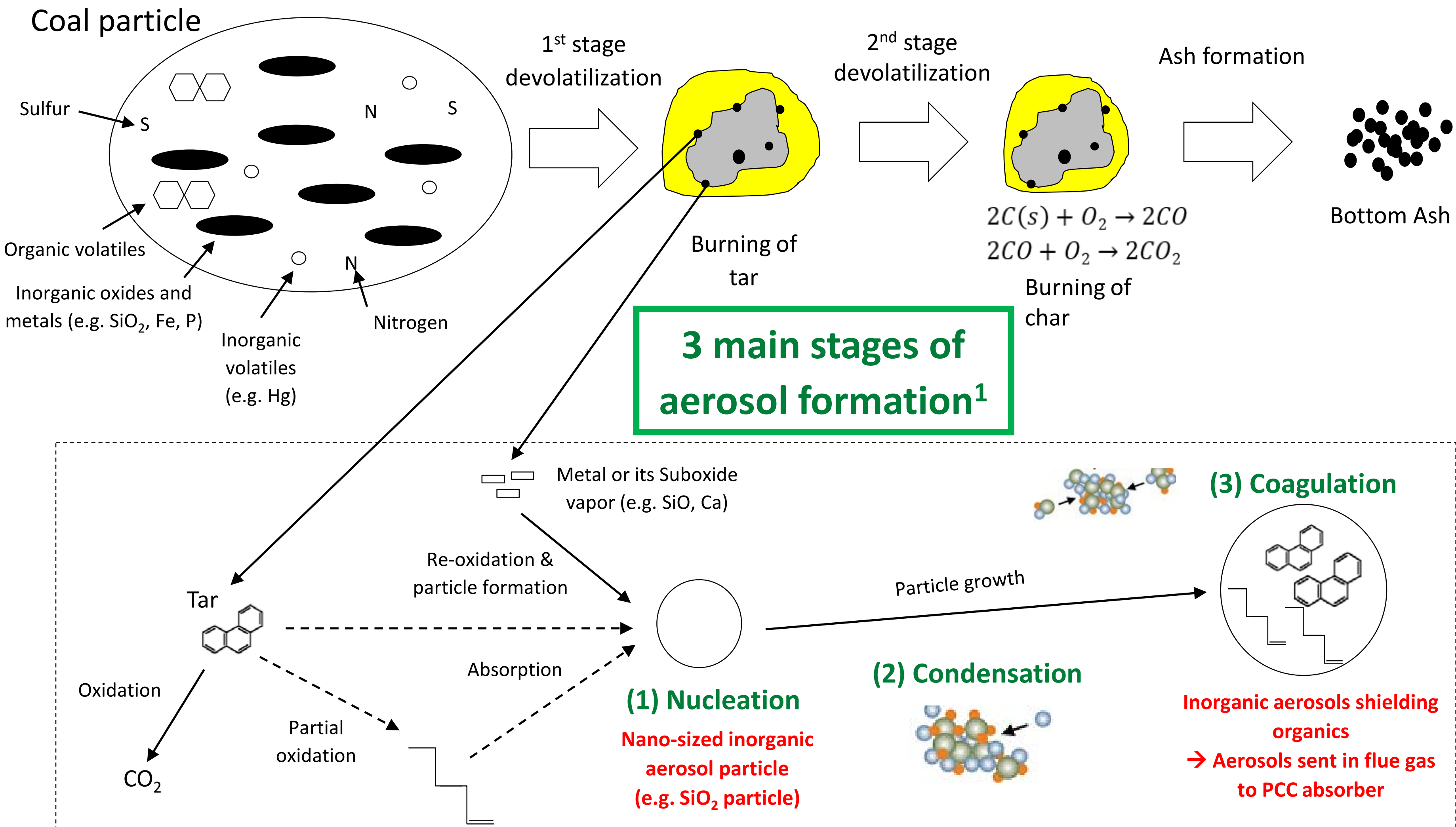

Particle Size 0.4 nm | 0.4 – 2 nm | 2 - 100 nm | 0.001-1000 mm

1. Wang, Xinlei & Williams, Brent & Tang, Y & Huang, Yuhsuan & Kong, L & Yang, Xin & Biswas, Pratim. (2013). Characterization of organic aerosol produced during pulverized coal combustion in a drop tube furnace. Atmospheric Chemistry and Physics. 13. 10.5194/acp-13-10919-2013.

