Flue Gas Aerosol Pretreatment Technologies to Minimize PCC Solvent Losses

DOE funding award DE-FE0031592

Project Kick-Off Meeting
DOE-NETL, Pittsburgh, PA
July 27, 2018
The Linde Group - Technology & Innovation - Group R&D

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Project Management and Participants

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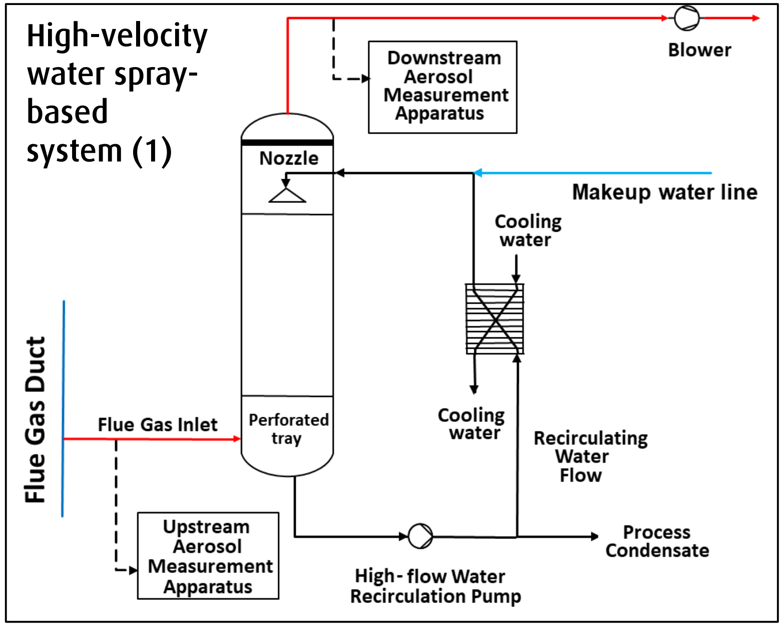
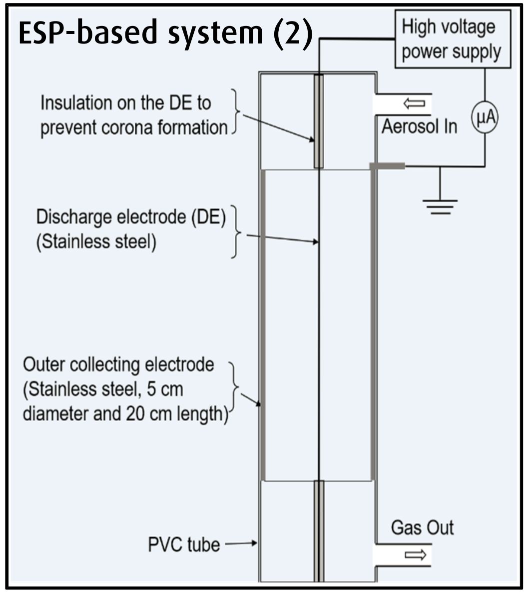
Project fact sheet





Coal-fired flue gas aerosol pretreatment technology pilot testing

A. Selected by DOE for funding in Feb. 2018
B. Prime contract received in May 2018
C. Pilot testing involves two independent systems:
   1. High-velocity water spray-based aerosol pretreatment
   2. Novel ESP-based aerosol pretreatment

Project essentials

- **Location:** Abbott combined heat and power plant in Champaign, IL owned and operated by UIUC; three coal-fired chain-grate stoker design boilers rated to produce a combined 35 MWe.
- **Pilot capacity**: 500-1000 scfm flue gas
- **Project start:** June 1, 2018
- **Project end:** November 30, 2020
- **Partners:** Linde LLC (lead), Washington University in St. Louis (WUSTL), University of Illinois Urbana-Champaign (UIUC) & Abbott power plant (host site), Affiliated Construction Services (ACS), and DOE-NETL
- **Project cost:** $3,534,795
- **DOE funding:** $2,827,374

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 novel, high velocity spray-based water injection concept

(2) An innovative 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 team and responsibilities

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U.S. DEPARTMENT OF ENERGY / NETL NATIONAL ENERGY TECHNOLOGY LABORATORY	**Project sponsorship and funding ; Development support** Project Officer: Andy Aurelio ; Contract Specialist: Amanda Lopez
THE LINDE GROUP Linde	**Prime awardee ; Project management ; Operations lead ; Technology benchmarking ; High velocity spray-based aerosol pretreatment technology provider** PI: Devin Bostick
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN — **UIUC**	**Subawardee ; Aerosol mechanisms review ; Operations liaison to Abbott ; Flue gas and liquid effluent composition measurement and analysis** Lead: Dr. Kevin O'Brien
Washington University in St. Louis — **WUSTL**	**Subawardee ; ESP-based aerosol control technology provider Monitoring and characterization of aerosols in flue gas; ESP operations Aerosol mechanistic modeling lead** Lead: Dr. Pratim Biswas
ACS — **Affiliated Construction Services (ACS)**	**Subawardee ; Procurement management for high velocity spray-based system Construction management for site modification and module installation** Lead: Greg Larson
 **Abbott Power Plant at UIUC**	**Pilot host site provider ; Utilities and flue gas provider** Lead: Mike Larson

Project budget: DOE funding and cost share by project member

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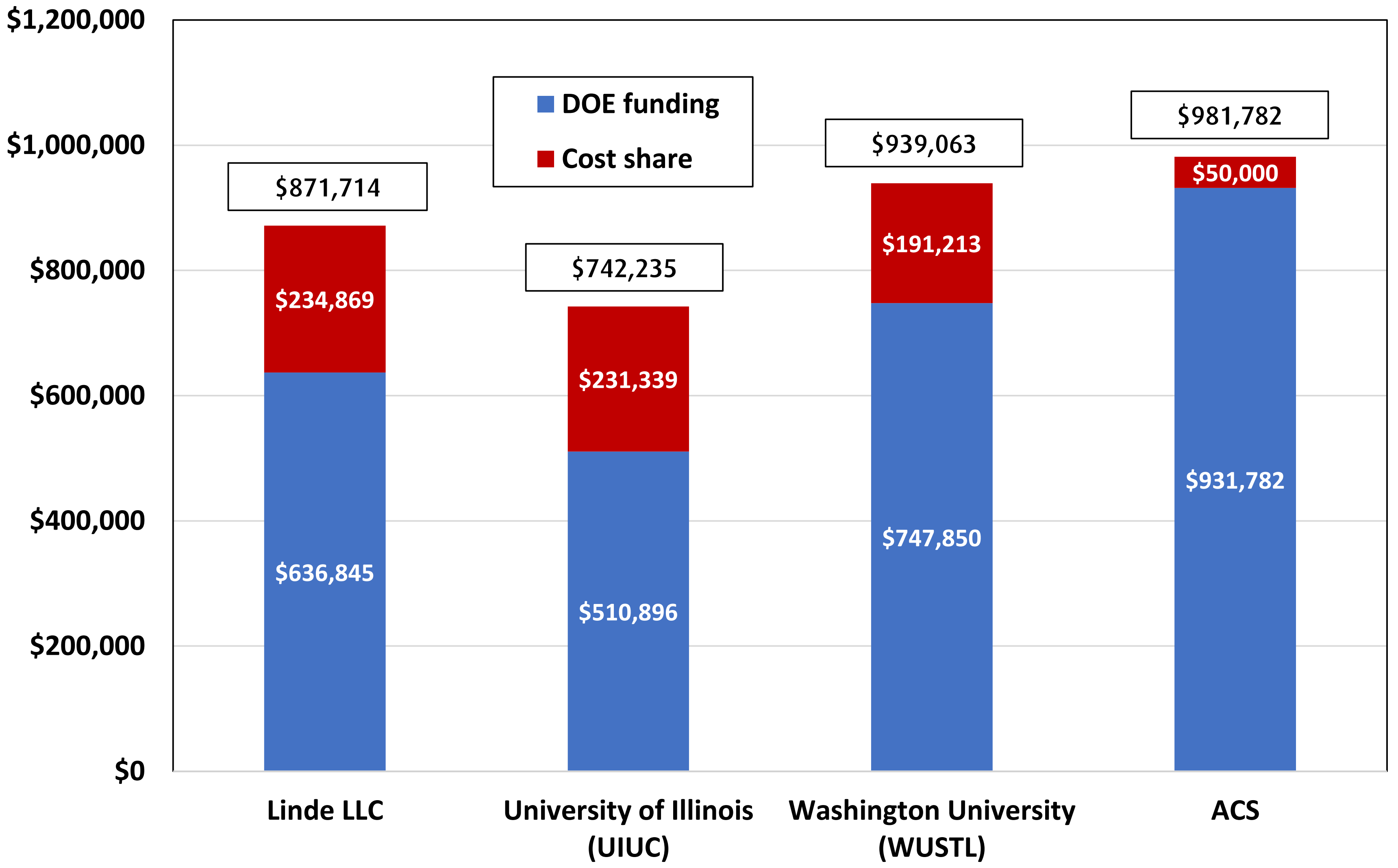
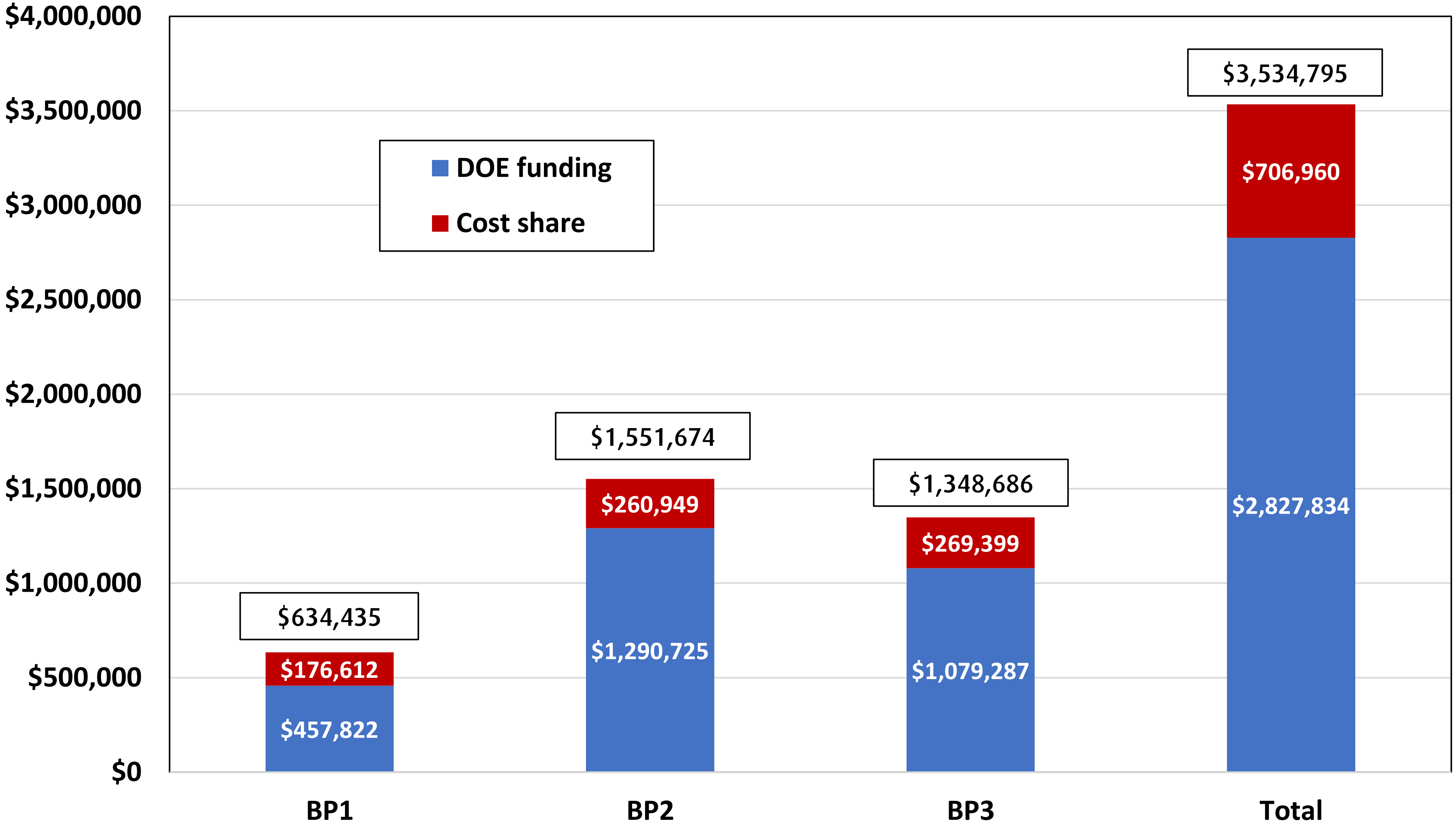


