Slipstream pilot plant demonstration of an amine-based post-combustion capture technology for CO_2 capture from coal-fired power plant flue gas

DOE funding award DE-FE0007453

Final Project Meeting

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Linde LLC

January 30, 2017
Pittsburgh, PA

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Project Objectives

Overall Objective

- Demonstrate Linde-BASF post-combustion capture technology by incorporating BASF's amine-based solvent process in a 1 MWel slipstream pilot plant and achieving at least 90% capture from a coal-derived flue gas while demonstrating significant progress toward achievement of DOE target of less than 35% increase in levelized cost of electricity (<$40/tonne CO_2)

Specific Objectives

- Complete a techno-economic assessment of a 550 MWel power plant incorporating the Linde-BASF post-combustion CO_2 capture technology to illustrate the benefits
- Design, build and operate the 1MWel pilot plant at a coal-fired power plant host site providing the flue gas as a slipstream
- Implement parametric tests to demonstrate the achievement of target performance using data analysis
- Implement long duration tests to demonstrate solvent stability and obtain critical data for scale-up and commercial application

Project participant(s) competency and contribution critical to successful outcome

U.S. Department of Energy, Office of Fossil Energy; NETL	Project sponsorship and funding
Southern Company; National Carbon Capture Center	Host site; Infrastructure & utilities for pilot plant build and op's
EPRI Electric Power Research Institute	Independent analysis of test results & TEA review
BASF We create chemistry	Technology owner, basic design & solvent supply
The Linde Group Linde	Overall program management, EPC, Operations & Testing

Project Budget : DOE funding and cost share (Amended Aug 2014)

Source	Budget Period 1 Dec 2011 – Feb 2013 Design & Engineer	Budget Period 2 Mar 2013 – Aug 2014 Procure & Build	Budget Period 3 Sep 2014 – Nov 2016 Operate & Test	Total
DOE Funding	$2,670,173	$11,188,501	$2,360,173	$16,218,847
Cost Share	$667,543	$4,335,102	$1,472,506	$6,475,151
Total Project	$3,337,716	$15,523,602	$3,832,679	$22,673,998

	Budget	Actual (Jan. 30, 2017)
Total	$22.69m	$22.08m
DOE	$16.22m	$16.22m
Cost share	$ 6.47m	$ 5.85m

Actual costs are lower due to lower decommissioning costs.

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Delivering total solutions with confidence

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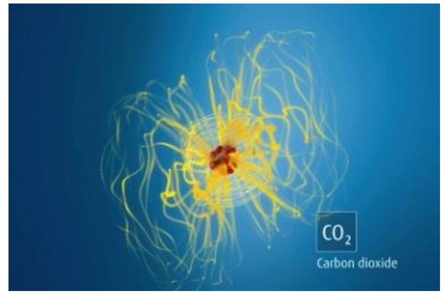
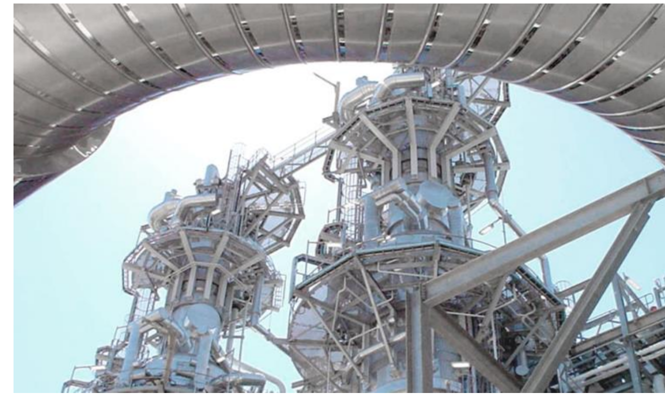




BASF Solvent/Process Expertise
- Basic Design Package
- Process performance
- Emissions performance

Linde Engineering Expertise
- Process optimization
- Basic/Detailed Engineering
- Package/EPC wrap

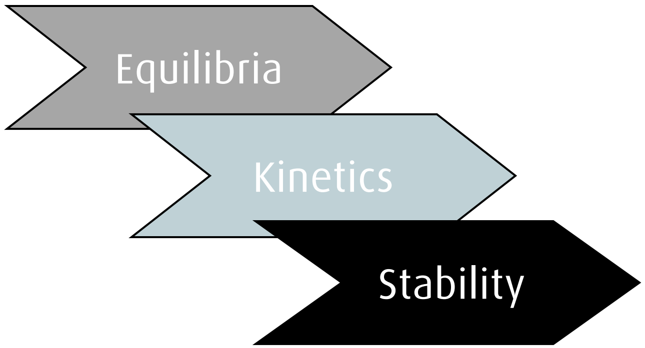
PCC capture

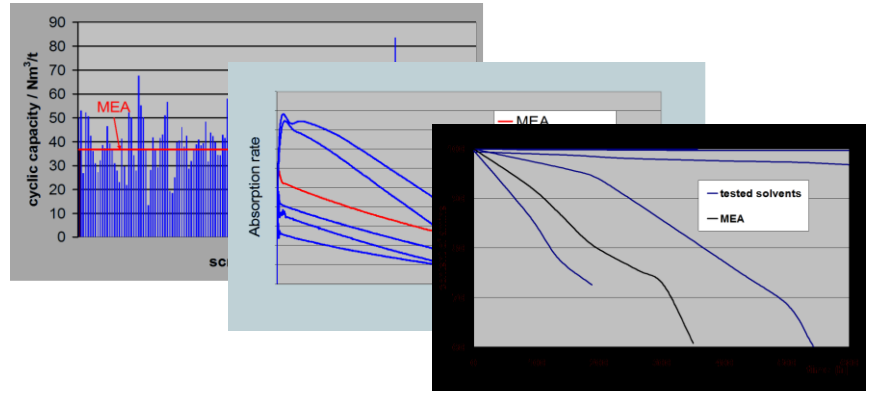
Founded	1865
Sales (2015)	€70.5 billion
Employees	~112,000

Founded	1879
Sales (2015)	€17.9 billion
Employees	~64,000

BASF OASE® blue technology roadmap

Adopted and optimized for PCC applications





Lab. & Mini plant (2004)	Pilot: 0.45 MWe (2009)	Pilot: 1.5 MWe (2014)	Large Pilot (proposed): 15 MWe (2016-2020)
— Ludwigshafen, Germany — Solvent selection & performance verification	— Niederaussem, Germany — Process opt., materials & emissions testing	— Wilsonville, AL (NCCC) — Design improvements, emissions confirmation	— Abbott power plant, UIUC, Champaign, IL — Full value chain demo.

Linde-BASF novel amine-based PCC technology features: NCCC 1 MWe pilot

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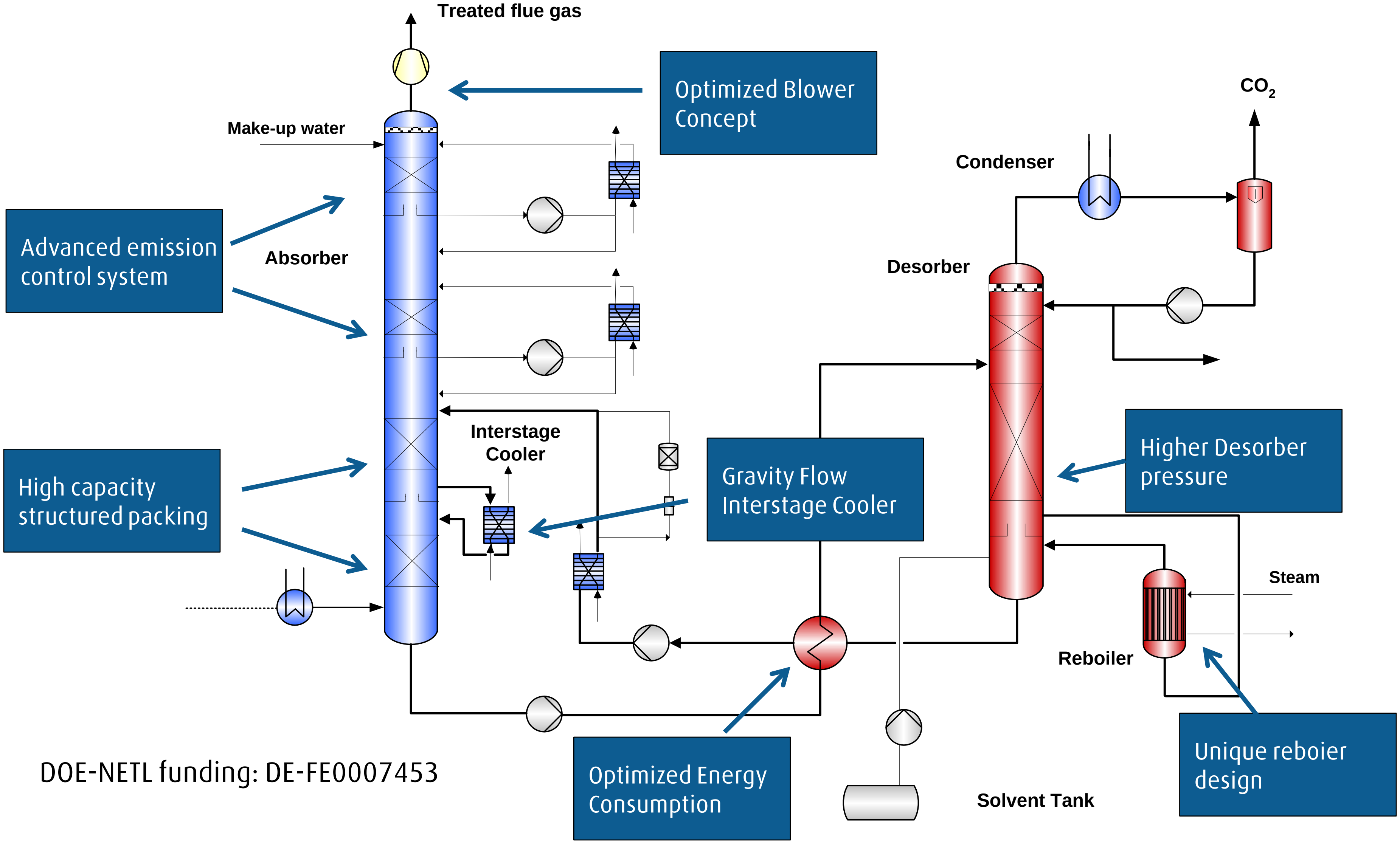

DOE-NETL funding: DE-FE0007453

Successful completion of design, engineering and costing in Budget Period 1 (Dec 2011 – Feb 2013)

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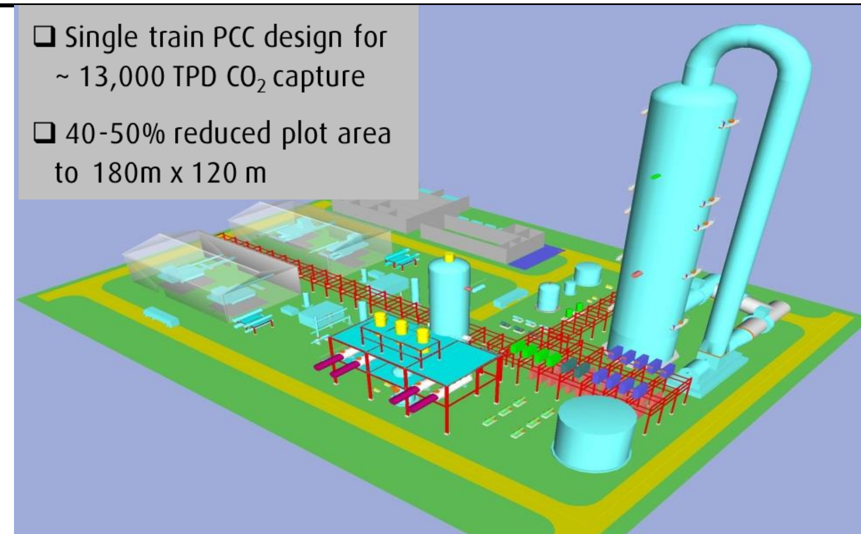
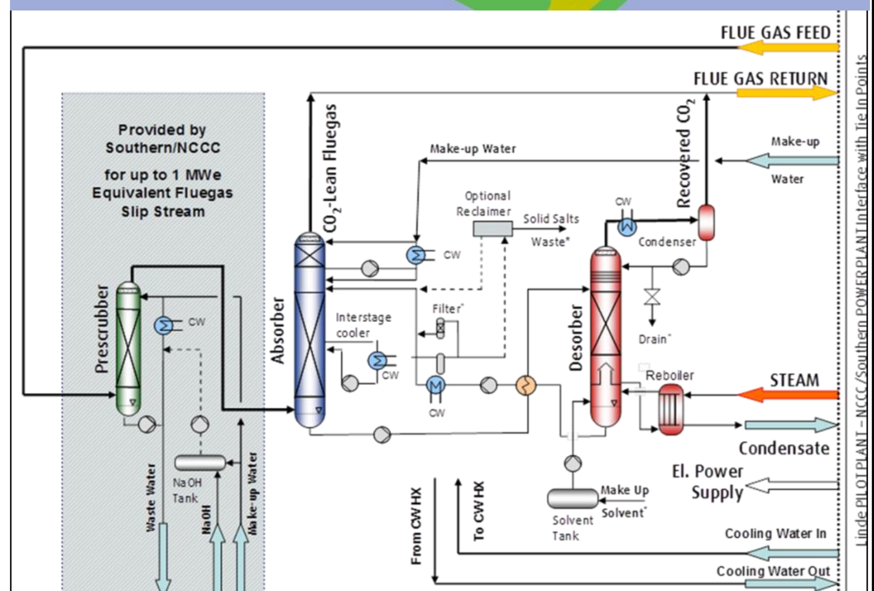
– Task 2: Techno-economic evaluation
  - TEA completed, report submitted & presentation made to DOE-NETL
  - Pilot plant performance targets set