Theory and mechanisms for aerosol-driven amine losses from PCC plant absorbers[1]

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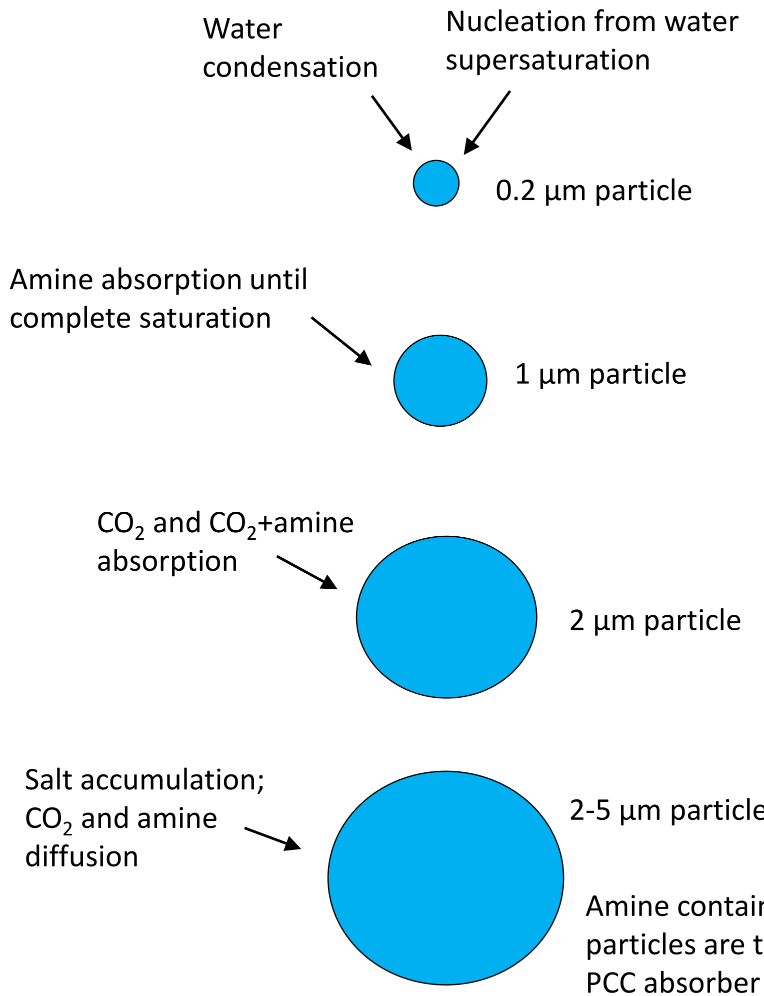
Phase I Aerosol growth and nucleation from water in absorber
Phase II Aerosol growth from amine in absorber
Phase III Buildup of captured CO_2 and amine bound to CO_2 in aerosols
Phase IV Salt accumulation inside particles causing further amine and CO_2 diffusion into aerosols



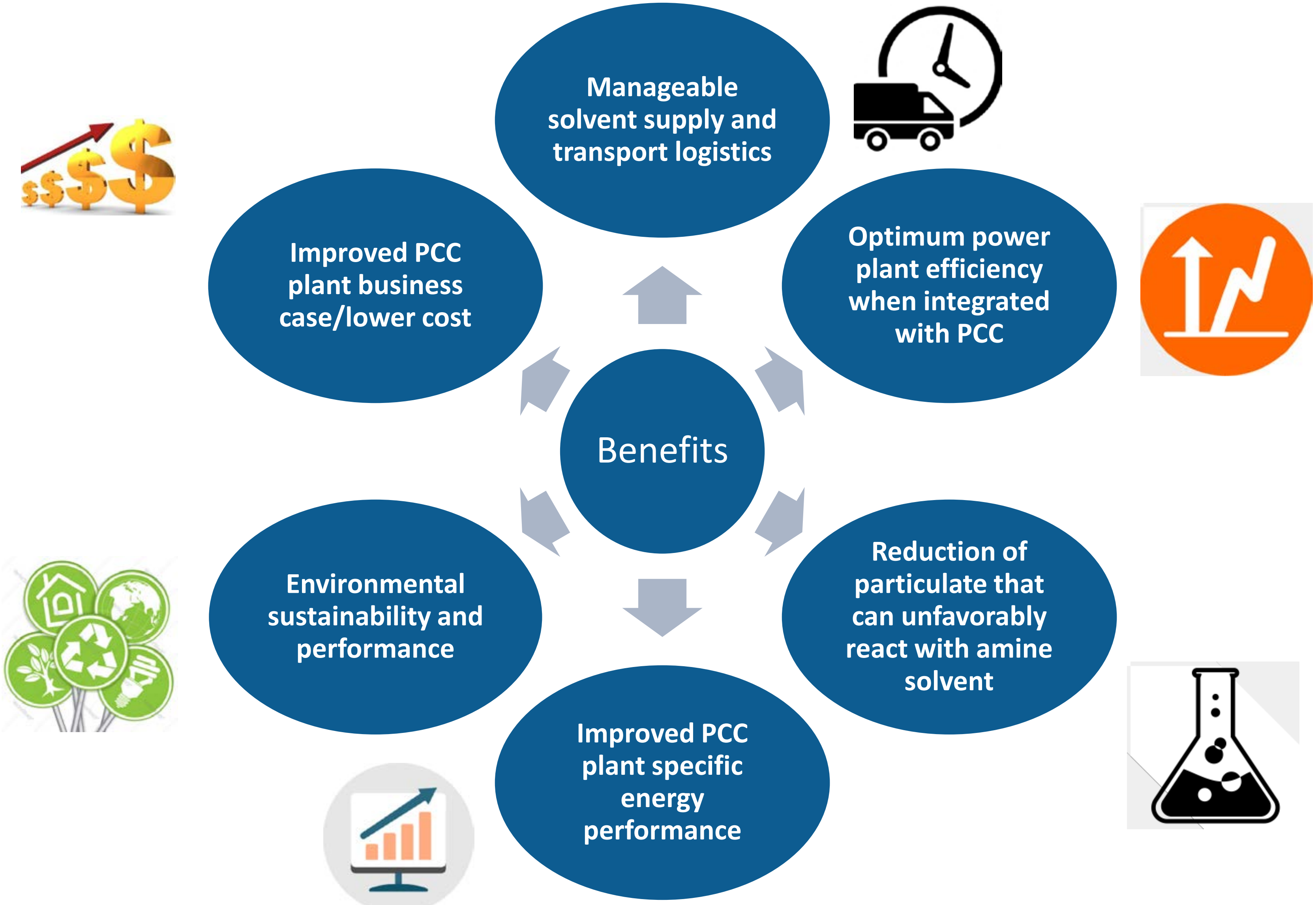
Amine contained in aerosol particles are then emitted from PCC absorber in treated gas stream