Project budget: DOE funding and cost share by budget period



Cost share per budget period:

BP1: 20%

BP1+BP2: 20%

BP3: 20%

Total: 20%

Project schedule, Gantt chart, and milestones

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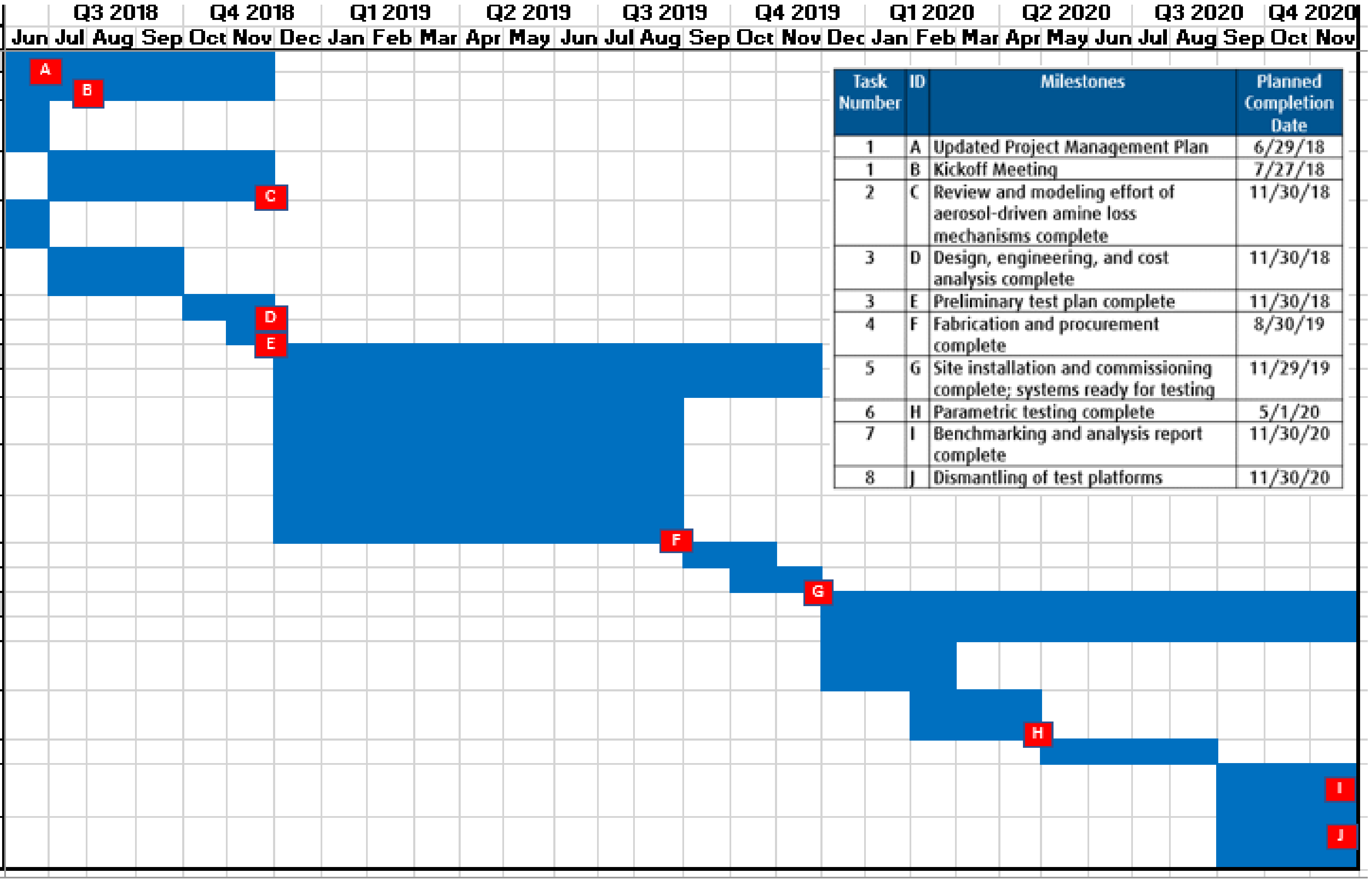
	Start	Finish
Budget Period 1	6/1/2018	11/30/2018
1.0: Project Management & Planning	6/1/2018	11/30/2018
2.1: Review of aerosol-driven amine loss mechanisms and EHS implications	6/1/2018	6/29/2018
2.2: Modeling of aerosol-driven amine loss mechanisms	7/2/2018	11/28/2018
3.1: Specification and design basis definition	6/1/2018	6/29/2018
3.2: Basic design package development and safety analysis	7/2/2018	10/5/2018
3.3: Detailed engineering and cost estimation	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 & Planning	12/3/2018	11/29/2019
4.1: Fabrication of ESP-based aerosol pretreatment system	12/3/2018	8/30/2019
4.2: Fabrication of high velocity spray-based aerosol pretreatment system	12/3/2018	8/30/2019
4.3: Procurement of components for installation	12/3/2018	8/30/2019
5.1: Site installation	9/2/2019	10/18/2019
5.2: Commissioning & start-up	10/21/2019	11/29/2019
Budget Period 3	12/2/2019	11/30/2020
1.0: Project Management & Planning	12/2/2019	11/30/2020
6.1: Parametric tests of ESP-based aerosol pretreatment system	12/2/2019	2/24/2020
6.2: Parametric tests of high velocity spray-based aerosol pretreatment system	2/17/2020	4/30/2020
6.3: Test analysis	5/4/2020	8/28/2020
7.0: Summary and comparison of aerosol mitigation performance	8/31/2020	11/27/2020
8.0: Dismantling and removal of equipment	8/31/2020	11/27/2020



Task Number	ID	Milestones	Planned Completion Date
1	A	Updated Project Management Plan	6/29/18
1	B	Kickoff Meeting	7/27/18
2	C	Review and modeling effort of aerosol-driven amine loss mechanisms complete	11/30/18
3	D	Design, engineering, and cost analysis complete	11/30/18
3	E	Preliminary test plan complete	11/30/18
4	F	Fabrication and procurement complete	8/30/19
5	G	Site installation and commissioning complete; systems ready for testing	11/29/19
6	H	Parametric testing complete	5/1/20
7	I	Benchmarking and analysis report complete	11/30/20
8	J	Dismantling of test platforms	11/30/20

Project structure and team responsibilities

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BP	Task #	Task Title	Linde	UIUC	WUSTL	ACS
1, 2, 3	1.0	**Project Management and Planning**	Lead	Support	Support	Support
1	2.0	**Review of aerosol-driven amine loss mechanisms for PCC Plants**				
	2.1	Review of aerosol-driven amine loss mechanisms and EHS implications	Lead	Support	Support	Support
	2.2	Modeling of aerosol-driven amine loss mechanisms	Support	Support	Lead	
	3.0	**Design and engineering**				
	3.1	Specification and design basis definition	Lead		Support	
	3.2	Basic design package development and safety analysis	Lead	Support	Lead	Support
	3.3	Detailed engineering and cost estimation	Support		Lead	Lead
	3.4	Test planning	Lead	Support	Support	
2	4.0	**Equipment procurement and fabrication**				
	4.1	Fabrication of ESP-based ACM			Lead	Support
	4.2	Fabrication of high velocity spray-based ACM	Support			Lead
	4.3	Procurement of components for installation			Lead	Lead
	5.0	**Installation and commissioning**				
	5.1	Site installation	Support		Lead	Lead
	5.2	Commissioning & start-up	Lead	Support	Lead	
3	6.0	**Testing and analysis**				
	6.1	Parametric tests of ESP-based ACM	Support	Support	Lead	
	6.2	Parametric tests of high velocity spray0based ACM	Lead	Support	Support	
	6.3	Test analysis	Lead	Support	Lead	
	7.0	**Summary and comparison of aerosol mitigation performance**	Lead	Support	Support	
	8.0	**Dismantling and removal of equipment**	Support	Support	Lead	Lead

Project deliverables

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Project Deliverables			
Task/ Subtask	Deliverable	Due Date	Status
1.0	Updated Project Management Plan	30 days after award	Completed
1.0	Host Site Agreement	End of BP1	In progress
2.0	Technical Report on pretreatment options and modeling results	30 days prior to the end of BP1	In progress
3.0	Statement of host site acceptance of HAZOP and safety reviews	30 days prior to the end of BP1	In progress
3.0	Technical Report on system design and cost estimate	End of BP1	In progress
3.0	Preliminary Test Plan	End of BP1	In progress
4.0	Technical Report on equipment fabrication and host site readiness	60 days prior to the end of BP2	Not started
7.0	Technical Report benchmarking results	End of BP3	Not started

Project success criteria and decision points

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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

Technology Development and Testing Rationale

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Overview of typical solvent-based post-combustion CO_2 capture (PCC) process