– Task 3: Pilot plant design optimization and basic design
  - Pilot plant design basis completed in conjunction with NCCC site input (integrated design)
  - Basic design and engineering completed to define pilot plant operating & testing envelope

– Task 4: Pilot plant system design and engineering
  - Completed optimization of pilot plant layout
  - Detailed engineering completed including an integrated 3-D model

– Task 5: Pilot plant cost & safety analysis
  - Completed preliminary EH&S assessment including all process safety reviews & HAZOP
  - Completed vendor packages & pilot plant cost estimates





Successful completion of procurement, fabrication and installation in Budget Period 2 (Mar 2013 – Aug 2014)

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– Task 6: Supply of plant equipment
  - Purchase orders for all equipment procurement and contracts for fabrication and site installation completed
  - Module and column fabrication completed at vendor sites and transported to site
  - Civils (foundation) and utility upgrades/connections completed by NCCC

– Task 7: Plant construction and pre-commissioning
  - Modules, columns (absorber/stripper), analytical container and storage tanks installed at site
  - Field piping, electricals and instrumentation completed and mechanical completion of pilot plant achieved
  - Pre-commissioning activities completed including instrument loop checks, potash wash for system passivation and initial water circulation tests for system functional verification

Successful completion of operations & testing and pilot plant decommissioning in Budget Period 3 (Sep 2014 – Nov 2016)

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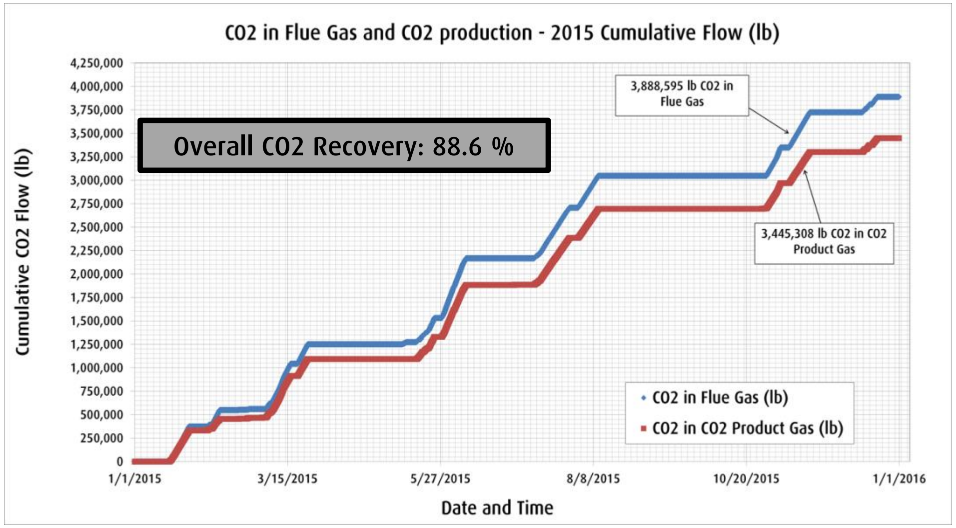
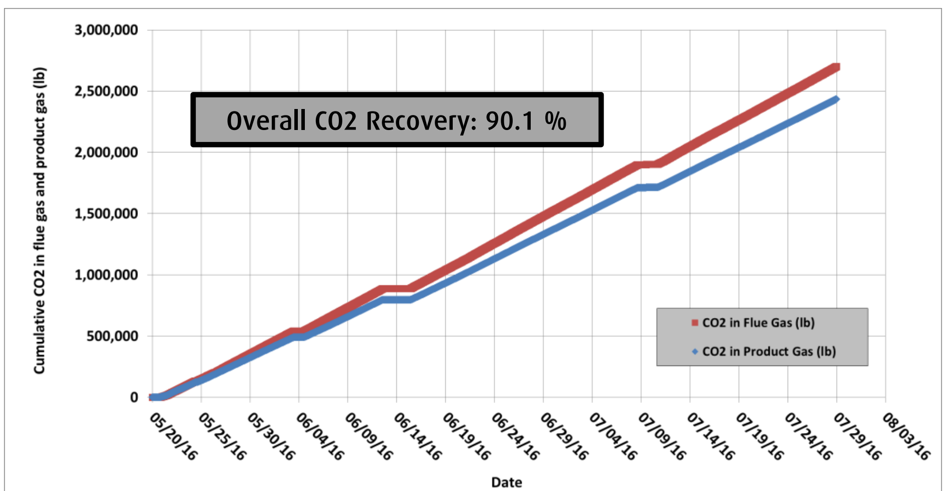
- Task 8: Pilot plant start-up (Jan-Mar 2015)
  - Stable operations achieved within one week
  - Excellent mass & energy balance closures
- Task 9:
  - Two campaigns (May 1-Aug 15, 2015) and (Oct 1-Dec 22, 2015)
  - Range of parametric testing completed. Validated higher pressure regeneration. Addressed aerosol-based amine carry-over.
- Task 10: Long Duration Testing
  - Pilot plant restart: May 16, 2016
  - Long duration test campaign: May 20-Jul 29, 2016
  - Continuous operation for 1520 hours
  - Flue gas flow: 10,500 lbs/hr (~1 MWe); 3.4 bar(a) Regen. Pressure
  - EPRI analysis performed: week of June 13, 2016
- Task 11: Final TEA & Commercialization Plan
  - Completed updated TEA & EH&S, Final report
  - Pilot plant dismantled and removed

Linde-BASF 1 MW_e pilot plant at the NCCC

Operating hours and Cumulative CO_2 in Flue Gas and CO_2 Product Gas Flowrates (lb)





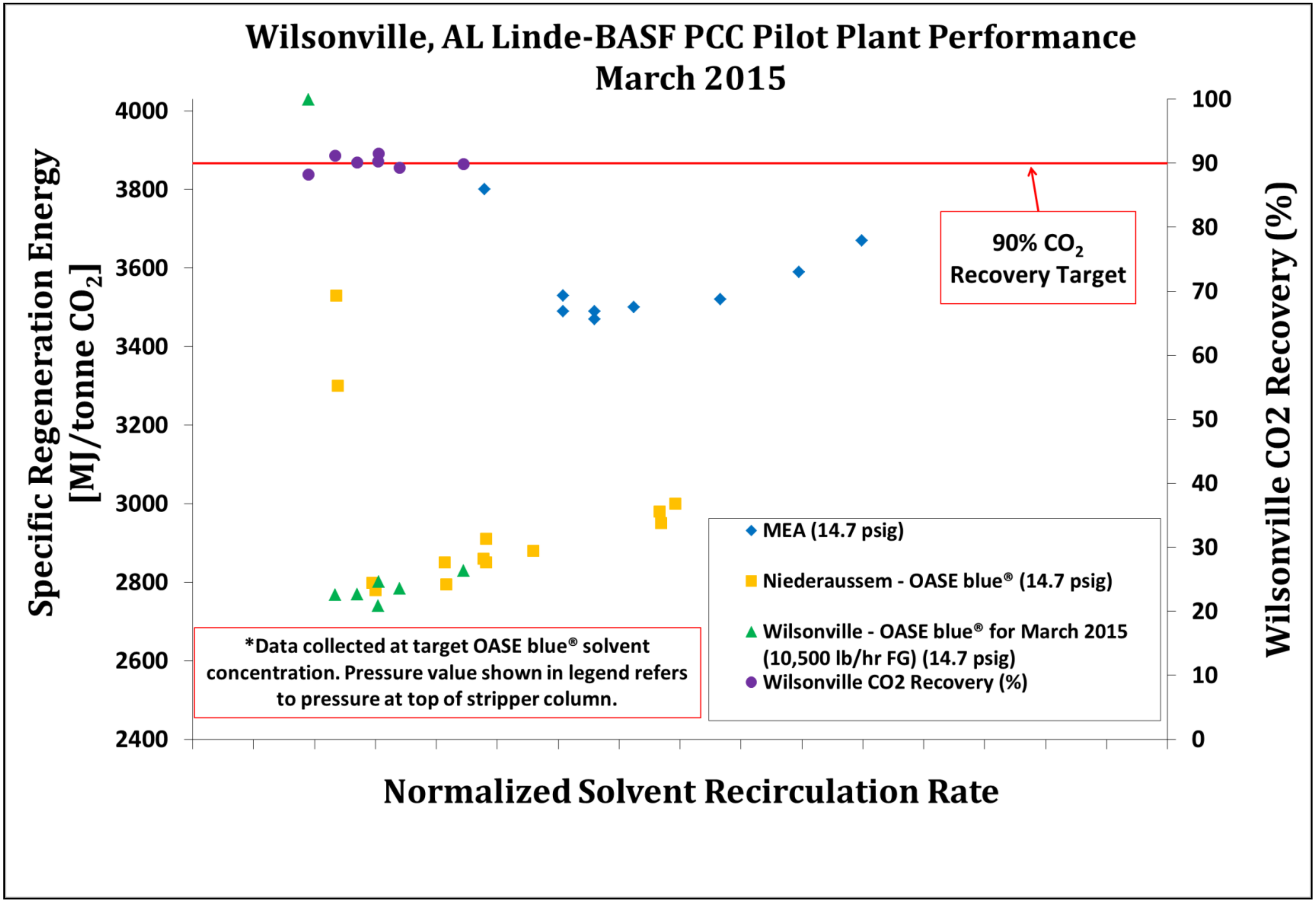
Parametric tests 2015: Operating hours

- Hours Flue gas testing: 2589
- Hours with steam on: 3841
- Hours of solvent circulation: 5096

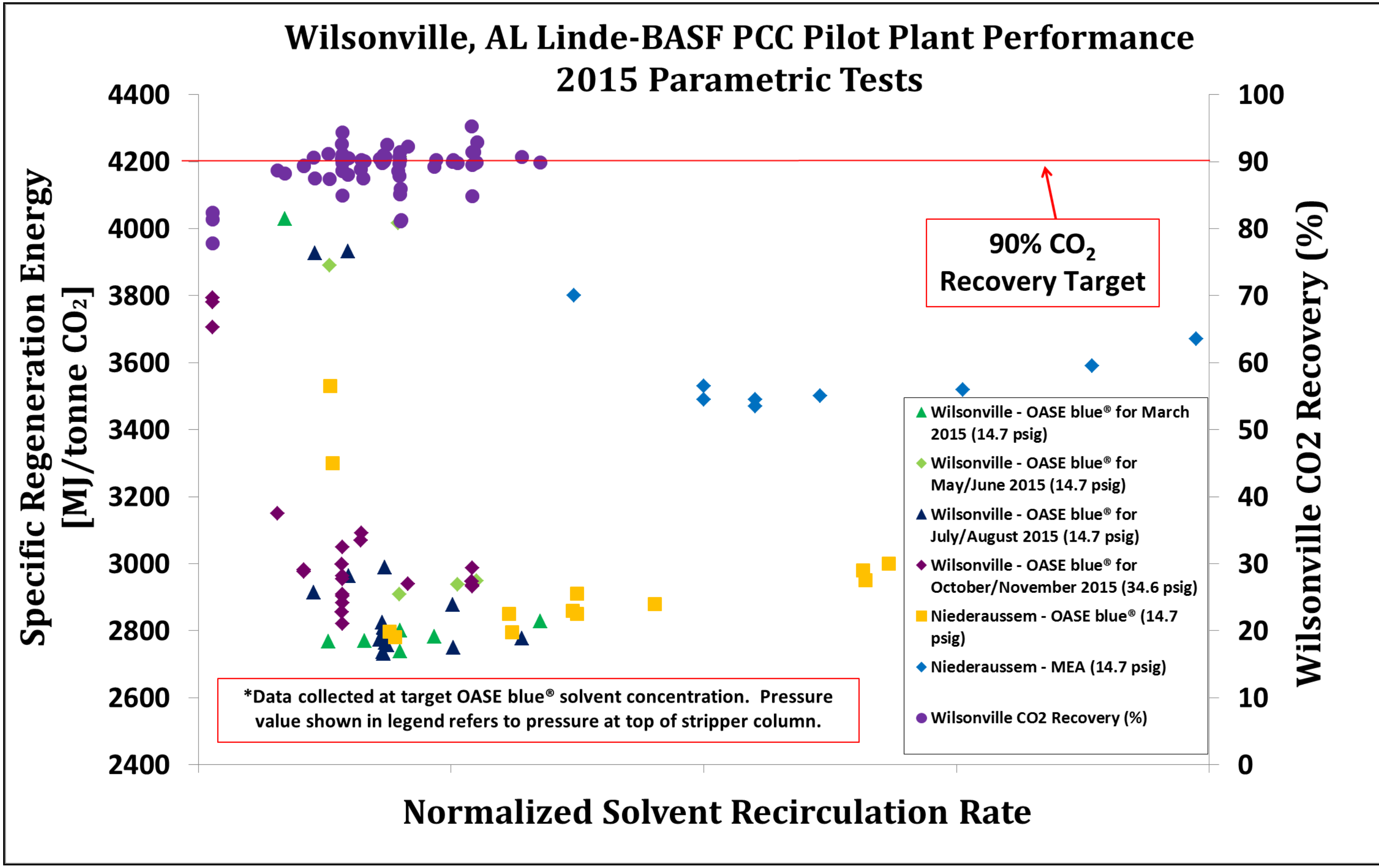
Long duration tests 2016: Operating hours