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

The Kelvin equation gives the minimum particle diameter, d*, of a liquid[1] → supersaturation leads to nucleation of smaller particles

1. G. Lombardo, B. Fostas, M. Shah, A. Morken, O. Hvidsten, J. Mertens, E. Hamborg; Results from Aerosol Measurement in Amine Plant Treating Gas Turbine and Residue Fluidized Catalytic Cracker Flue Gases at the CO2 Technology Centre Mongstad, GHGT-13, Energy Procedia 2017; 114: Pages 1210-1230.

Benefits of aerosol particle reduction



Methods to reduce aerosol-driven solvent losses: Flue gas aerosol pretreatment provides optimum solution[1]

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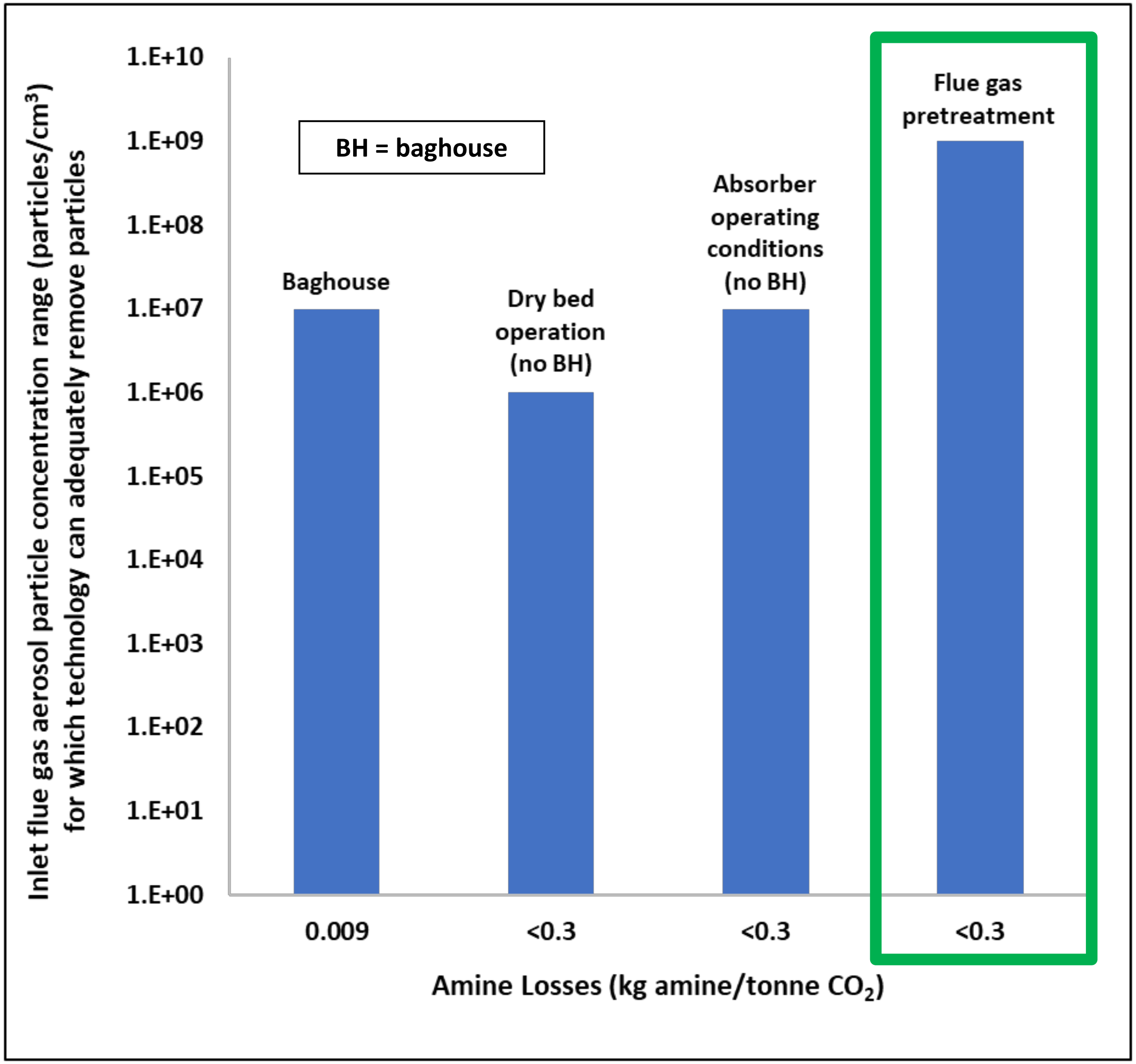