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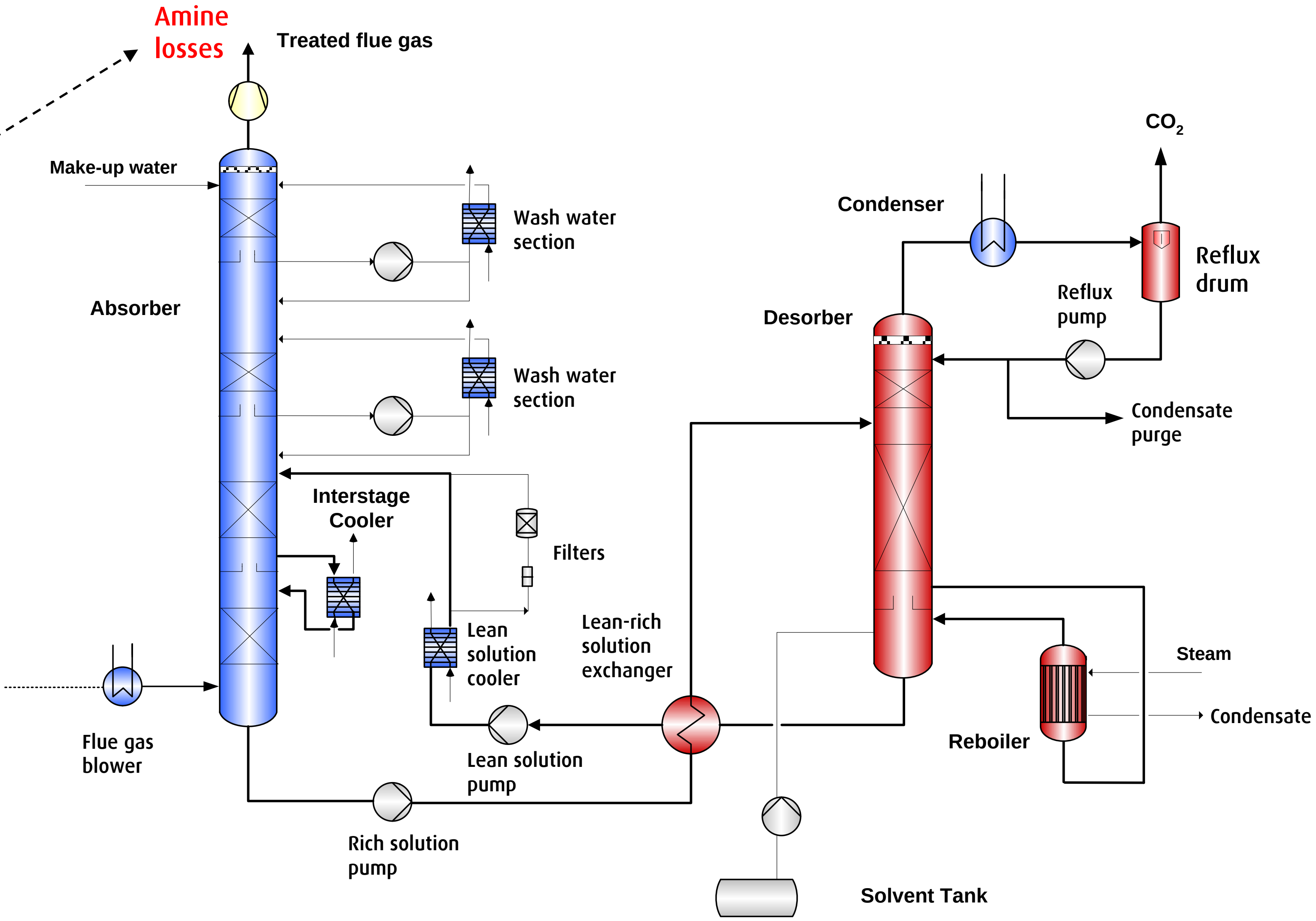
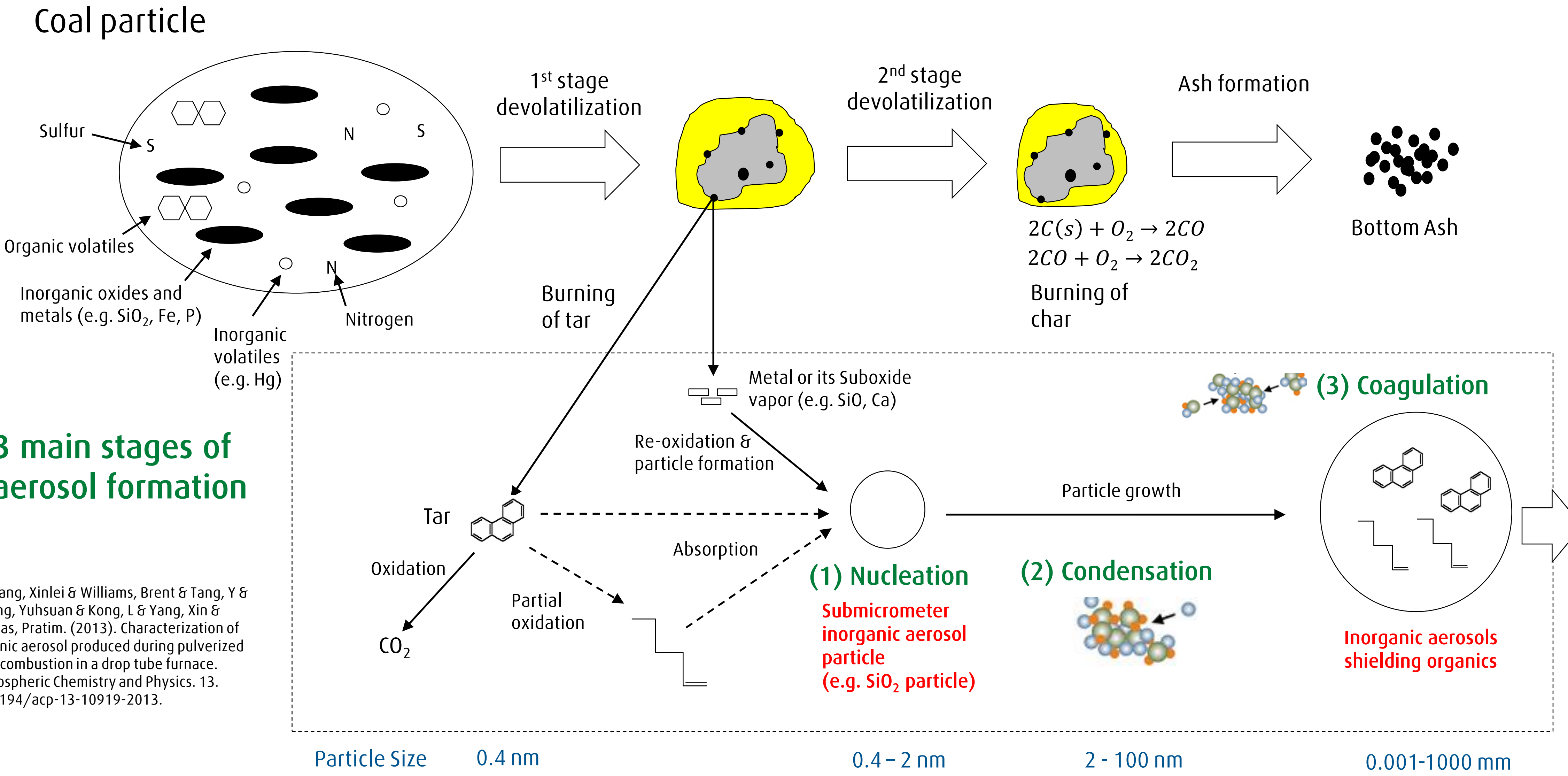
- Amine solvent-based PCC technology remains one of the leading methods to combat CO_2 emissions from coal-fired power plants.
- Treated flue gas exiting absorber is typically the largest source of amine losses; mechanisms include vapor liquid equilibria and the effects of **high aerosol concentrations**.
- **Aerosols are micro- and nano-sized particles** produced during coal combustion. Aerosol particles in flue gas are initially comprised of **H_2SO_4, Na_2SO_4, and mineral oxides.**
- More minor amine loss mechanisms include solvent degradation due to exposure to very high temperatures or unfavorable reactions with flue gas components (e.g. SO_2 and SO_3).



How aerosols are formed during coal combustion

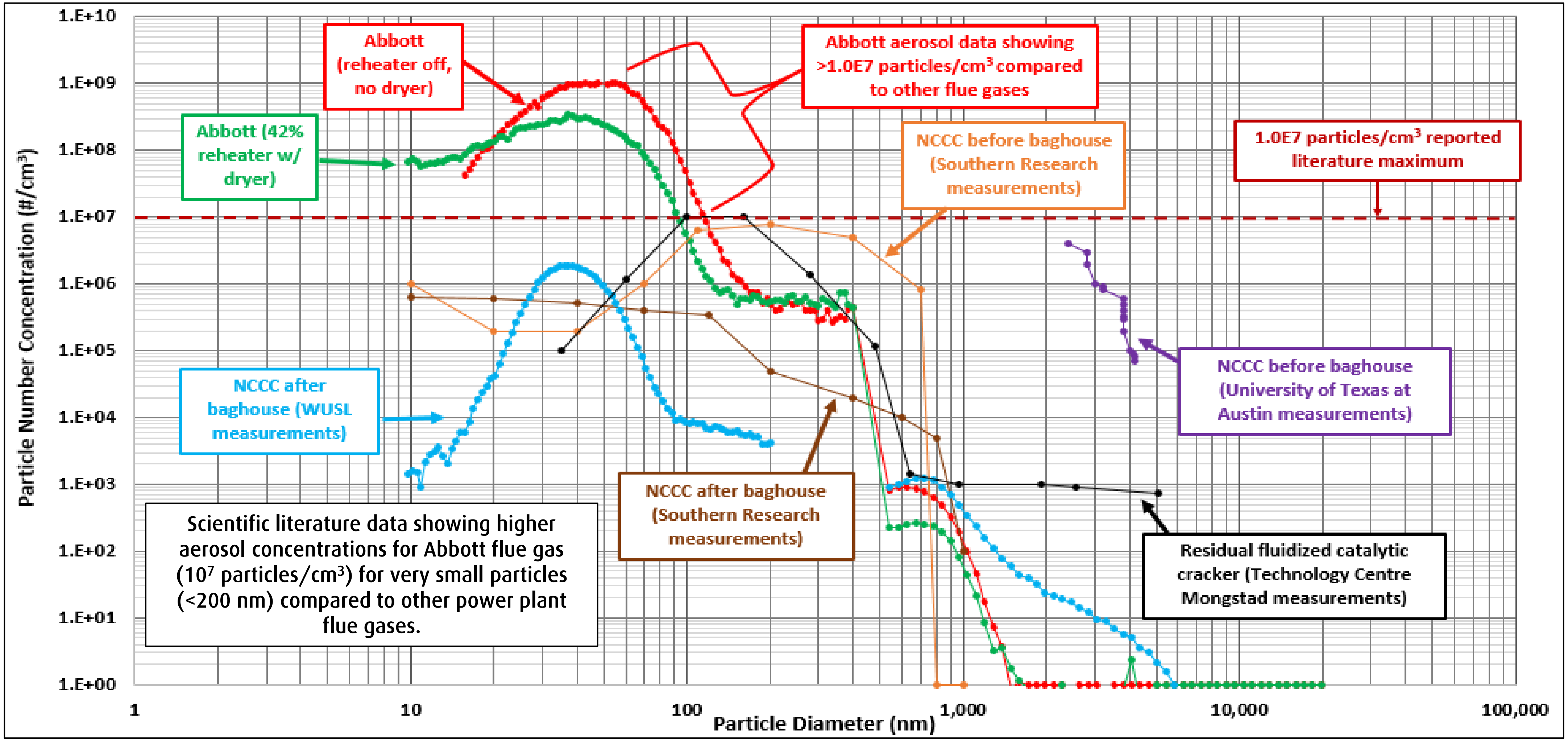


3 main stages of aerosol formation

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.