- Hours Flue gas testing: 1520
- Hours with steam on: 1532
- Hours of solvent circulation: 1668

Parametric testing (March 2015): Specific regeneration energy optimization



Parametric testing (Jan-Dec 2015): Specific regeneration energy optimization



Parametric testing (Jan-Dec 2015): Effect of regenerator pressure on specific regeneration energy

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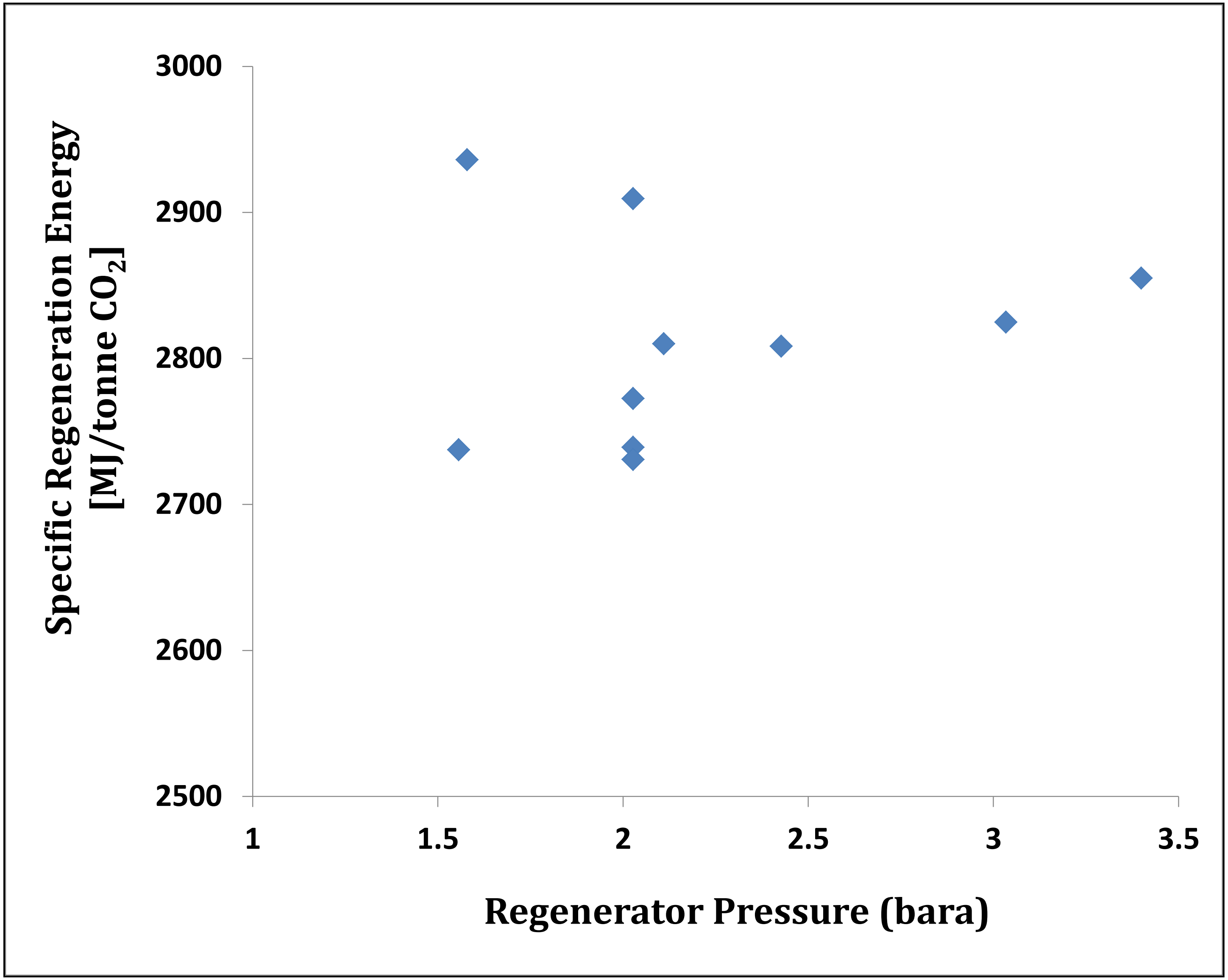

Wilsonville PCC Pilot Plant

Parametric Testing Performed

S.No.	Key variable	Status
1	Flue gas flow rate	7,500 to 15,750 lbs/hr
2	Flue gas temperature to absorber	86ºF to 104ºF
3	Treated gas temperature exit absorber	86ºF to 115ºF
4	Lean solution temperature to absorber	104ºF to 140ºF
5	Inter-stage cooler	On (104ºF) /Off
6	Regeneration pressure	1.6 to 3.4 bara
7	Solvent circulation rate	Varied from 80 to 120%
8	CO_2 capture rate	90% typical Varied from 85% to >95%

Parametric testing (Jan-Dec 2015): Impact of parameters tested on specific regeneration energy

Test Parameter	Impact on specific regeneration energy (GJ/tonne CO_2)
Flue Gas Temperature (°F)	Temperatures between 92-96 °F provided improvement compared to 104 °F and above.
Absorption Intermediate Cooler Outlet Temperature (°F)	104 °F offers optimum specific regeneration energy. Temperature was only varied during operation at 34.6 psig stripper pressure.
CO_2-lean Solution Cooler Outlet Temperature (°F)	Temperature equal to 104 °F provided improvement compared to higher temperatures.
Treated Gas Temperature (°F)	Treated gas temperatures equal to or below 100 °F provided improvement compared to higher temperatures.
Pressure at top of regenerator column (psig)	34.6 psig (3.4 bara) stripper pressure increases specific regeneration energy slightly (~2.2%) compared to 14.7 psig (2 bara) stripper pressure.

Pilot plant performance against targets: Accomplishments and next steps

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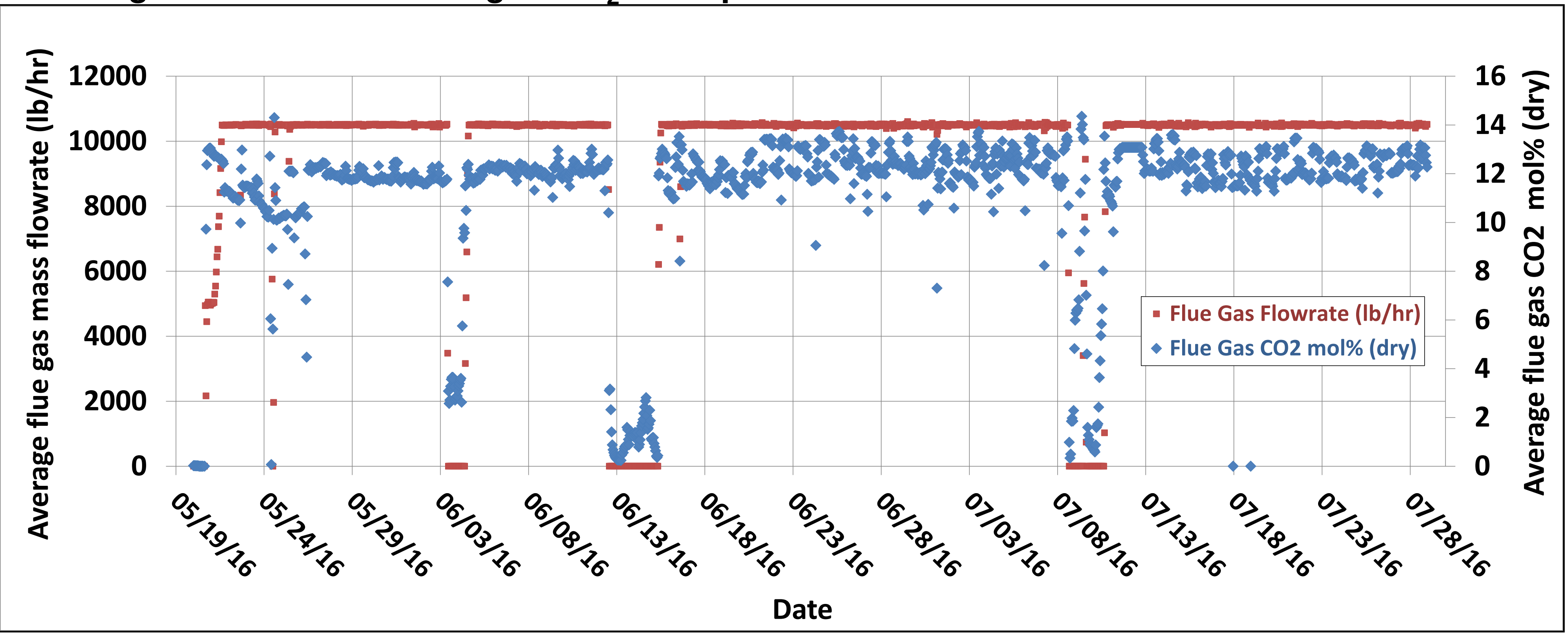
Performance Attribute	Current achievement against target	Remarks
1. CO_2 capture rate	>90% per target	Achieved. Capture rate can be optimized for specific energy.
2. CO_2 purity	99.9% dry basis per target	Achieved. Low O_2 impurity level for EOR and other applications.
3. Plant capacity	> 1.5 MWe per design target (>15,500 lbs/hr flue gas)	Achieved. Higher capacity testing performed ~10 days in May-June. Further 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 & treated gas) performed.
6. Regenerator operating pressure	- Testing performed up to 3.4 bars	Pressure parametric testing completed in Nov 2015
7. Validation of unique features	(i) high capacity packing (ii) gravity driven intercooler (iii) blower downstream of abs (iv) unique reboiler design	Design options for regenerator heat reduction through heat integration identified. Stripper interstage heater designs can result in ~ 2.3 GJ/tonne.