For power plants integrated with solvent-based PCC without an existing baghouse, **optimized flue gas aerosol pretreatment** is the **only viable option** to reduce aerosol concentrations from >10^9 particles/cm^3 to manageable levels near 10^4-10^6 particles/cm^3 for particles with diameters in the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

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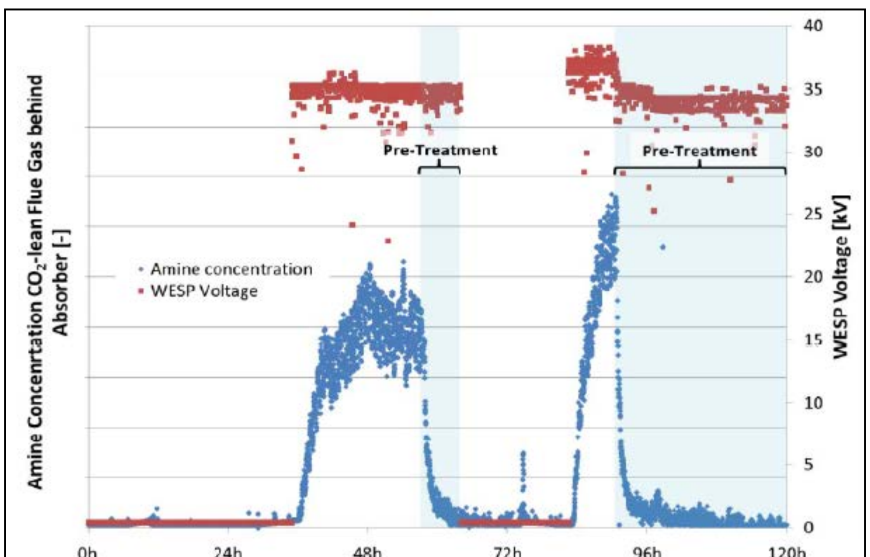
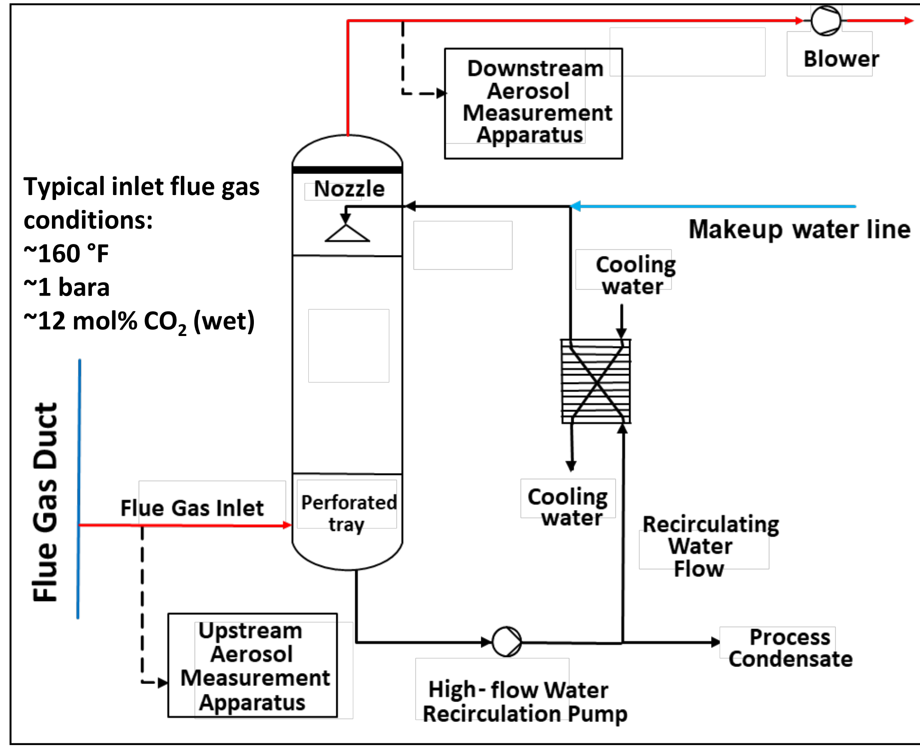
Mechanism of action

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 MW_e PCC pilot in Niederaussum that began in 2009[1].