Aerosol particles sent in flue gas to PCC plant absorbers

Coal-fired power plant aerosol particle concentration and size distribution data found in scientific literature[1,2,3,4,5,6]



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.
2) 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.
3) Y. Wang, Z. Li, P. Biswas; Aerosol Measurements in Coal Combustor Exhaust Gas at Abbott Power Plant, IL, Washington University in St. Louis, February 22, 2016.
4) C. Saha, J. Irvin; Linde Aerosol Characterization Tests Conducted at the National Carbon Capture Center, Energy and Environment, Southern Research, January 22, 2016.
5) C. Saha, L. Berry; Linde Aerosol Characterization Tests Conducted at the National Carbon Capture Center, Energy and Environment, Southern Research, February 2, 2017.
6) S. Fulk, M. Beaudry, G. Rochelle; Amine Aerosol Characterization by Phase Doppler Interferometry, GHGT-13, Energy Procedia 2017; 114: Pages 939-951.

Theory and mechanisms for aerosol-driven amine losses from PCC plants

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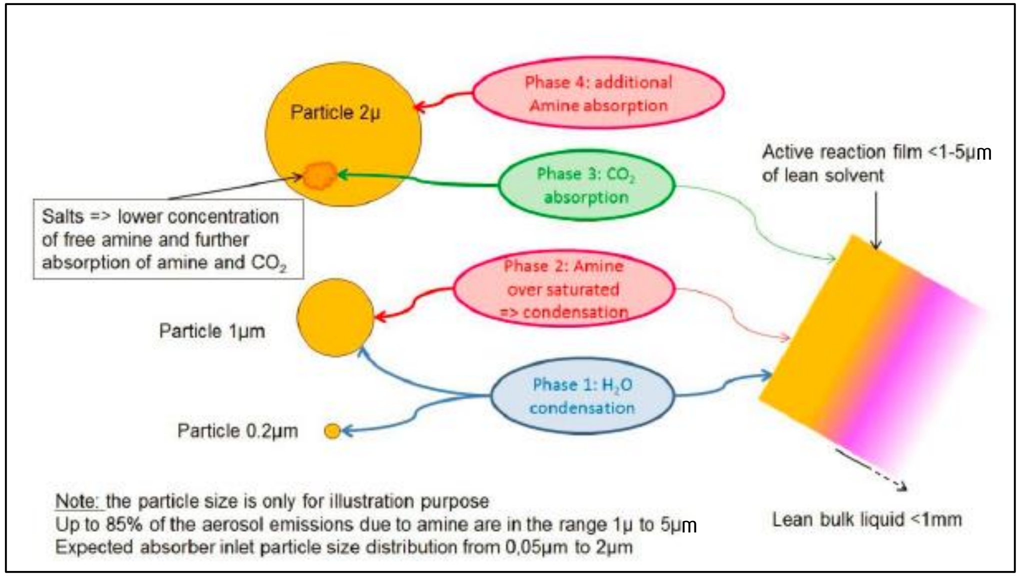
The Kelvin effect states that the vapor pressure over a curved interface is always higher for the same component than over a flat surface. The Kelvin equation gives the minimum particle diameter, d*, of a liquid[1].

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

Where:
d* = Particle diameter [m]
σ = Surface tension of liquid drop [N/m]
M = Average molecular weight of the condensable liquid [kg/Kmol.]
ρ = Liquid density [kg/m^3]
T = Temperature [°K]
R = Universal gas constant [J/Kmol./°K]
p = Sum of the partial pressures of all condensable components in the mixture [Pa]
p_0 = Corresponding sum of partial pressure when saturated (equilibrium conditions) [Pa]
The saturation of the gas mixture is $S = p/p_0$. The gas phase is supersaturated if $S > 1$

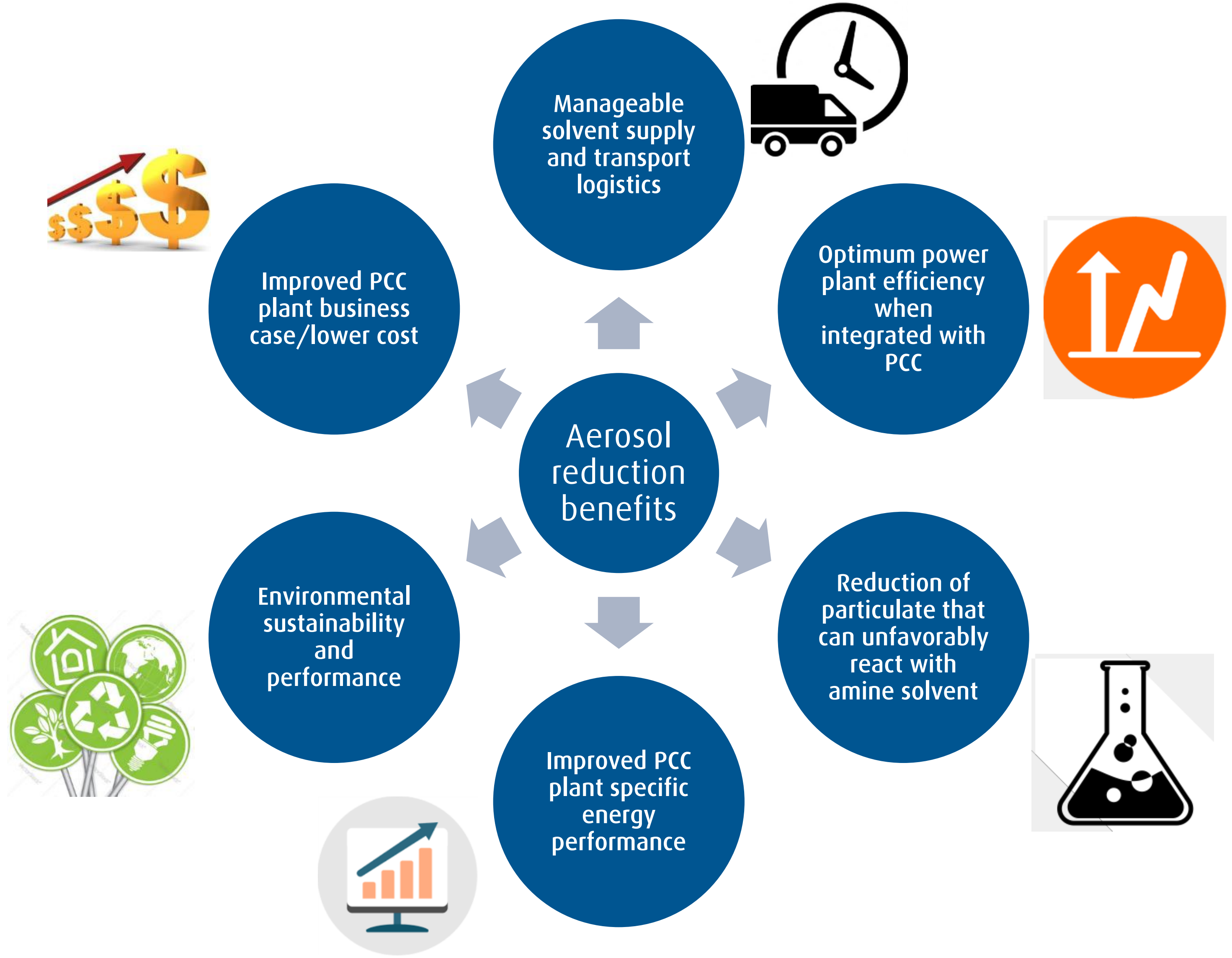
Particle type	Size range	Description
Small particles	<0.1 micron	Stable; large supersaturation is needed to form new droplets or grow existing particles.
Medium-sized particles	0.1-1 micron	Aerosol growth may occur with supersaturation of water or amine vapor
Large particles	>1 micron	Supersaturation not needed to form particles. The relatively large particles may be considered a flat surface. Aerosol growth may occur once saturation is reached.

Mechanisms for aerosol-driven solvent losses include[1]
(1) aerosol growth from water and homogeneous nucleation from high water supersaturation
(2) aerosol growth from amine until complete amine saturation in the aerosols
(3) buildup of captured CO_2 along with amine bound to the CO_2 inside aerosol particles
(4) salt accumulation inside aerosol particles enabling amine and CO_2 diffusion into aerosols



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.

Why reduce aerosols?



Linde-BASF 1.5 MWe pilot plant at NCCC[1]

1. D. Bostick; Final Testing Report to NCCC – Slipstream pilot plant demonstration of an amine-based post-combustion CO2 capture technology on coal-fired power plant flue gas. DOE/NETL Contact No. DE-FE0007453, January, 2017.

Methods to reduce aerosol-driven solvent losses:
Varying absorber operating conditions → too energy intensive

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Absorber operating parameters that reduced solvent losses 5-10 times during Linde-BASF 1.5 MWe PCC pilot testing at NCCC before baghouse installation (DE-FE0007453)[1]	Proposed solvent loss reduction mechanisms	Effects on specific energy consumption (MJ/kg CO_2)
Increased CO_2-lean solution return temperature to absorber after lean solution cooler (104°F design temp.) Increased solution return temperature to absorber after abs. int. cooler (104°F design temp.)	Higher solution temp. raises flue gas temp. in absorber and increases vapor saturation pressure. This leads to particle coalescence and formation of larger aerosol particles. Larger particles can be more easily captured by absorber demister systems, so related amine losses are reduced.	104°F design temp. provided optimal performance → **Increasing T above 104°F greatly increases specific energy consumption**[1]
Higher absorber pressure (0.93-0.99 bara design pressure)	Reduces vaporization of amine at slightly higher T. p/p_0 for liquid droplets ↓ with ↑ T, so critical diameter d* ↑ and larger particles are formed that are captured by absorber demister. Demisters are most effective at capturing particles with diameters >200 nm, so larger particles lead to reduced aerosol-driven solvent losses.	Effect of higher absorber pressure on energy consumption was not assessed during test campaign[1], but likely higher absorber P and T lead to reduced solvent absorption capacity and higher flue gas blower duty → **higher absorber pressure increases specific energy consumption**
Reduced treated gas temperature (110.7°F design temp.)	Decreases vaporization of amine.	Treated gas temperatures equal to or below 100°F provides little effect compared to higher temperatures[1]

Result: Not ideal solution due to high specific energy penalty → varying absorber conditions should only be used as a temporary last resort aerosol mitigation option until a better long-term solution can be implemented.