Note: Regenerator steam consumption above is intrinsic and does not include process and heat integration

Long duration testing: 1520 hours continuous & steady operation from May 20 – July 29, 2016

Flue gas flowrate and flue gas CO_2 mole percent



Test Set-up

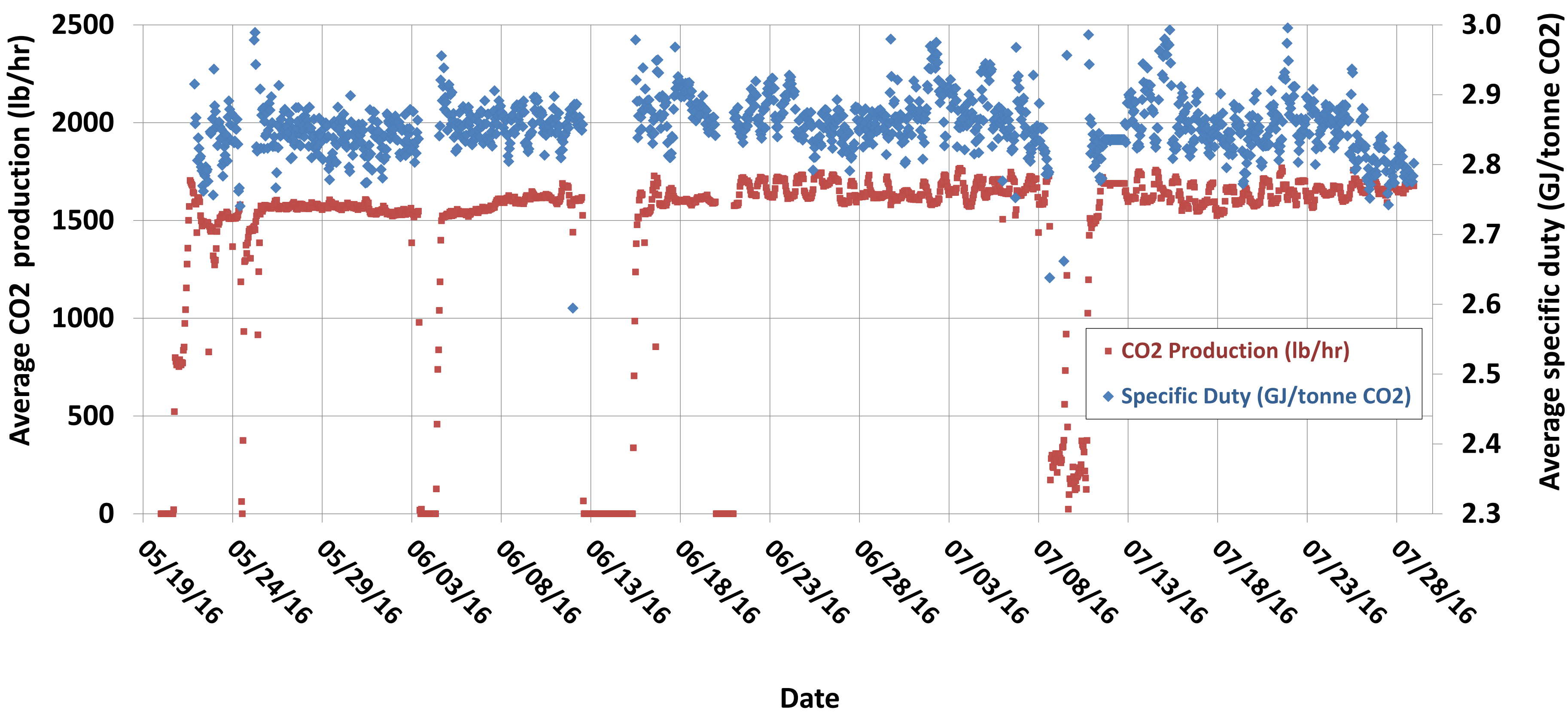
- Absorber inter-stage cooling : 40°C
- Absorber exit treated gas temp : 40°C
- CO_2 Capture rate : 90% (target)

- FG flow rate : 10,500 lb/hr (~1 MWe)
- Flue gas CO_2 conc. : 12% target
- Regenerator pressure : 3.4 bara
- Temp of FG to absorber : 35°C

Long duration test performance

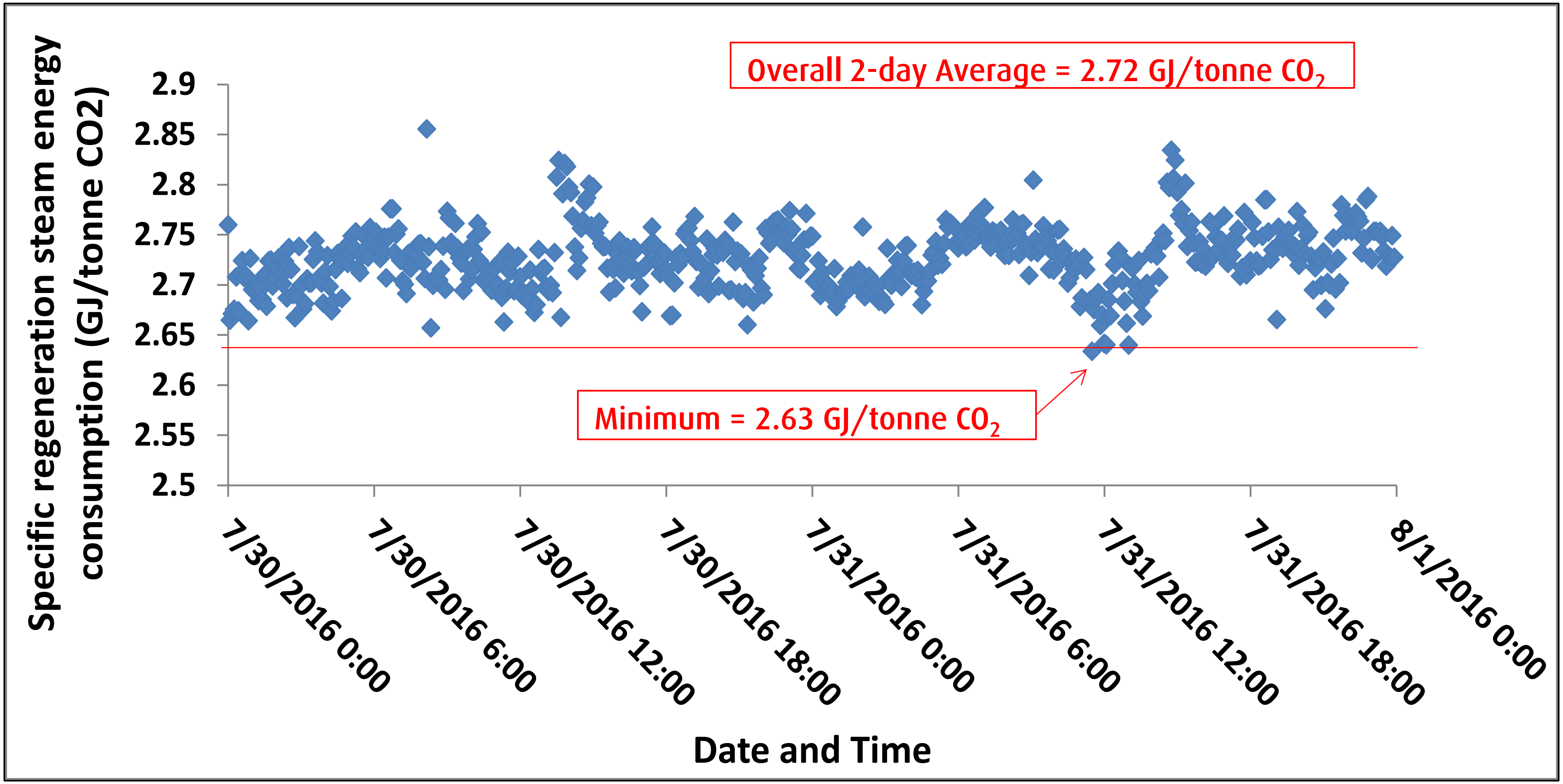
CO_2 production and specific regeneration energy consumption

Average CO_2 capture rate over entire test duration: 90.1%



Long duration test performance

Increased concentration of OASE blue® solvent slightly at end of long-duration test period
-> further reduced specific regeneration energy to ~2.72 GJ/tonne CO_2

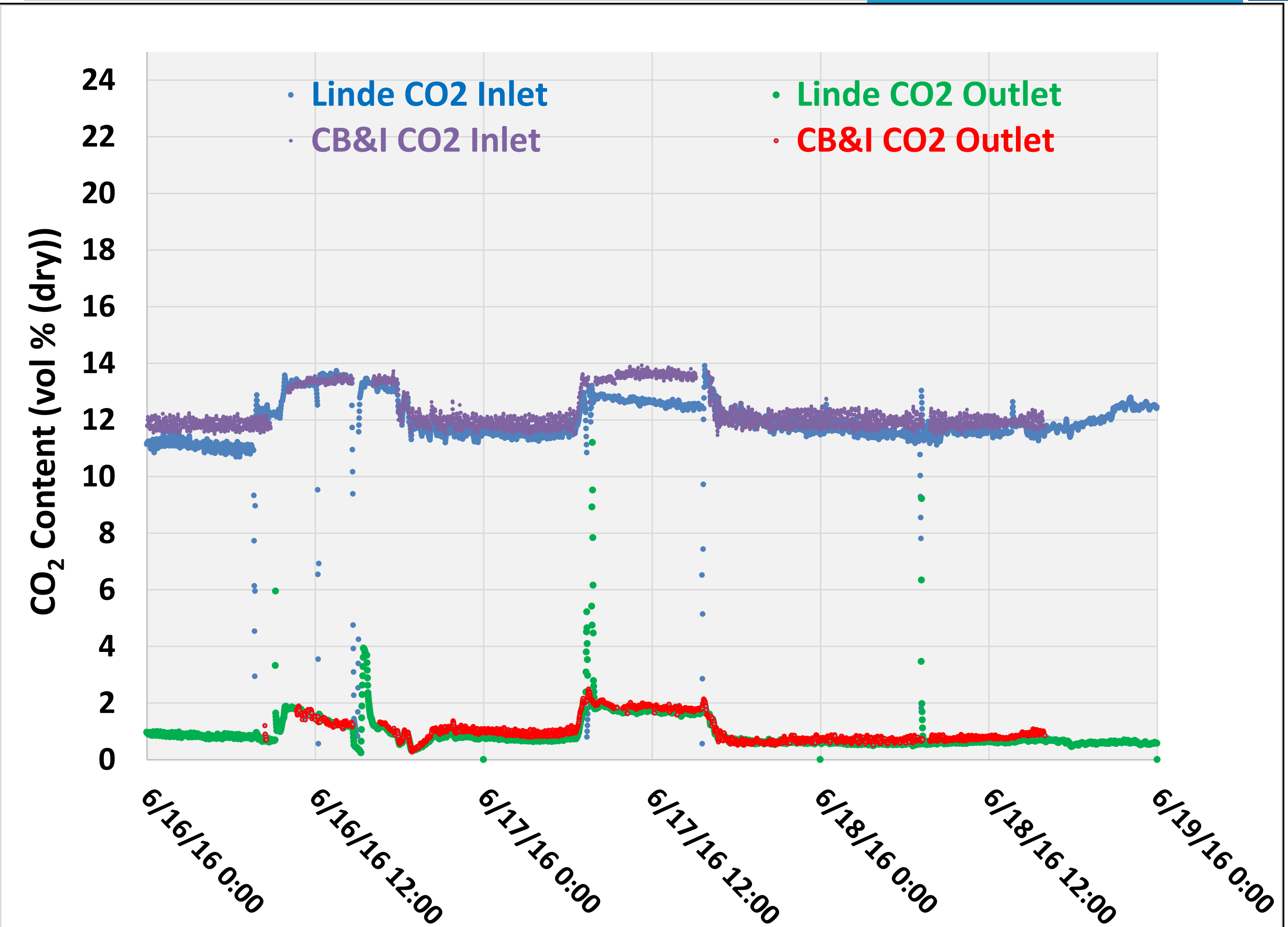


Long duration testing: Averages of key process variables and results

Average Process Parameters during Long-Duration Test Campaign in 2016*	
Flue gas mass flowrate (lb/hr)	10,498
Flue gas CO_2 composition (mol%, dry)	12.17
Flue gas CO_2 mass flowrate (lb/hr)	1791
CO_2 product mass flowrate (lb/hr)	1613
CO_2 capture rate (%)	89.9
Specific regeneration energy (GJ/tonne CO_2)	2.86
Treated gas CO_2 composition (mol%, dry)	0.69
Overall Mass Balance Closure (% difference between inlet and outlet flows, wet basis)	0.76

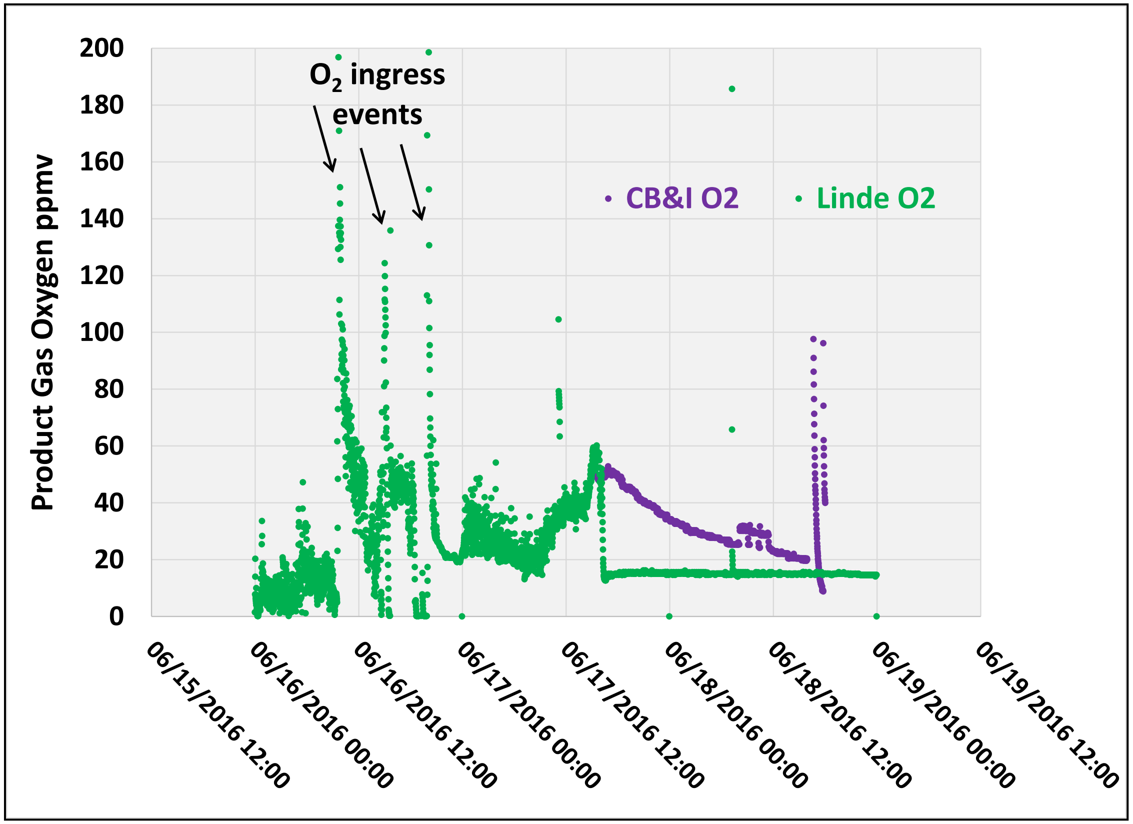
*Data shown above is based on hourly averages during long-duration testing and does not include data measured during plant shutdown periods.