Tests

Planned tests will evaluate new nozzle & perforated tray designs and the impact of several operating conditions (flows, temperatures, etc.) on performance.

1) P. Moser, G. Vorberg, T. Stoffregen, et. A; The wet electrostatic precipitator as a cause of mist formation – Results from the amine-based post-combustion capture pilot plant at Niederaussem. International Journal of Greenhouse Gas Control, 41 (2015) 229–238.

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

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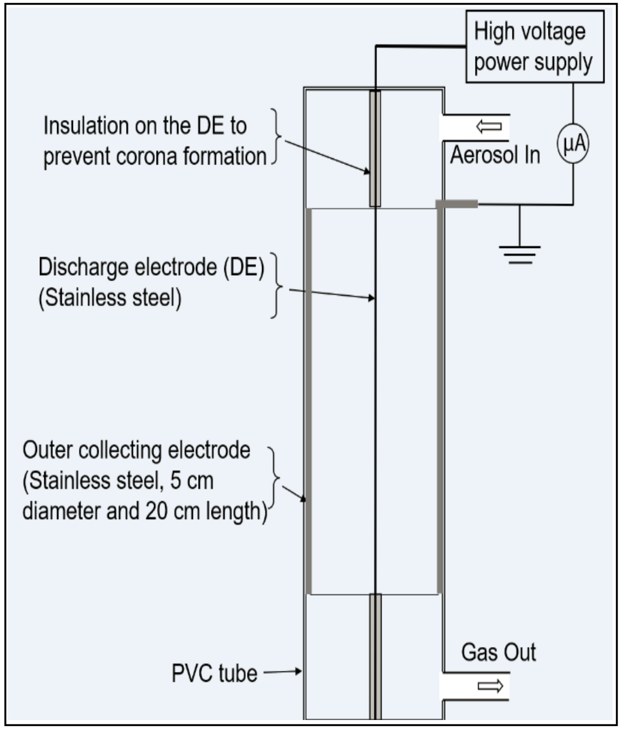
Mechanism of action

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.

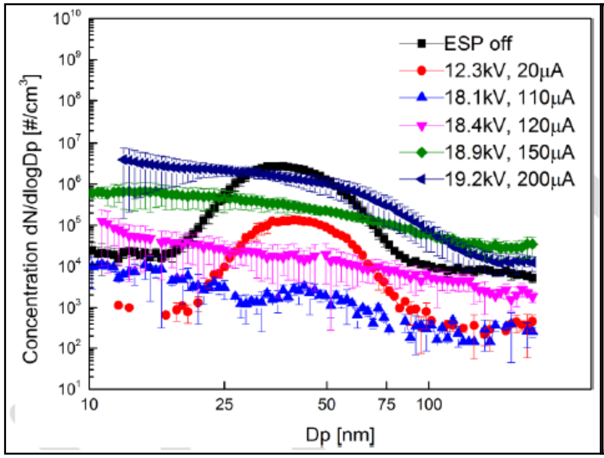


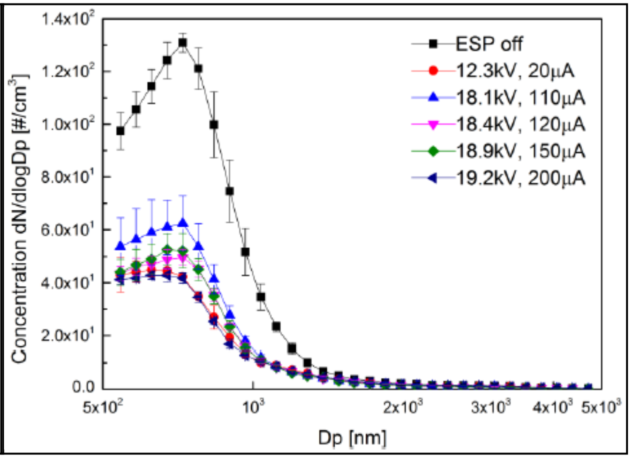
Performance

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 $m^2/(m^3/s)$, which can be increased to remove more particles in the size range of 10-500 nm.[1]

Tests

Planned tests will evaluate voltage & current effects and the impact of the photo-ionizer on ESP performance.





1) Y. Wang, Z. Li, P. Biswas; Aerosol Measurements in Coal Combustor Exhaust Gas on 1.5 MWe Advanced Aqueous Amine-Based PCC Pilot Plant in Wilsonville, AL, Washington University in St. Louis, August 8, 2016.