1. D. Bostick; Final Testing Report to NCCC – Slipstream pilot plant demonstration of an amine-based post-combustion CO2 capture technology on coal-fired power plant flue gas. DOE/NETL Contact No. DE-FE0007453, January, 2017.

Methods to reduce aerosol-driven solvent losses:
Baghouse installation → too costly and requires large footprint & plant retrofit

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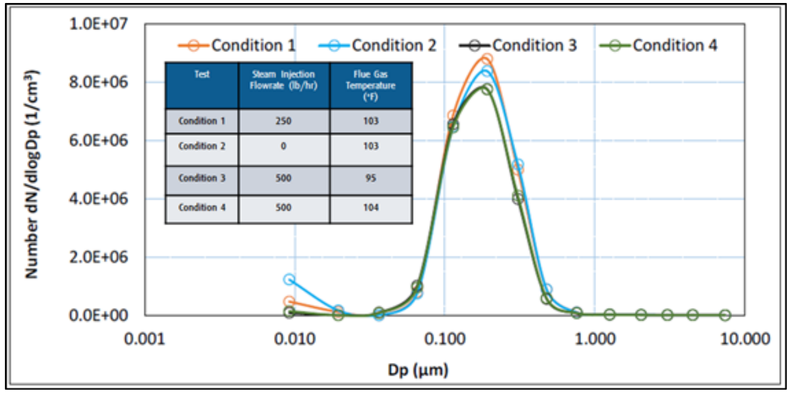
- Linde-BASF parametric testing at NCCC[1] before baghouse installation showed aerosol concentrations between 10^6 and 10^7 particles/cm^3 for 70-200 nm particles.
- Particle concentrations for 70-200 nm particles were reduced to ~10^4 particles/cm^3 after baghouse installation.
- Calculated solvent losses reduced up to 100 times after baghouse installation; losses measured by isokinetic sampling and analysis.
- Common metric used industrially to evaluate solvent losses for PCC plants is the threshold of **0.3 kg amine/tonne CO_2 captured**.

However, installation and maintenance of a new commercial baghouse at an existing power plant involves high capital and labor costs for retrofit as well as a large site footprint & lengthy plant shutdown time.

Result: baghouse solution is not always feasible or cost-effective.

Before baghouse installation at NCCC*

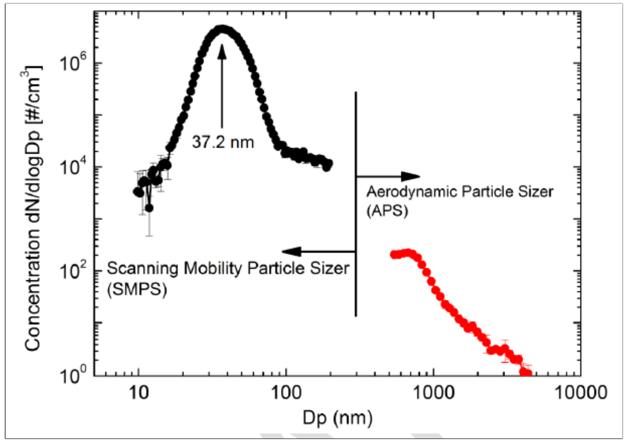
Peak conc. = 9E+06 particles/cm^3 at 200 nm

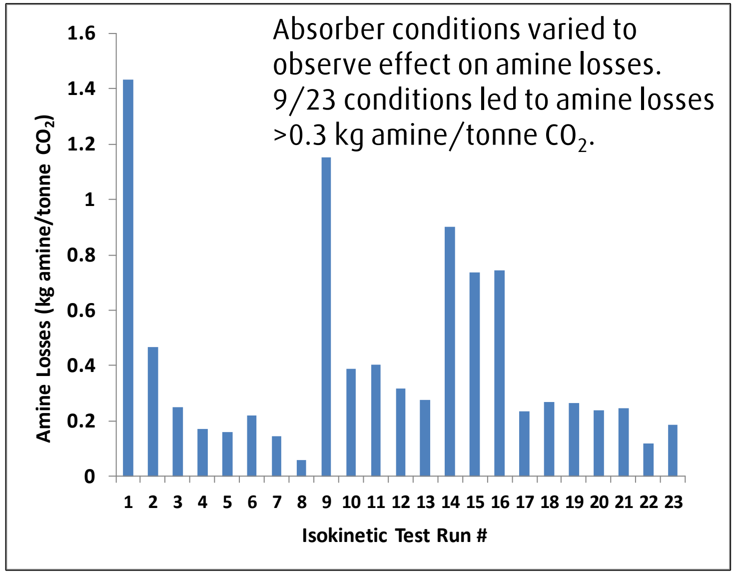


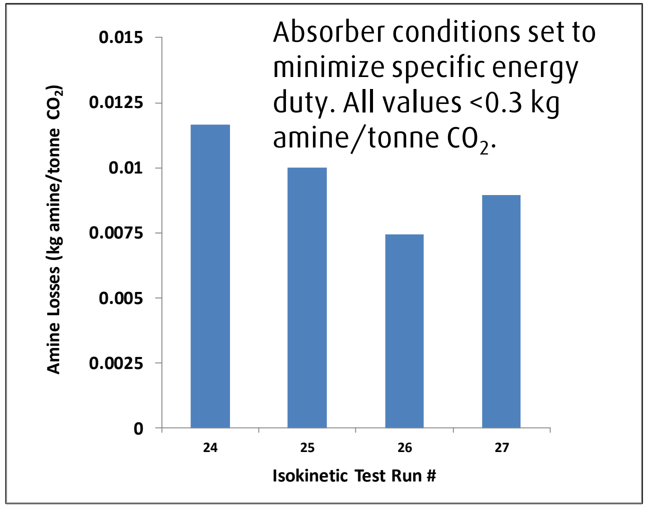
Test	Steam Injection Flowrate (lb/hr)	Flue Gas Temperature (°F)
Condition 1	250	103
Condition 2	0	103
Condition 3	500	95
Condition 4	500	104

After baghouse installation at NCCC*

Peak conc. = 5E+06 particles/cm^3 at 37.2 nm







1. D. Bostick; Final Testing Report to NCCC – Slipstream pilot plant demonstration of an amine-based post-combustion CO2 capture technology on coal-fired power plant flue gas. DOE/NETL Contact No. DE-FE0007453, January, 2017.

Methods to reduce aerosol-driven solvent losses:

Absorber water wash section conditions → only sufficient for conc. up to 10^6 particles/cm³

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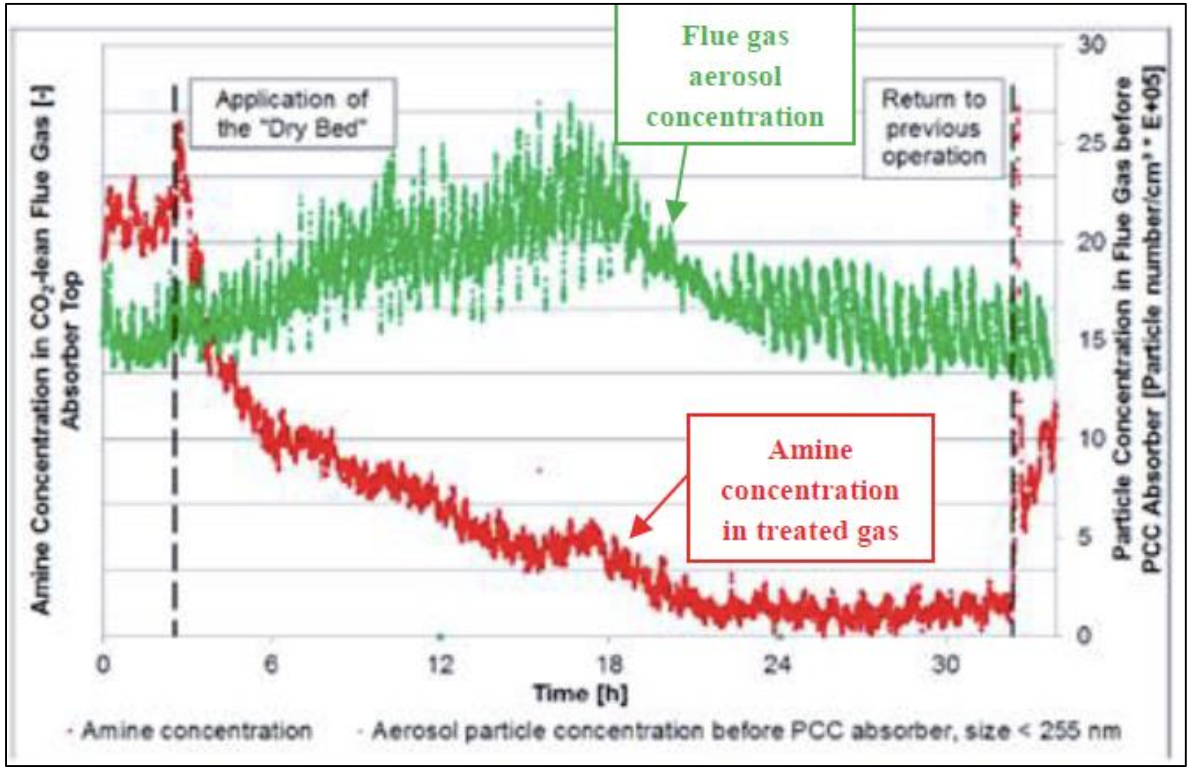
- For flue gas with particle concentrations b/t 10^5 and 10^6 particles/cm³, water wash section operating conditions at absorber top can reduce aerosol-driven solvent losses to below the 0.3 kg amine/tonne CO_2 threshold.
- Linde-BASF's patented dry bed wash section configuration[1] can reduce solvent losses for flue gas with particle concentrations at or slightly above 10^6 particles/cm³.
- Niederaussem, Germany[1] and NCCC[2] tests of Linde-BASF system proved that dry bed wash section configuration can reduce solvent losses for particle concentrations up to 10^6 particles/cm³.



Wash water section conditions can reduce solvent losses for flue gas particle concentrations from 10^5 - 10^6 particles/cm³, but not significantly above 10^6 particles/cm³. Other solution is needed to span full range of aerosol concentrations far above 10^6 particles/cm³.

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.
2) D. Bostick, K. Krishnamurthy; Final Testing Report to NCCC, DOE-NETL Contract No. DE-FE0007453, Murray Hill, NJ, 2017.