Comparison between EPRI and Linde measured data for flue gas and treated gas CO_2 composition



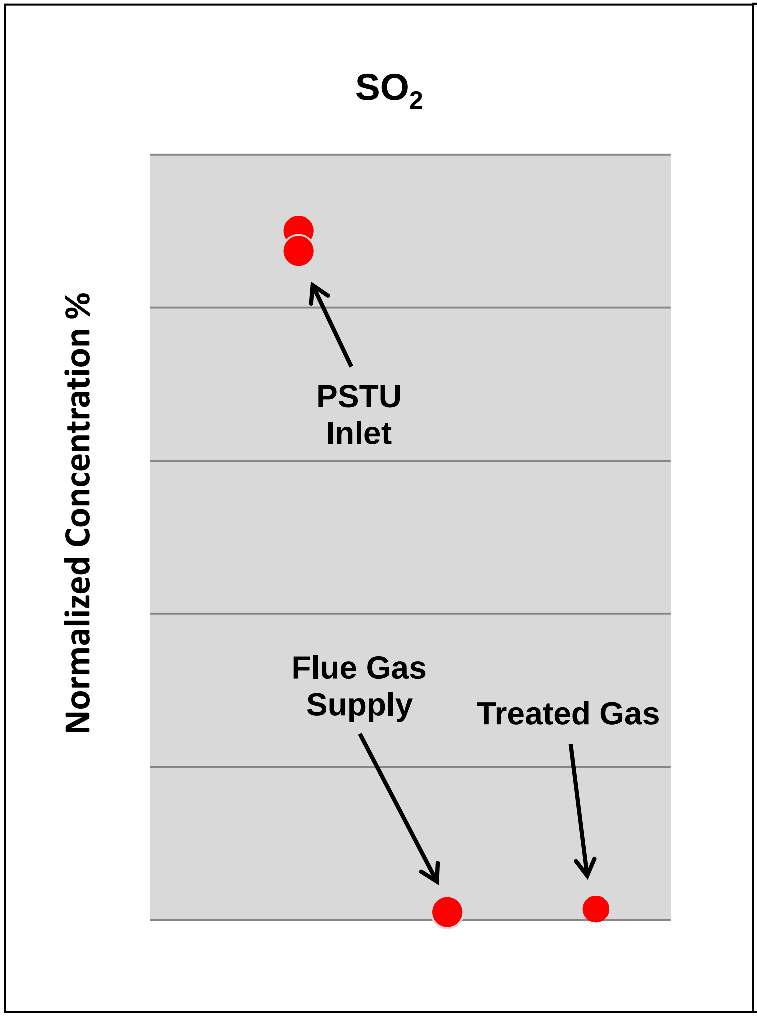
- Linde and EPRI CO_2 inlet measurements match on 6/16 in afternoon and on 6/18. Daily calibration of Linde equipment provides accurate measurements.
- Deviation in CO_2 inlet for Linde is shown on 6/17 due to instrument calibration error that is fixed later in day.
- Linde and EPRI measurements are generally within 1 vol% at inlet and within 0.5 vol% at outlet.
- CO_2 outlet measurements (treated gas) for Linde and EPRI show good consistency.

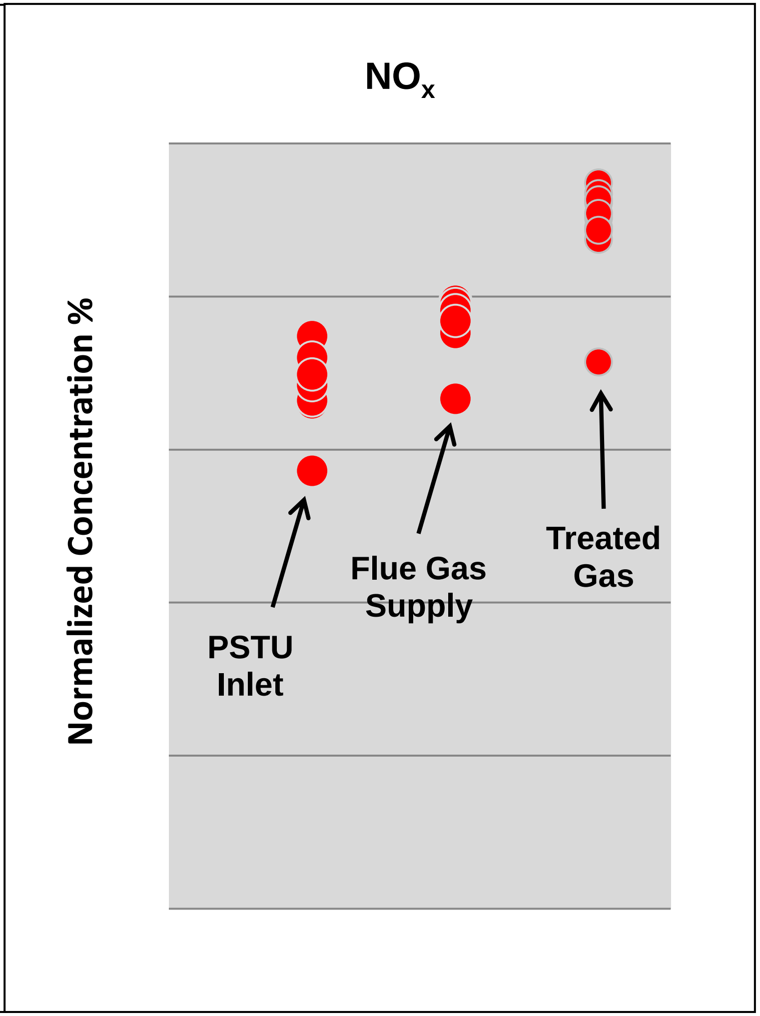
Comparison between EPRI and Linde measured data for CO_2 product composition (ppmv O_2)



- CO_2 purity is ~100% vol (dry): 20-40 ppm O_2 observed in CO_2 product gas when sampling is acceptable.
- Linde O_2 measurement in CO_2 product gas is sensitive to O_2 ingress from air due to vacuum (-0.5 to -1 psig) downstream of Linde stripper pressure control valve. Intensity of vacuum fluctuates during operation, which allows a small amount of O_2 from air to penetrate analyzer tubing and seals resulting in peak concentrations shown.
- O_2 sensors require time to recover from high O_2 exposure from air leading to delay of accurate measurement after O_2 ingress.

EPRI measurements of contaminant distribution in flue gas and treated gas (SO_x and NO_x)





- NCCC PSTU SO_2 scrubber very effective at removing SO_2 from flue gas supply.
- SO_3 below detection limit at both inlet and outlet of absorber.
- NO_x likely not absorbed in solvent and hence goes with treated gas.

EPRI measurements of contaminant distribution in flue gas and treated gas (HAP metals)

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HAP metal	Absorber Inlet Mass Flow, mg/hr*				Absorber Outlet Mass Flow, mg/hr*			
	Test 1 PM-1	Test 2 PM-2	Test 3 PM-3	Average	Test 1 PM-1	Test 2 PM-2	Test 3 PM-3	Average
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**

*Gray color indicates data below accurate detection limits ; n/a = not applicable

- Limited measurements suggest that most HAP metal contaminants go with treated gas (not absorbed by solvent), although Cr, Se, and Ni data are mixed.
- Tests are useful in assessing interaction of solvent with plant steel. However, most measurements are below detectable limits.

- Measurements are based on 2-hour gas sample collection intervals using inductively-coupled argon plasma spectroscopy.
- Tests 1 and 2 were conducted on 6/16/16 and Test 3 was conducted on 6/17/16.
- Tests were conducted after baghouse installation in 2016, which may have reduced HAP metal content in flue gas to NCCC compared to 2015 conditions.

Solvent heat stable salt (HSS) measurements during parametric and long-duration test campaigns

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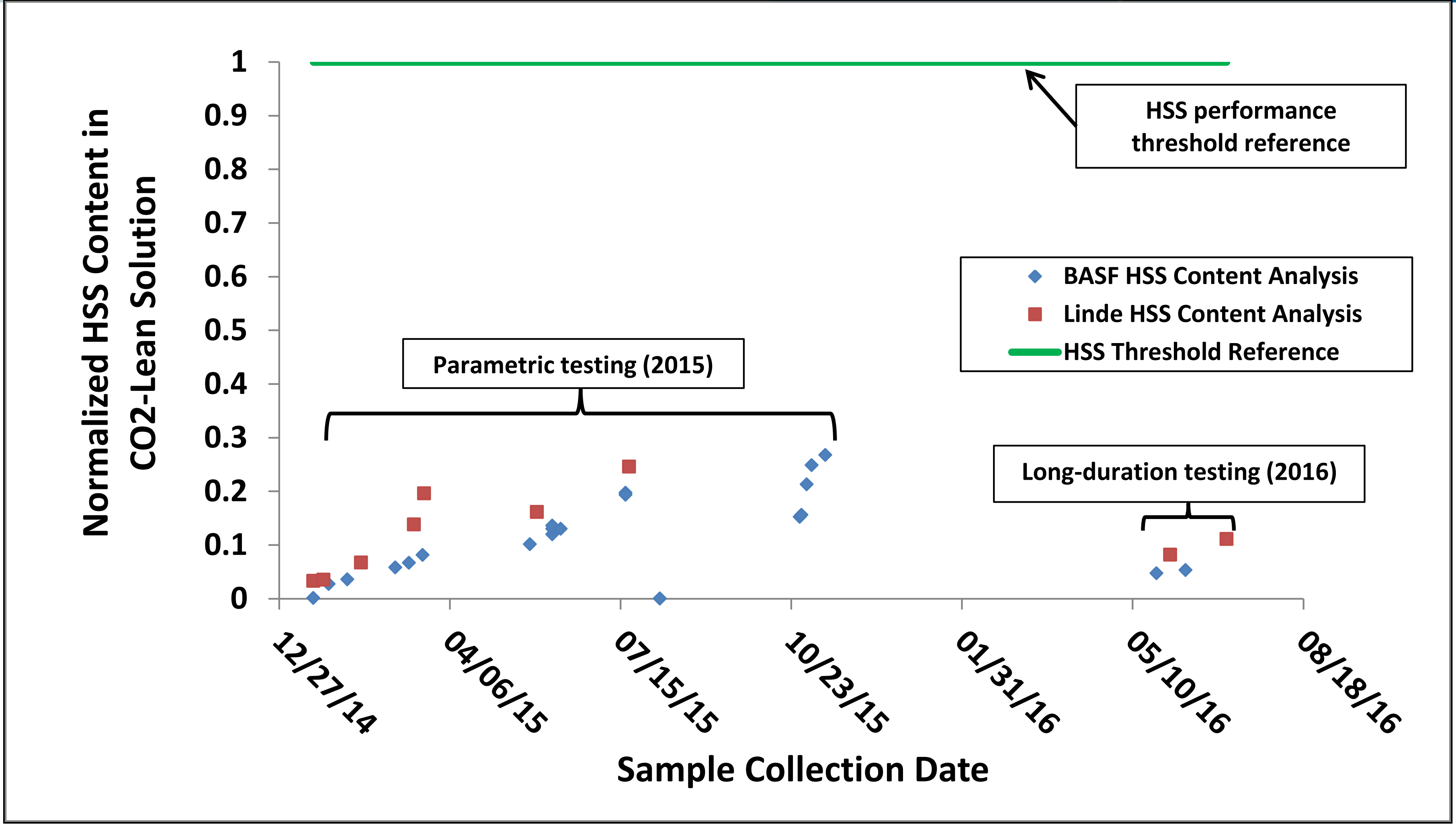

Heat stable salt content in CO_2 lean solution was consistently below the reference threshold wt% for OASE blue solvent, above which specific regeneration energy has been shown to measurably increase. Values show relative HSS content as a fraction of the HSS performance threshold. In addition, Linde and BASF analysis results show excellent consistency, confirming accuracy of HSS analytical measurement methods.