Economic & technical advantages and potential challenges of each technology

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Scenario	DOE-NETL Case B12B: PP* w/ 90% CO_2 capture**	Case 1: PP* w/ 90% CO_2 capture; high-velocity spray aerosol pretreatment	Case 2: PP* w/90% CO_2 capture; novel ESP aerosol pretreatment
Baghouse	Yes	No	No
Added CAPEX w/ aerosol pretreatment ($)	N/A	$3,261,720	$2,338,318
Added energy consumption w/ aerosol pretreatment (MW)	N/A	11	1.32
Total Overnight Cost ($)	$2,384,351,816	$2,356,810,371	$2,328,373,523
PCC plant specific energy consumption (MJ/kg CO_2)	2.48	2.48	2.48
Cost of electricity w/o T&S (COE, $/MWh)	$133.20	$133.05	$131.31
Key advantages	N/A	Manageable footprint & high performance; low CAPEX; can easily be integrated into direct contact cooler of PCC plant	Very small footprint & high performance; low CAPEX & OPEX
Potential challenges	N/A	Higher energy consumption could lead to decreased power plant efficiency	High voltage equipment can pose a safety concern; scale-up of novel components may present issues

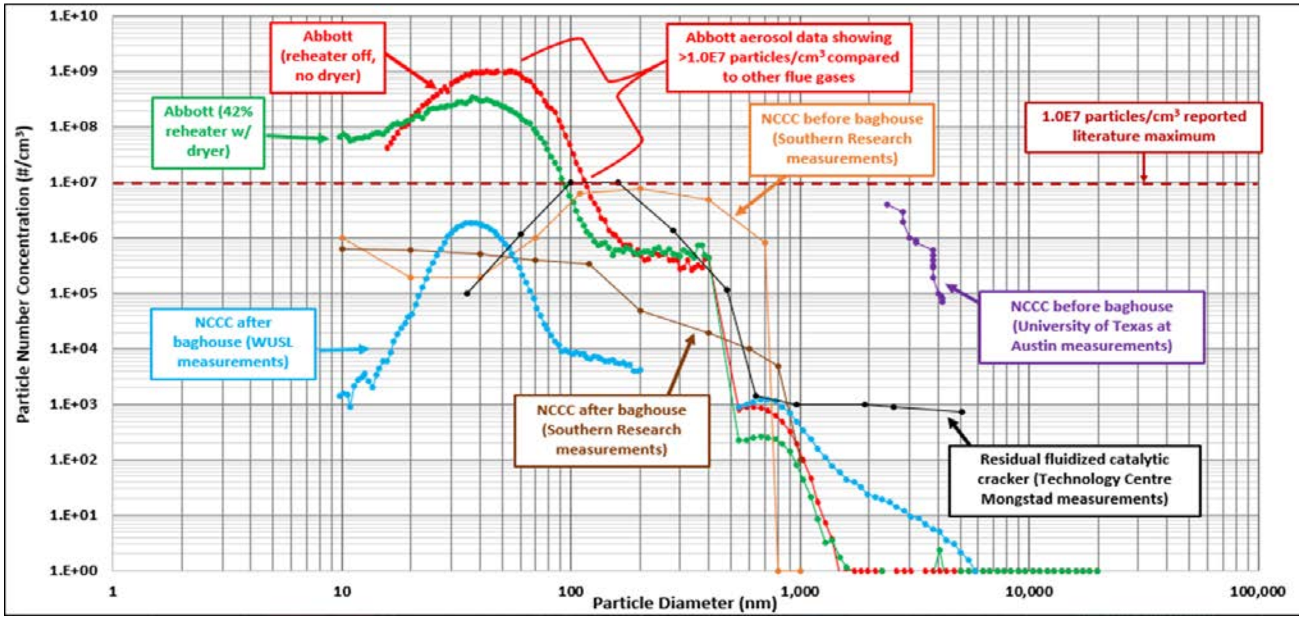
*PP: 550 MWe supercritical power plant with high flue gas aerosol concentrations leading to very high amine losses for an integrated PCC plant with no aerosol mitigation used.

**Baghouses require significant footprint area and power plant retrofit costs including shutdown periods; baghouses also produce a pressure drop so flue gas fan power must be increased; the costs associated with these factors are not included.