Methods to reduce aerosol-driven solvent losses:

Flue gas aerosol pretreatment → cost-effective, optimizable solution to manage aerosols

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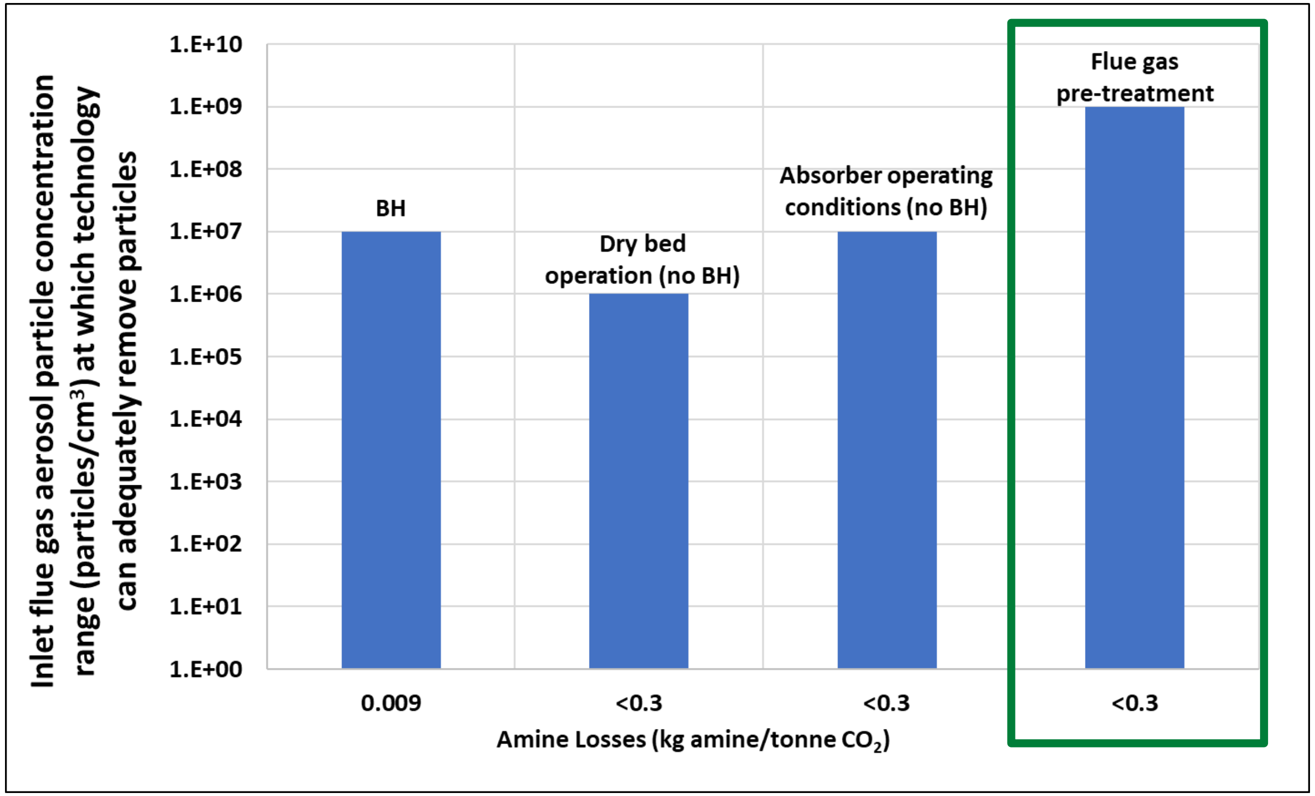
- One other possible solution is to continuously makeup solvent lost due to high aerosol particle concentrations; this becomes extremely expensive and logistically challenging for a long-term solution.
- Hence → For power plants without a baghouse producing flue gas with particle concentrations > 10^7 particles/cm^3, **the only realistic option available to mitigate aerosol-driven amine losses from PCC plants is flue gas aerosol pretreatment.**
- Pretreatment has traditionally been performed using simple ESPs and Brownian filters, but no systematic study has been conducted to evaluate performance over a full range of conditions.



For power plants without a 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

High velocity water spray-based aerosol pretreatment technology
Developed by RWE & tested in Niederaussem at lignite-fired coal power plant

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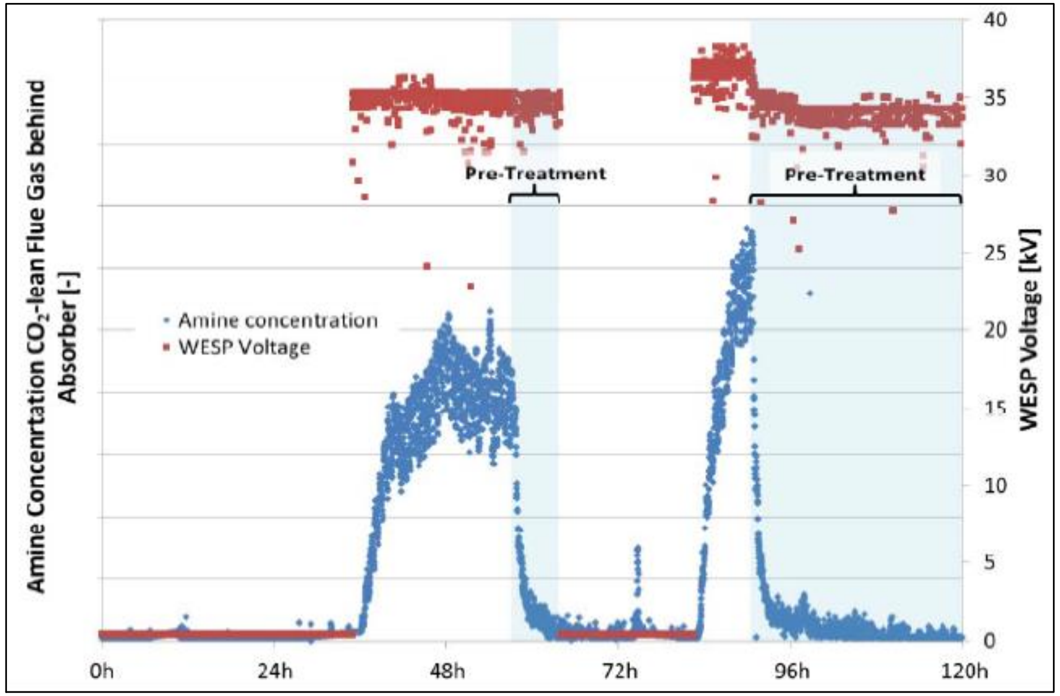
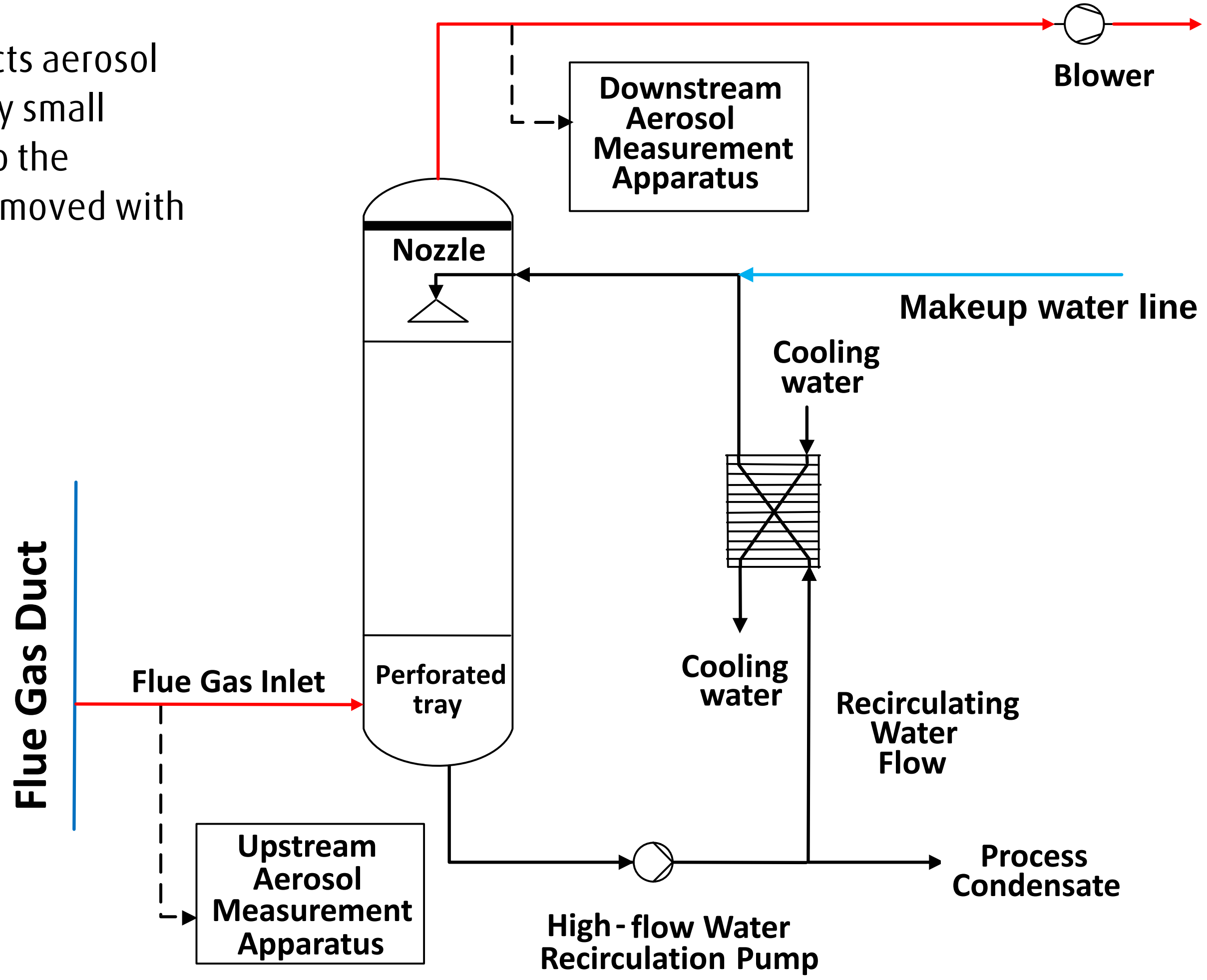
Technology description
Water circulates in loop at very high velocity; cooler is optional. Water contacts aerosol particles in the flue gas using spray injected through nozzle comprised of very small holes. Contacting spray causes aerosol particle growth and condensation into the circulating loop. Water cools flue gas causing condensation; condensate is removed with purge and stored in vessel on site.

Performance
Pretreatment reduced amine losses ~15-18 times at Niederaussum pilot[1].