Normalized CO_2 Lean solution amine content (wt% basis) during parametric and long-duration test periods

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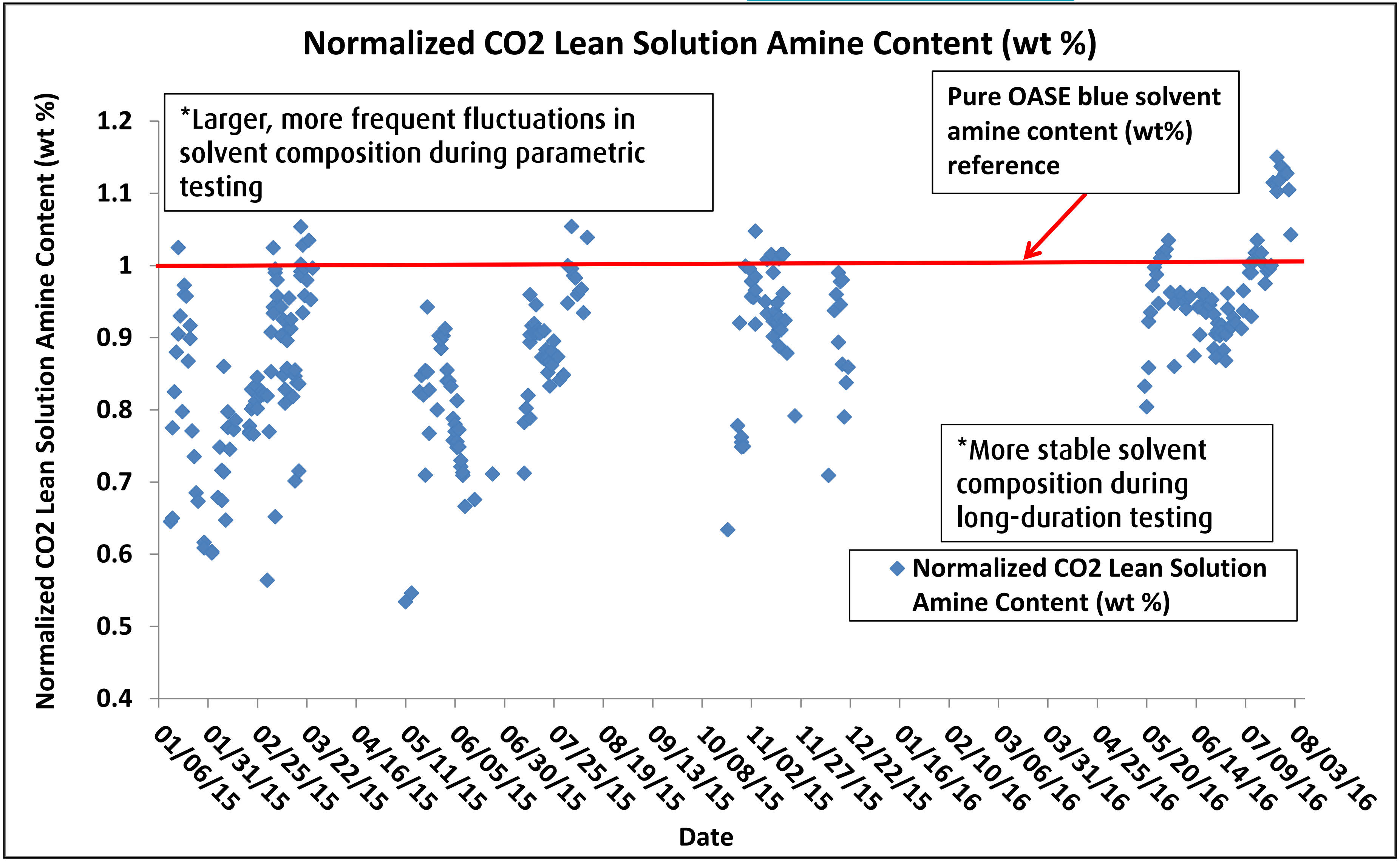
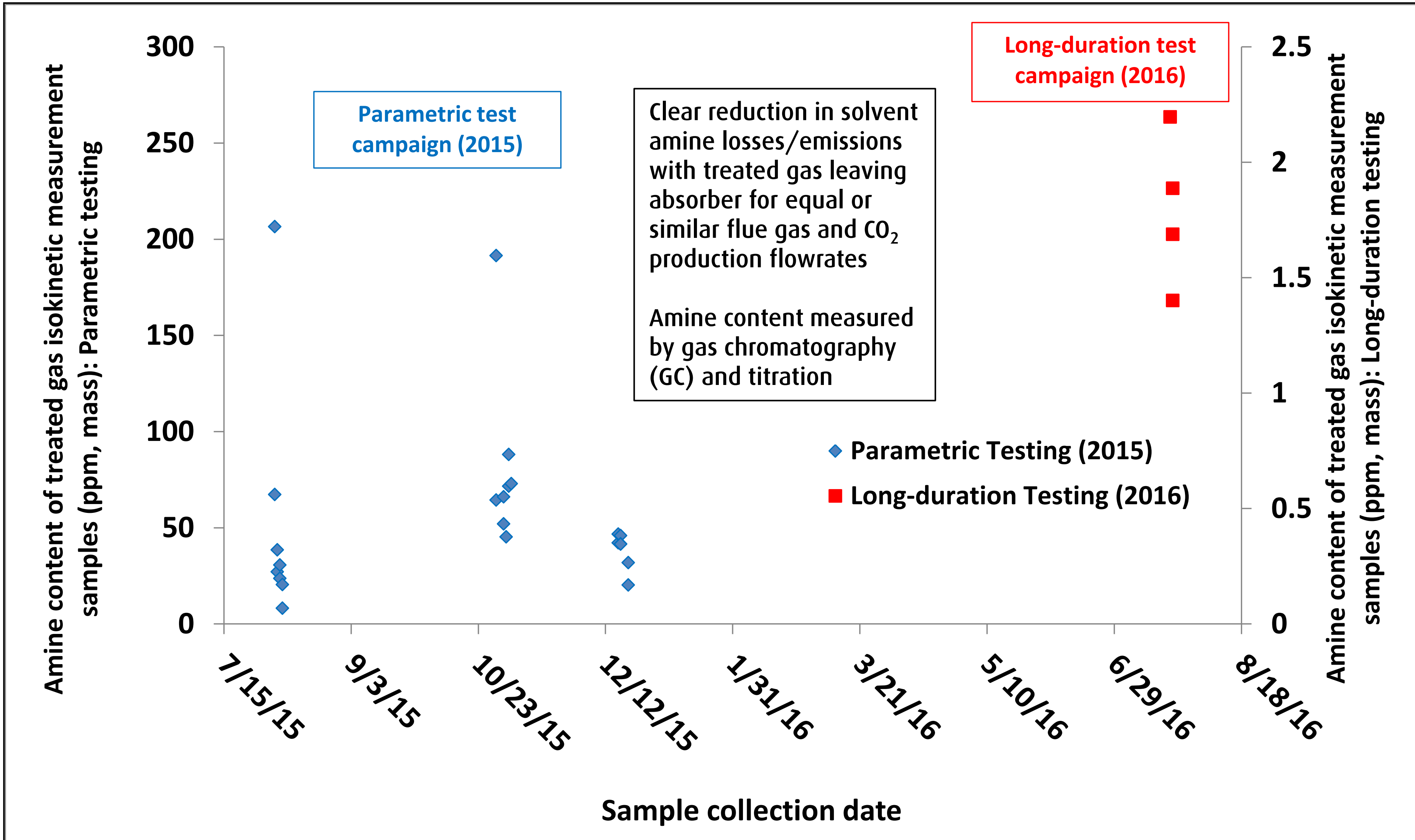


Treated gas isokinetic sample measurements summary 2015 and 2016 testing



Specific amine losses during parametric and long-duration testing

Parametric Test Campaign (before baghouse)		
Isokinetic Test #	Isokinetic Sample Collection Date	Specific Amine Losses (kg amine/MT CO2)
1	08/04/15	1.43
2	08/04/15	0.47
3	08/05/15	0.25
4	08/05/15	0.17
5	08/06/15	0.16
6	08/06/15	0.22
7	08/07/15	0.15
8	08/07/15	0.06
9	10/30/15	0.27
10	10/30/15	1.15
11	11/02/15	0.39
12	11/02/15	0.40
13	11/03/15	0.32
14	11/04/15	0.28
15	11/04/15	0.90
16	11/05/15	0.74
17	12/17/15	1.01
18	12/17/15	0.75
19	12/18/15	0.24
20	12/18/15	0.27
21	12/18/15	0.27
22	12/21/15	0.24
23	12/21/15	0.25

Long-Duration Test Campaign (after baghouse)		
Isokinetic Test #	Isokinetic Sample Collection Date	Specific Amine Losses (kg amine/MT CO_2)
24	07/21/16	0.0116
25	07/21/16	0.0100
26	07/22/16	0.0074
27	07/22/16	0.0090

Quantification of specific amine losses (kg amine/MT CO_2) shows substantial decrease in amine losses (up to 99.8%) as assessed during long-duration testing compared to parametric test campaign.

Hypothesis that high flue gas aerosol concentrations leads to increased solvent losses from absorber is largely confirmed by aerosol and solvent emissions measurements conducted before and after baghouse installation.

Corrosion Coupons and FRP Spool Piece Locations

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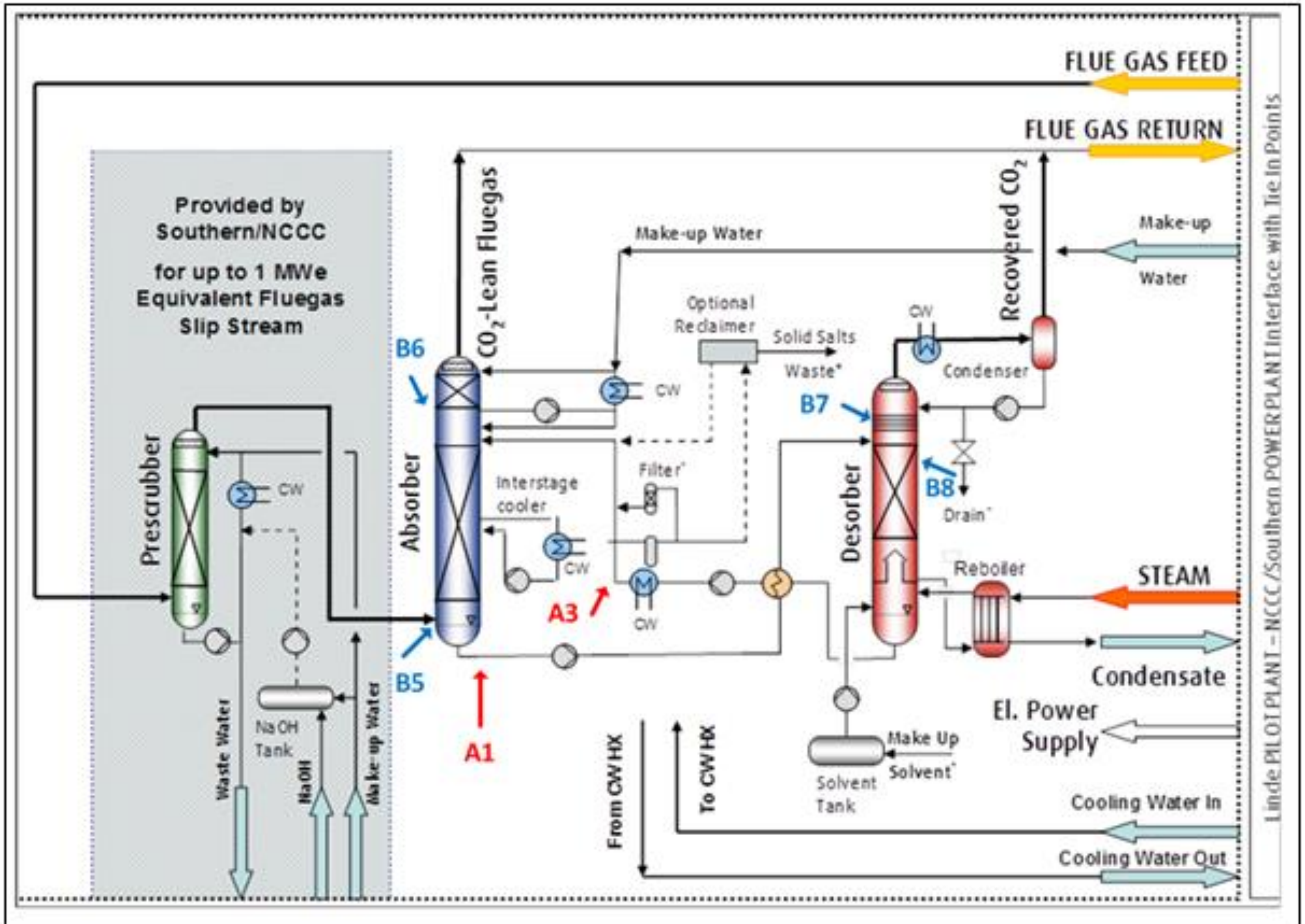

Material Analysis of Pilot Plant Corrosion Coupons and FRP Spool Pieces Showed No Significant Degradation

Conclusion: all materials analyzed would be acceptable for their respective services in the PCC pilot based on the thorough examination conducted by BASF.