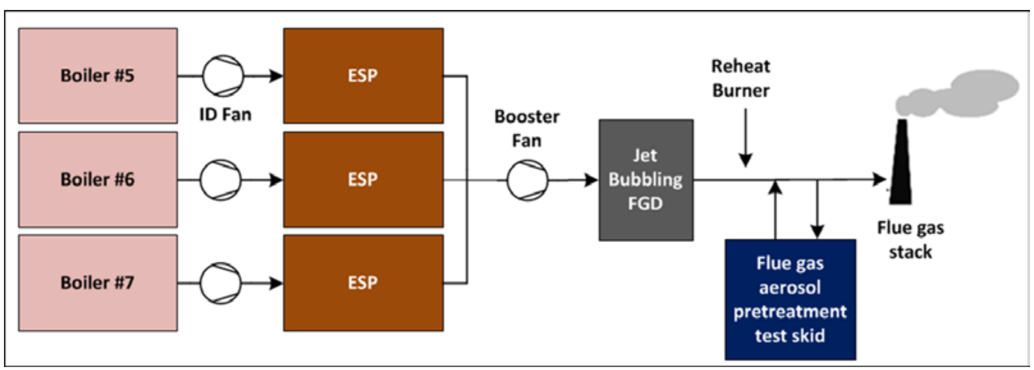
Technical Approach

Host Site Setup, Innovation Targets, Success Criteria & Project Risks and Mitigation Strategies

Pilot host site: Abbott Power Plant at UIUC in Champaign, IL



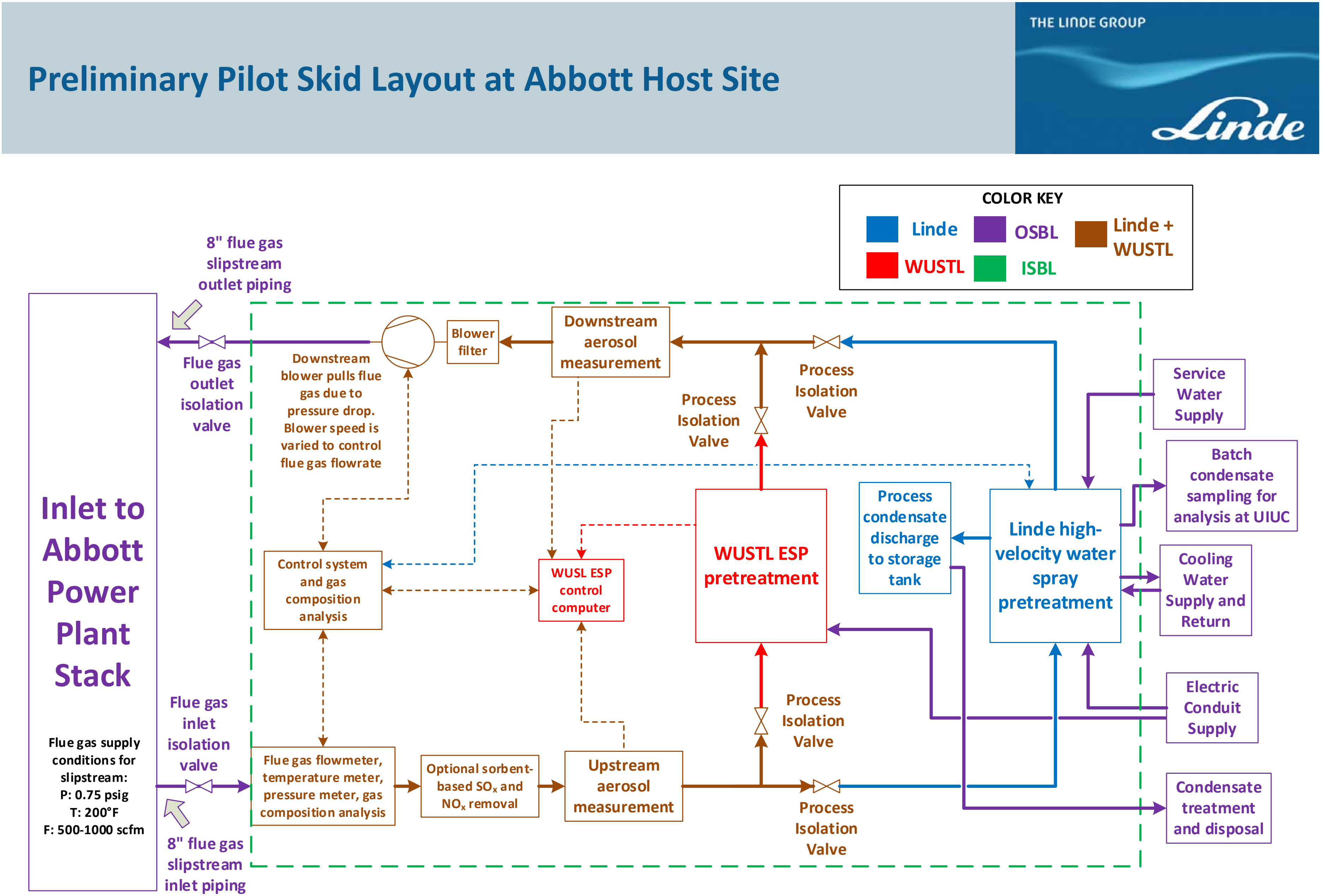
Abbott chosen as optimal host site for testing since aerosol concentrations were measured to be among the highest in scientific literature