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Novel ESP-based aerosol pretreatment technology

Developed by Washington University in St. Louis (WUSTL)

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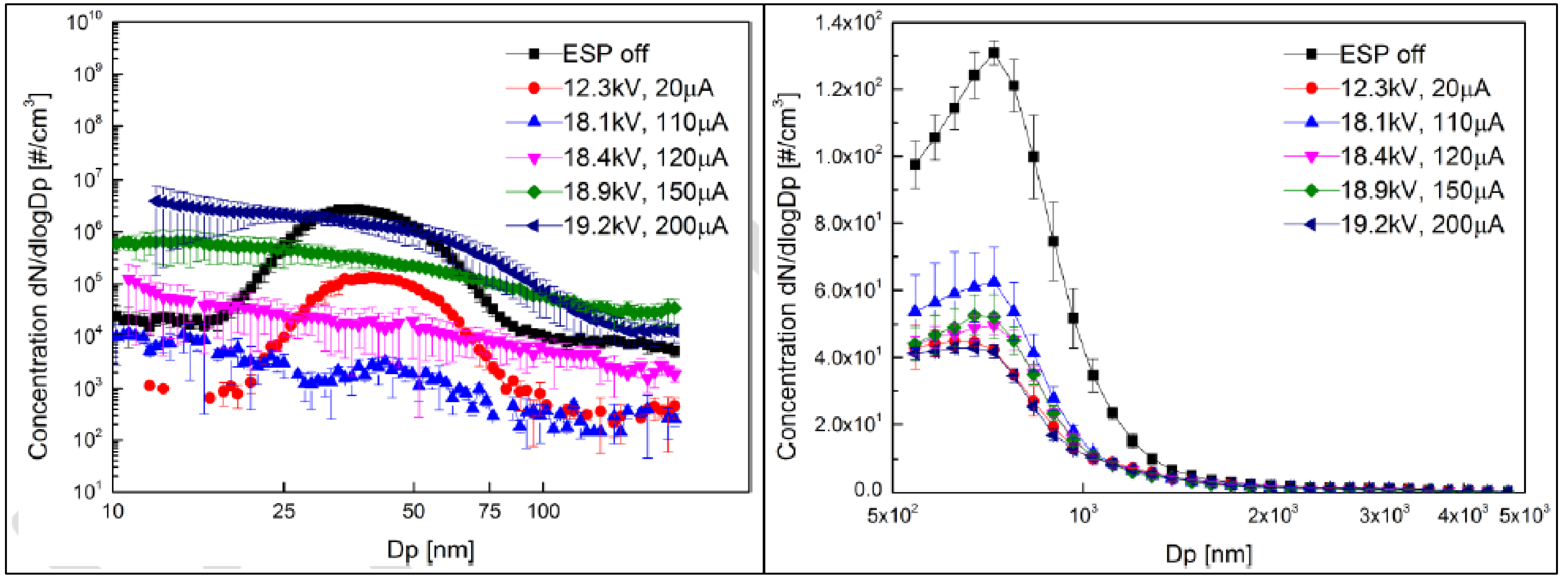
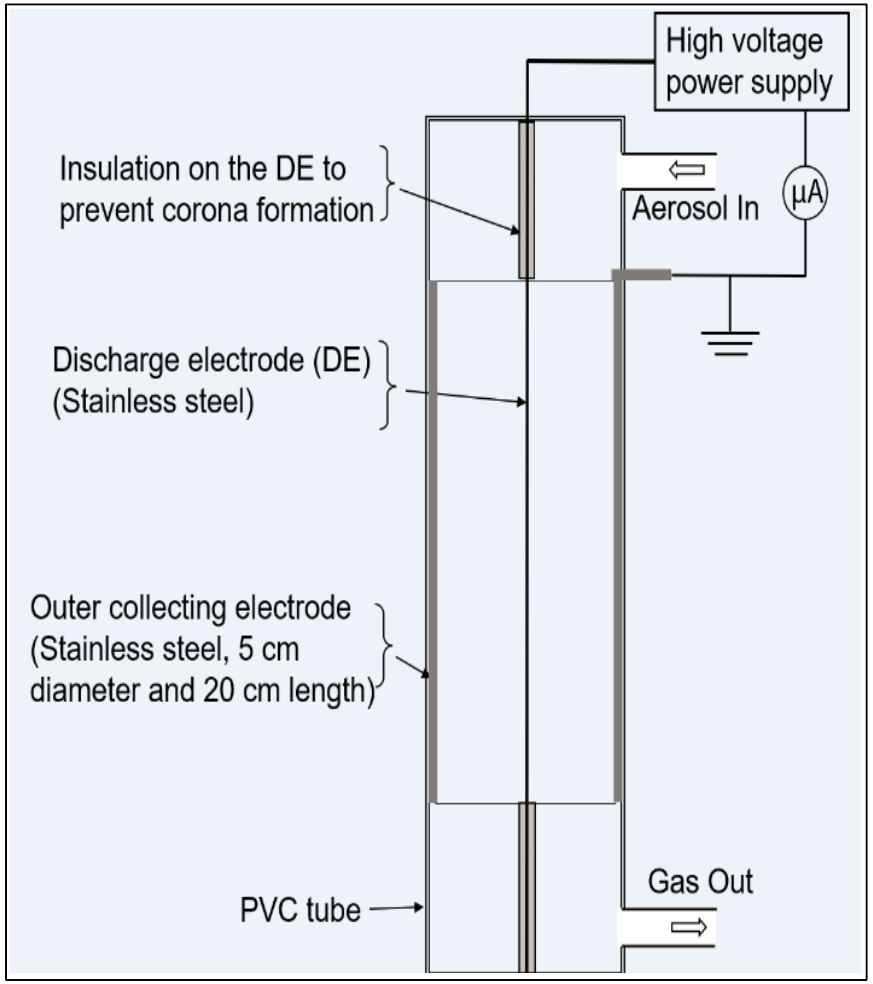
Technology description

ESP applies high voltage between plate and wire. Voltage ionizes aerosol particles in flue gas. Due to electrostatic force, ionized particles are diverted from gas phase towards collecting plates that remove them from the gas. Specific collection area (SCA) is the most important design parameter. WUSTL's ESP can provide 98-99% removal efficiency for 1000 scfm gas flow and an SCA of 95 $m^2/(m^3/s)$. SCA can be increased to remove particles in range of 10-500 nm at very high efficiencies. WUSTL's system will include a patented photo-ionizer technology that enhances charging capacity to further increase particle capture efficiency; this photo-ionizer can be retrofitted to existing commercial ESP systems, reducing CAPEX.

Performance

Pretreatment reduced aerosol particle concentrations for 25-80 nm diameter particles by 99.9%[1].





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.

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 (#/cm³) - Particle concentration after aerosol pretreatment (#/cm³))/(Particle concentration before aerosol pretreatment (#/cm³)) * 100*

*** when integrated with PCC technology for a 550 MWe supercritical coal-fired power plant without a baghouse*

Preliminary comparative techno-economic analysis
Selected flue gas aerosol pretreatment solutions provide the most cost-effective solutions

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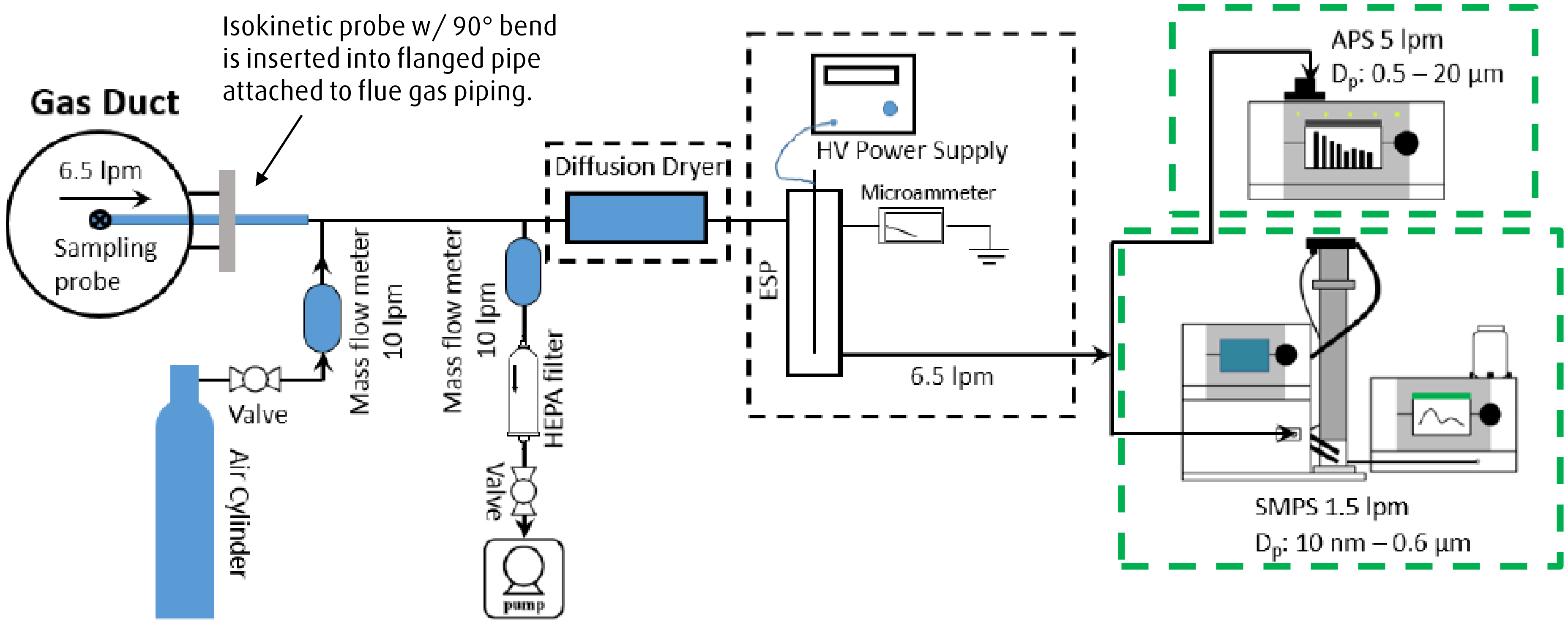
Techno-economic analysis comparing cost and performance of supercritical power plants (PP*) integrated with PCC with and without flue gas aerosol pretreatment					
Scenario	DOE-NETL Case B12B: PP 2/ 90% CO2 capture**	Case 1: PP w/ 90% CO2 capture; 4X solvent makeup needed to offset high solvent losses	Case 2: PP w/ 90% CO2 capture; varying absorber conditions to reduce solvent losses	Case 3: PP w/ 90% CO2 capture; high-velocity spray aerosol pretreatment	Case 4: PP w/90% CO2 capture; advanced ESP aerosol pretreatment
Baghouse	Yes	No	No	No	No
Added CAPEX w/ aerosol pretreatment ($)	N/A	N/A	N/A	$3,261,720	$2,338,318
Added energy consumption w/ aerosol pretreatment (MW)	N/A	N/A	N/A	11	1.32
Total Overnight Cost ($)	$2,384,351,816	$2,331,909,536	$2,364,444,218	$2,356,810,371	$2,328,373,523
PCC plant specific energy consumption (MJ/kg CO_2)	2.48	2.48	3.00	2.48	2.48
Net power plant efficiency (%)	32.50	32.50	31.67	31.93	32.46
Cost of electricity w/o T&S (COE, $/MWh)	$133.2	$136.86	$133.68	$133.05	$131.31
Cost of CO_2 captured w/o T&S ($/tonne CO_2)	$58.00	$64.13	$58.94	$58.72	$57.69

*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; the costs associated with these factors are not included.