Samples Analyzed	Material(s)	Analysis Results BASF Corrosion and Materials Testing Laboratory (CMTL) in McIntosh, AL
B7 series (corrosion coupons)	321 SS, 316L SS, and duplex 2205	No noticeable corrosion (NNC)
B8 series (corrosion coupons)	321 SS, 316L SS, and duplex 2205	NNC
B5 series (corrosion coupons)	321 SS and 316L SS	NNC
B6 series (corrosion coupons)	321 SS	NNC
Fiber-reinforced plastic (FRP) flanged spool pieces (A1 and A3)	Derakane 411-350 resin	No indications of degradation; corrosion barrier was smooth, bright, and clear.

Significant Operational Findings: Daily variation in flue gas CO_2 mol%

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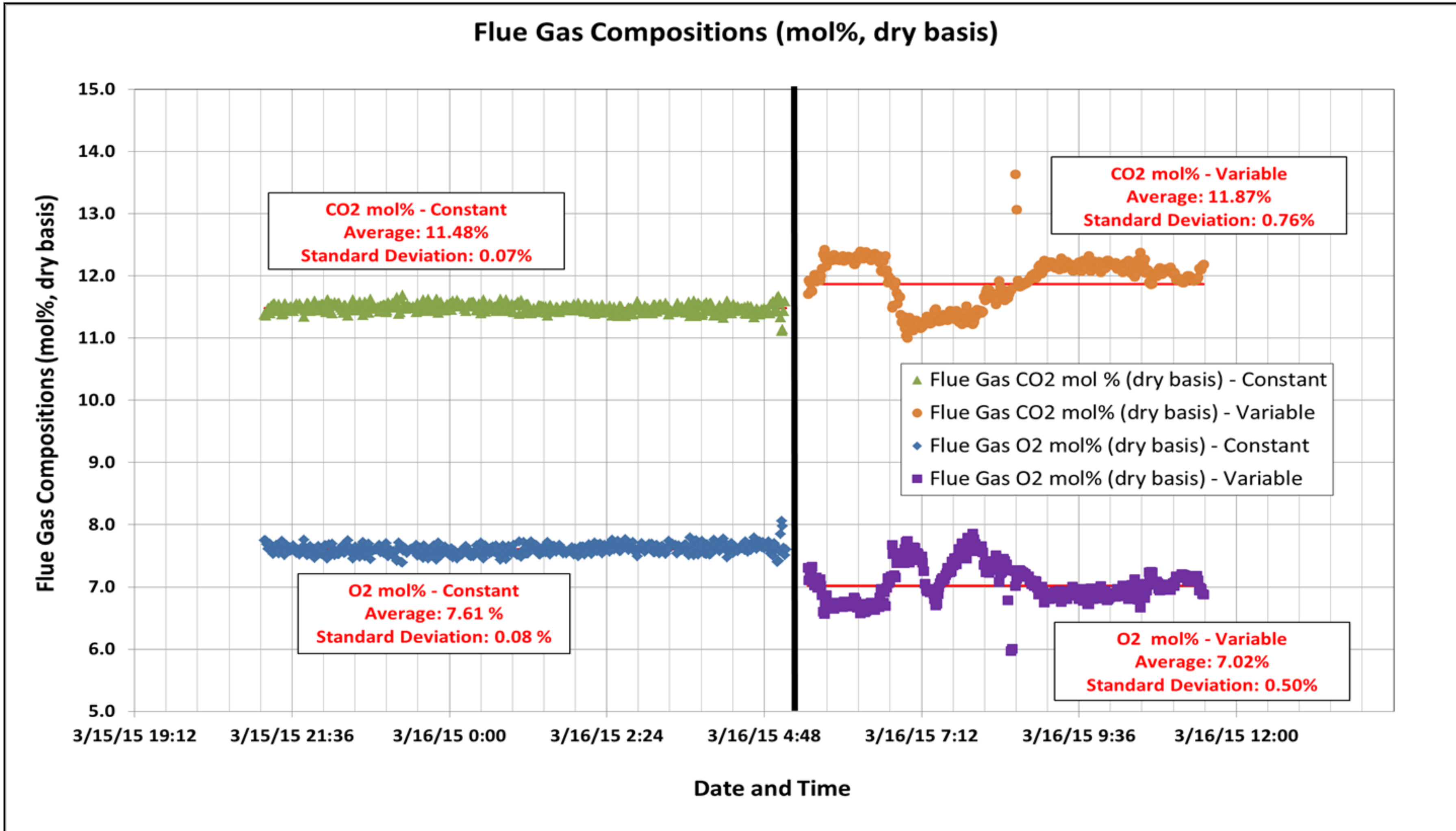

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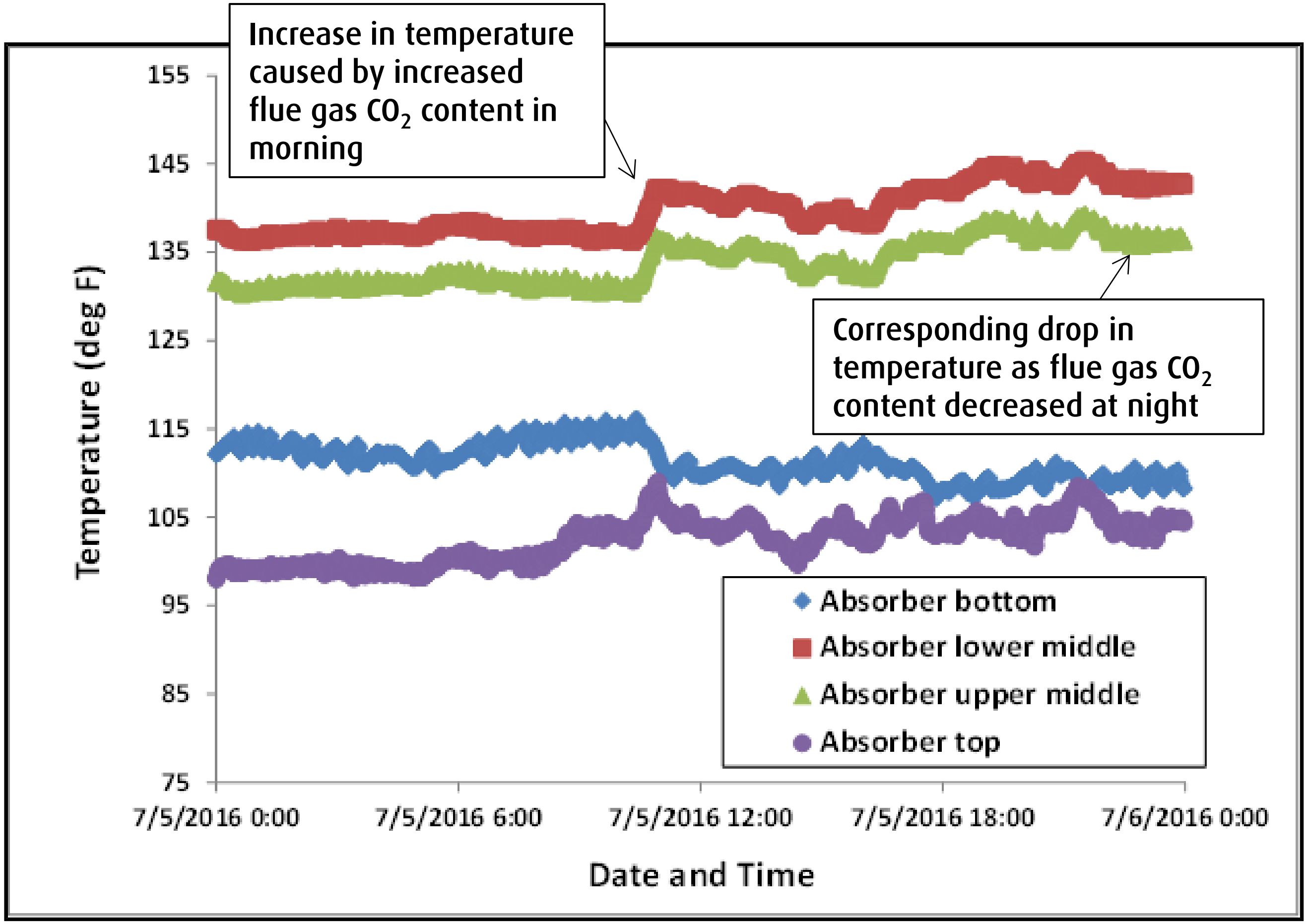
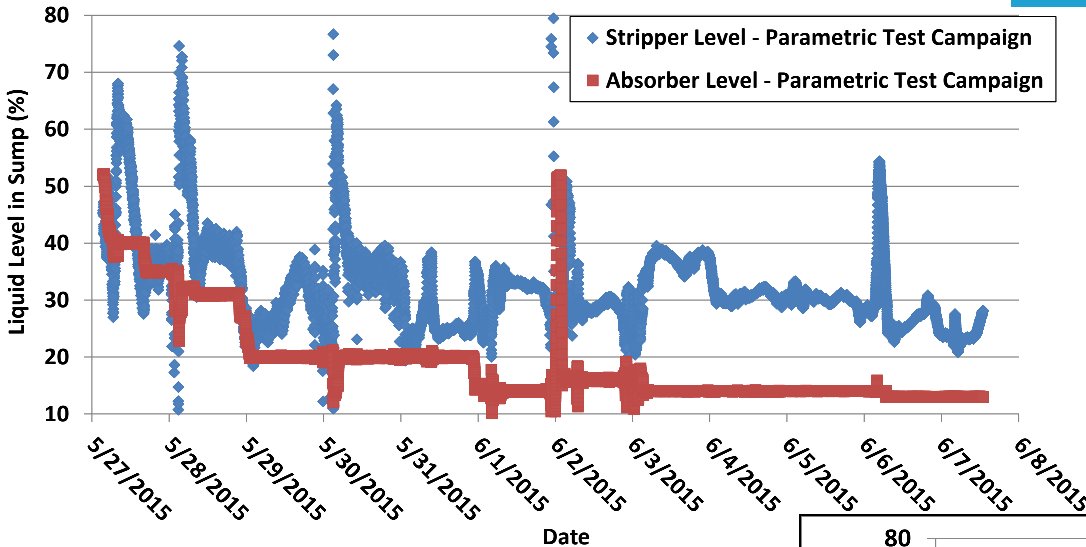


Increased flue gas CO_2 composition in morning of each day caused increased exothermic CO_2 absorption by solvent, resulting in higher temperatures in absorber column

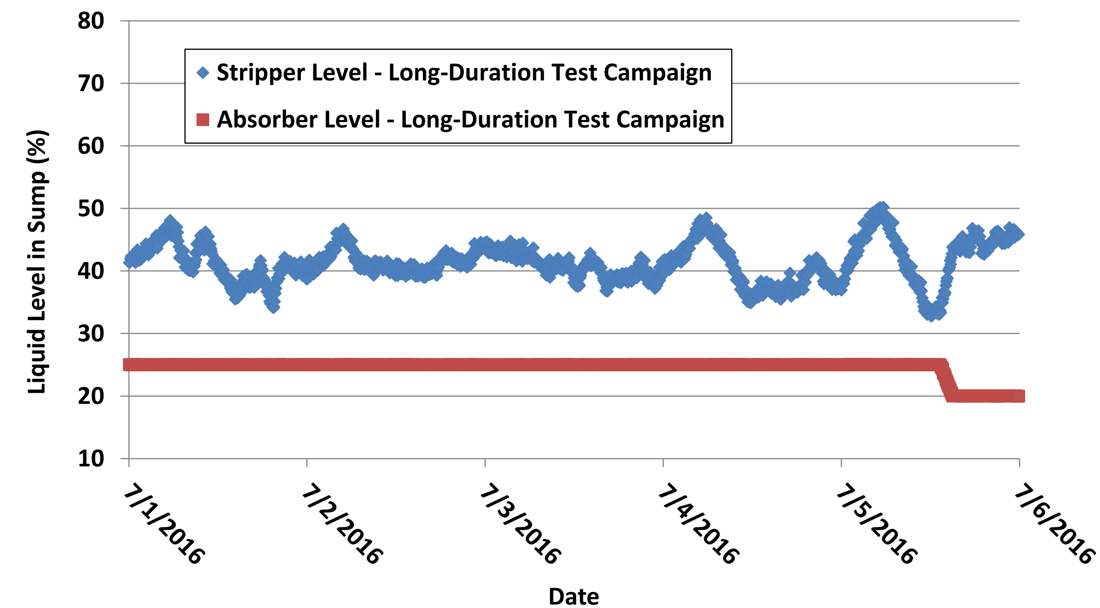
Operational strategy was adopted to mitigate temperature change effects by pre-emptively changing cooling water flowrates to absorber wash section coolers before anticipated flue gas CO_2 mol% content variation occurred to prevent large swings in absorber temperatures during operation

Significant Operational Findings: Column sump levels stability



Notable improvement in stripper and absorber column level stability during long-duration test campaign -> can be attributed to improved knowledge of control strategies, significantly reduced solvent losses during testing, as well as more consistent operating conditions

Absorber level used automatic control. Stripper level (and corresponding process material balance) was controlled using temperature of treated gas leaving absorber since the water content of the gas saturated with water is proportional to temperature.