Abbott plant schematic and tie-in points to pilot skid

Abbott plant aerial view

Preliminary Pilot Skid Layout at Abbott Host Site



Pilot Testing Innovation Targets

Parameter	Rationale	Expected target
Particle removal efficiency* for 500-1000 scfm flue gas slipstream (%)	Flue gas aerosol particles in size range 70-200 nm lead to amine losses in the treated gas of amine-based PCC plants	>98%
Cost competitiveness** (COE = cost of electricity)	Reduced capital and operating costs are required for commercial application of enabling technologies for PCC	COE < $133.20/MWh and cost of CO2 captured < $58/tonne when compared to DOE-NETL reference case B12B
Energy efficiency**	Low electricity consumption reduces parasitic load for enabling technologies	Energy consumption < 14 MWe (threshold above which energy consumption greatly impacts COE and cost of CO_2 captured)
Environmental sustainability when integrated with PCC technology for supercritical coal-fired power plants without a baghouse	Minimal environmental impact is required to meet process safety & regulatory requirements for customers	Process condensate adequately removed & treated as needed ; ESP solids removed and treated as needed

**Particle removal efficiency = (Particle concentration before aerosol pretreatment (#/cm^3) - Particle concentration after aerosol pretreatment (#/cm^3))/(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

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Decision Point	Date	Success Criteria
Equipment procurement and fabrication of both aerosol pretreatment systems and components for installation	11/30/2018	• 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 Project Risks and Mitigation Strategies

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Technical Risks:			
Material Compatibility	Low	Medium	• 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.
Waste Handling	Low	Medium	• Batch analysis of flue gas condensate and other liquid waste streams for regulatory compliance before disposal. • Treated flue gas will be sent back to the Abbott power plant stack for monitoring before exhaust. • Solid waste (flue gas particles) is expected to be low.
Flue gas aerosol variability	Medium	Medium	• The aerosol control methods being tested are expected to work over wide ranges of aerosol particle concentrations and size distributions.
Plugging process equipment	Low	Medium	• 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.
Flue gas condition variability affecting aerosol measurements	Low	Medium	• Online flue gas analysis (temperature, composition, pressure, humidity, etc.) during testing; team experience handling various flue gas qualities.

Resource & Project Management Risks and Mitigation Strategies

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Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Resource Risks:			
Flue gas and utility non-availability from power plant	Medium	High	• Availability of required utilities will be confirmed with the host site and will be included as part of the design basis. Power plant schedule will be confirmed prior to installation decision.
Unavailability of operators and key individuals with experience and know-how	Low	Medium	• Commitment from all participants to make project successful. • Management of all team members' availability and schedule through resource planning. • Team members have overlapping skills and knowledge and substitutions are possible.
Project cost overruns	Low	High	• Clear scope definition and specifications sent to vendors and subcontractors for pricing; suitable scope management and limit change orders.
Equipment/module fabrication delay	Low	Medium	• Project schedule includes contingency for delays in procurement or fabrication. • Team will select reputable suppliers and obtain firm commitments during purchase order process.
Project Management Risks:			
Poor communication among team members	Low	Medium	• Maintain communication on a regular basis to align team on decision making.
Conflicts among team members	Low	Medium	• Team members have existing relationships from participation in prior projects and have worked well together in the past.

Progress and Current Project Status

Budget Period 1

Project Progress: Status of Key Project Milestones (Budget Period 1)

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Budget Period 1 (June 1, 2018 – November 30, 2018)

Completed

— Submit updated project management plan (06/29/2018) √

— Conduct kick-off meeting with DOE-NETL (07/27/2018) √

In Progress (planned completion by 11/30/2018)

— Review and modeling effort of aerosol-driven amine loss mechanisms

— Design, engineering, and cost analysis for pilot skid

— Preliminary test plan drafted

Key Project Milestones (Budget Periods 2 and 3) & Future Plans

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Budget Period 2 (December, 2018 – November, 2019)

- Complete fabrication and procurement of aerosol pretreatment systems and components for installation (08/30/2019)
- Complete site installation and commissioning of aerosol pretreatment systems; ensure both systems are ready for testing (11/29/2019)

Budget Period 3 (December, 2019 – November, 2020)

- Complete parametric testing of both aerosol pretreatment systems (05/01/2020)
- Complete technology benchmarking and analysis close-out report based on test results (11/30/2020); complete comparison against innovation targets and other state-of-the-art aerosol mitigation technologies found in literature (11/30/2020)
- Dismantling and removal of test equipment and platform (11/30/2020)

Future plans

Further scale-up of optimized aerosol pretreatment systems to be integrated with large-scale or demonstration PCC plants & economic analysis to accurately understand cost implications when incorporated with PCC technology

Thank you for your attention!

Project DE-FE0031592
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Devin Bostick, Linde LLC
August 16, 2018
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