WUSTL aerosol measurement setup and equipment



- WUSTL equipment is about 2'x2' in area
- Aerosol measurements will be performed at the common inlet and outlet gas piping connected to the test skid.

- Scanning mobility particle sizer (SMPS) characterizes particles 10-600 nm in diameter using a differential mobility analyzer to determine particle size as a function of electrical mobility size and a condensation counter to measure particle concentrations.
- Aerodynamic particle sizer (APS) measures aerodynamic size distributions of particles ranging from 0.5-20 microns and measures particle concentrations using a condensation particle counter.

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.

Project Setup at Abbott Power Plant Host Site

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

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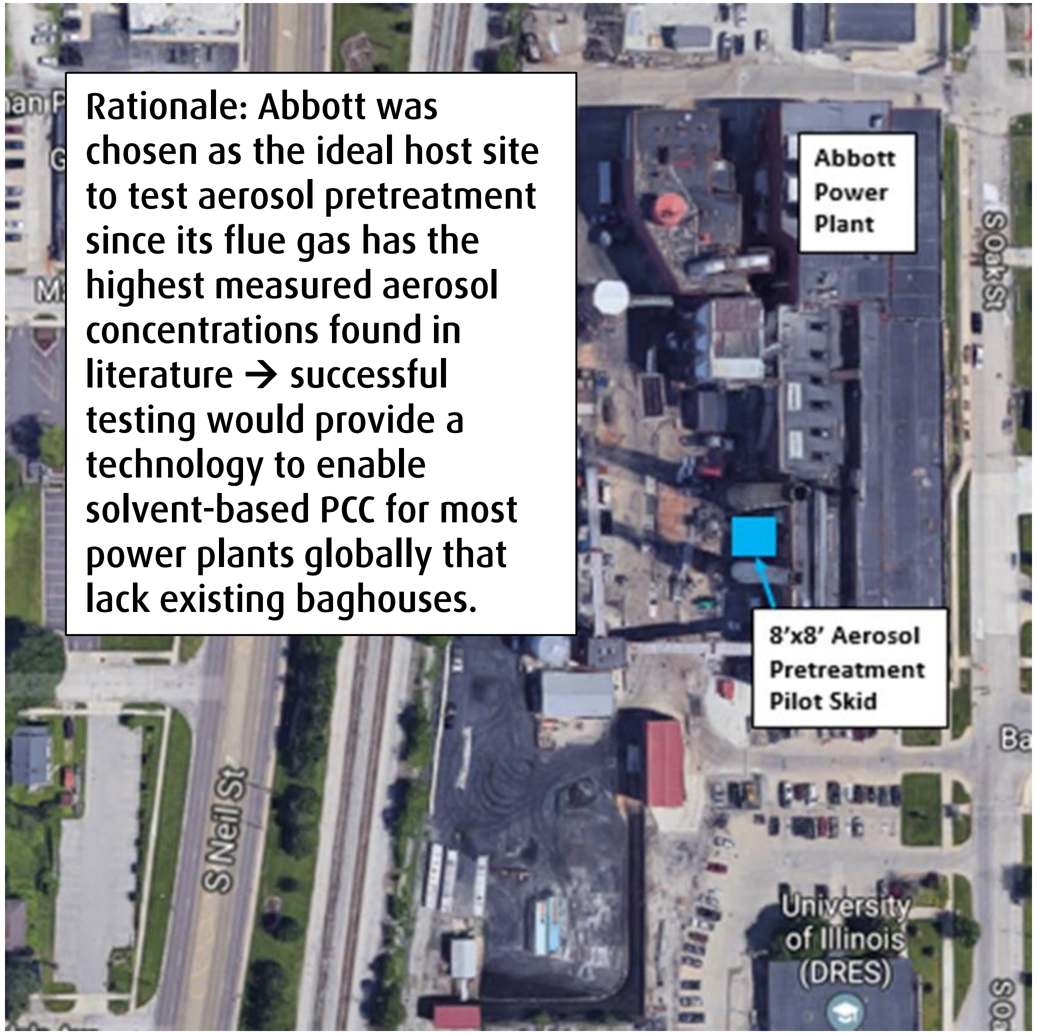
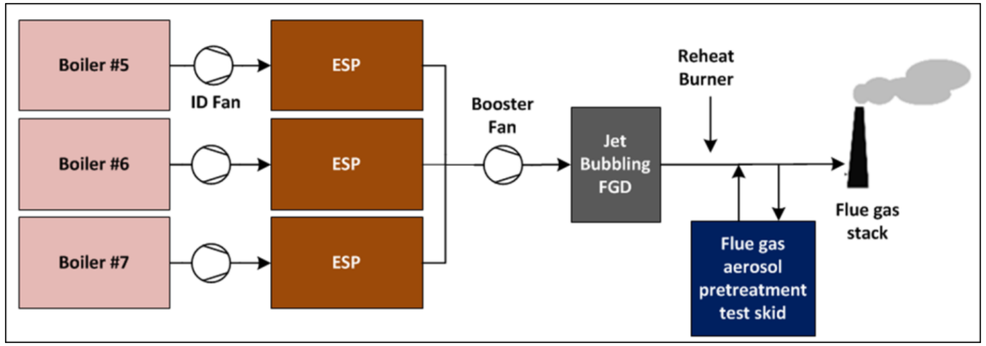


Item	Unit	Value
Temperature	deg F	200
Pressure (gauge)	psig	0.75
Gas composition		
Moisture	vol%	19.2
CO_2	vol% (dry)	9.2
O_2	vol% (dry)	7.35
SO_2	ppmv (wet)	177
NO_x	ppmv (wet)	211

Abbott flue gas conditions after FGD & reheat burner



Abbott plant schematic and tie-in points to pilot skid

Preliminary skid layout at Abbott host site

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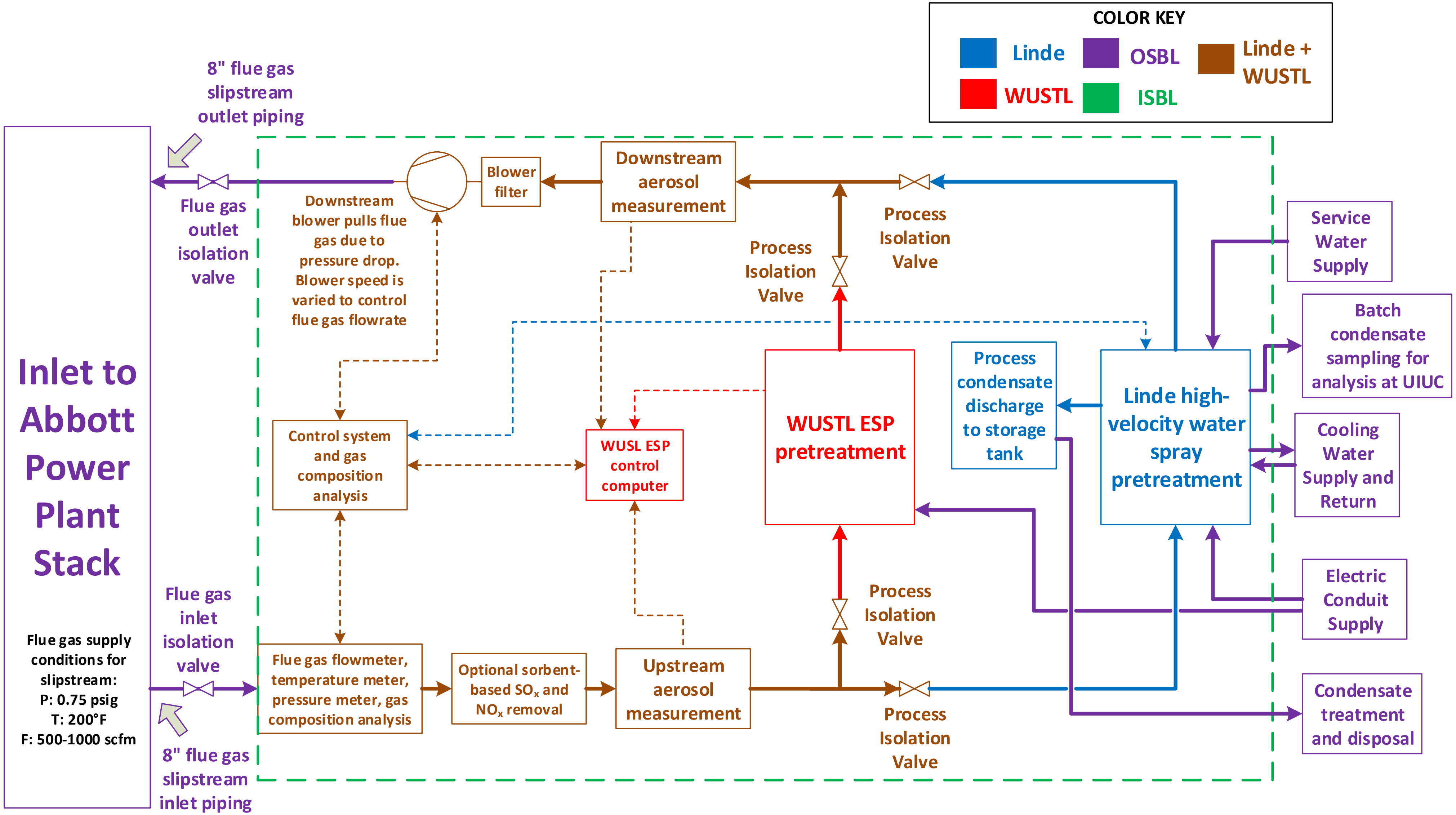

Project Risk Assessment and Mitigation Strategies

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Project management plan: technical 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.

Project management plan: 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.

Current progress and next steps

Current progress

- Project subaward contracts with UIUC, WUSTL, and ACS have been drafted and are under review and negotiation.
- Project subaward Statements of Work (SOW) have been completed and agreed upon as apart of subaward contracts.
- Updated PMP and Gantt chart (milestone 1 completed).
- Review of aerosol-driven amine loss mechanisms and EHS implications (Task 2.1) is in progress by UIUC and Linde; modeling of aerosol-driven amine loss mechanisms is underway by WUSTL.
- Specification and design basis definition for both pre-treatment systems (Task 3.1) has been completed. Basic design package development and safety analysis (Task 3.2) has been underway since 7/2/18.

Next steps

- Fully execute sub-award contracts with UIUC, WUSTL, and ACS.
- Finish aerosol-driven amine loss mechanism analysis and review (Task 2.1) and provide key information for modeling work (Task 2.2).
- Continue progressing aerosol-driven amine loss mechanism modeling work with WUSTL. Completion expected by 11/1/18 followed by report generation.
- Continue to work on basic design package development and safety analysis (Task 3.2), including HAZOP and safety analysis. Completion expected by 10/5/18.
- Work on BP 2 continuation application due to DOE by 8/30/18.
- Draft quarterly report for June 2018 work and submit to DOE by 7/31/18.

Thank you!

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