Significant Operational Findings: Throttling of inlet valve to stripper column

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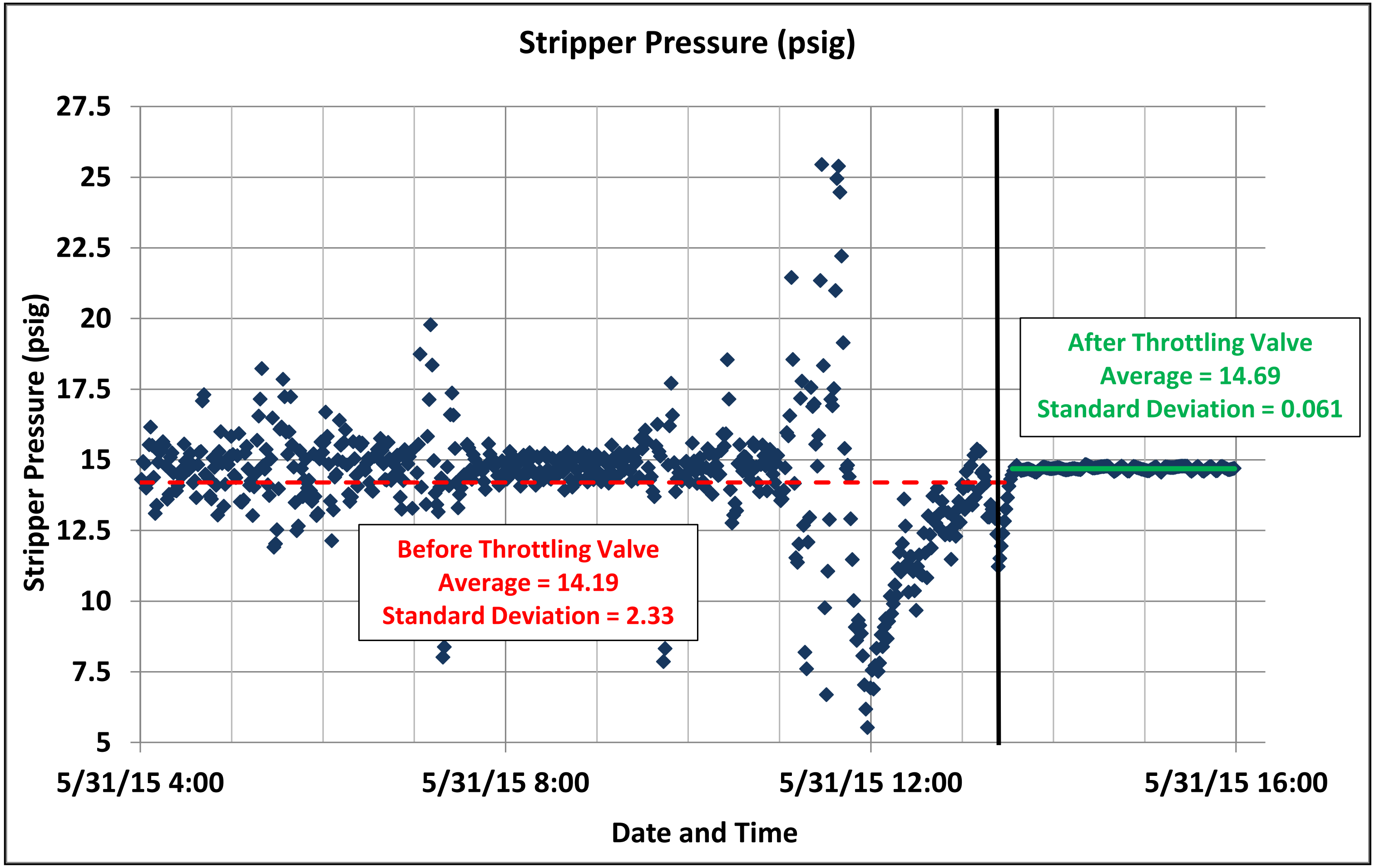
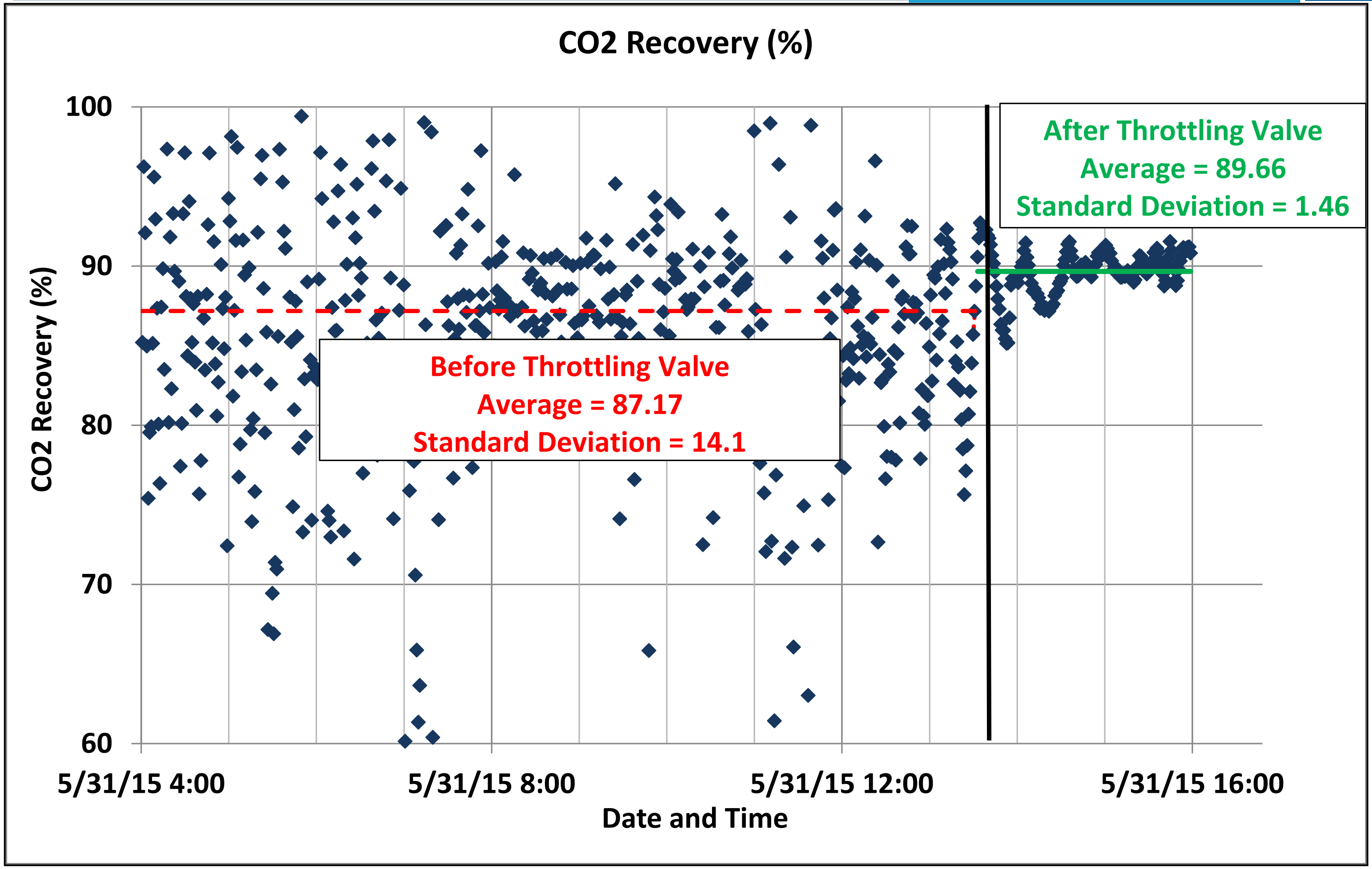


Inlet valve of CO_2-rich solution to stripper column was throttled from 50% opening to 2% opening on 5/31/15 during parametric test campaign.

Throttling inlet valve reduced vaporization of CO_2 in hot CO_2-rich solution entering stripper due to back pressurization, leading to reduced gas-liquid flow inconsistencies as solution entered stripper.

Significant Operational Findings: Throttling of inlet valve to stripper column



Throttling inlet valve of CO_2-rich solution to stripper column led to substantial improvement in CO_2 recovery stability and resulting CO_2 production rate and specific energy consumption stabilities during normal operation.

Techno-Economic Assessment (TEA): Supercritical PC power plant with CO_2 capture

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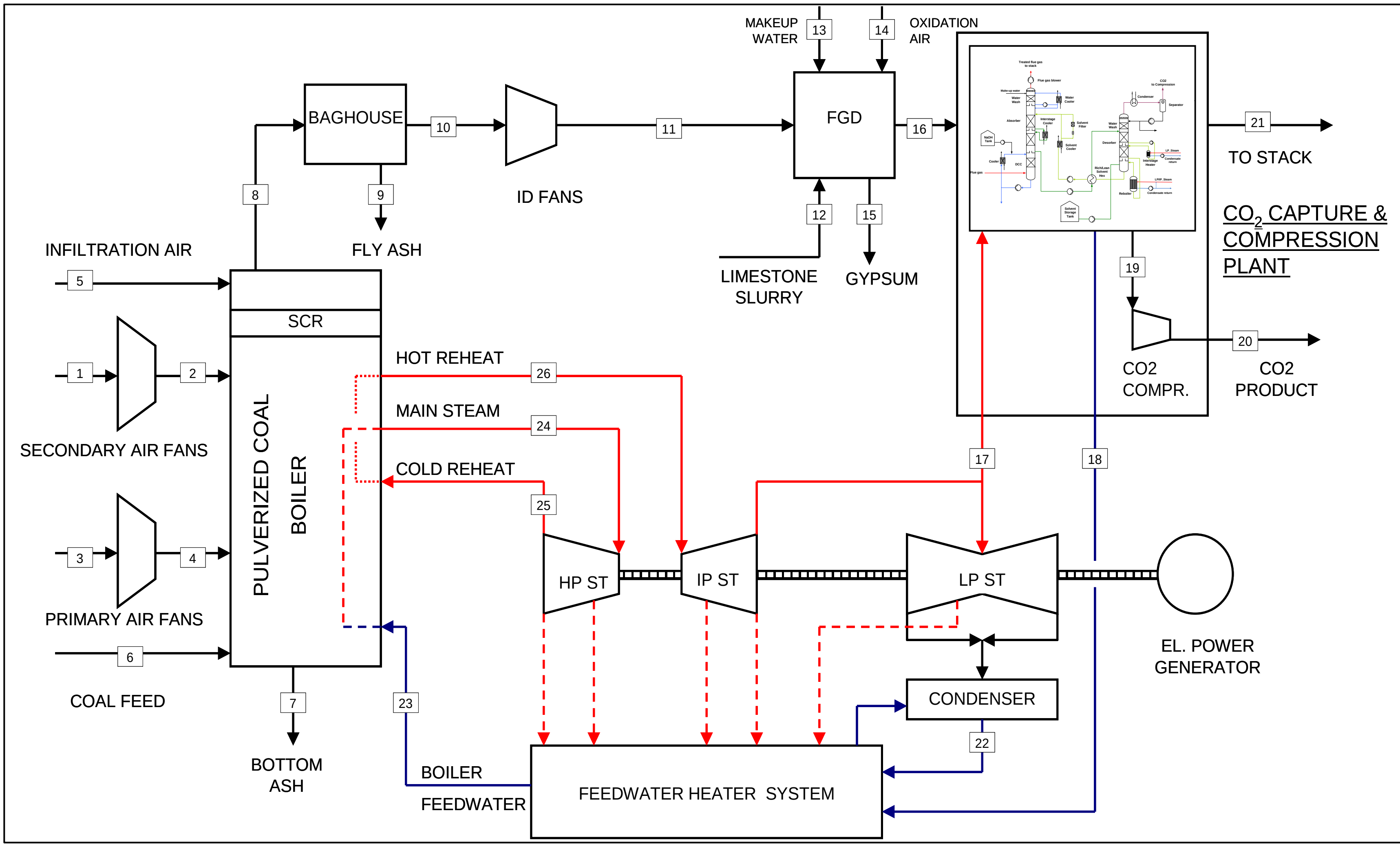

Techno-economic analysis: Stripper Inter-stage Heater (SIH) CO_2 capture process option (energy optimization)

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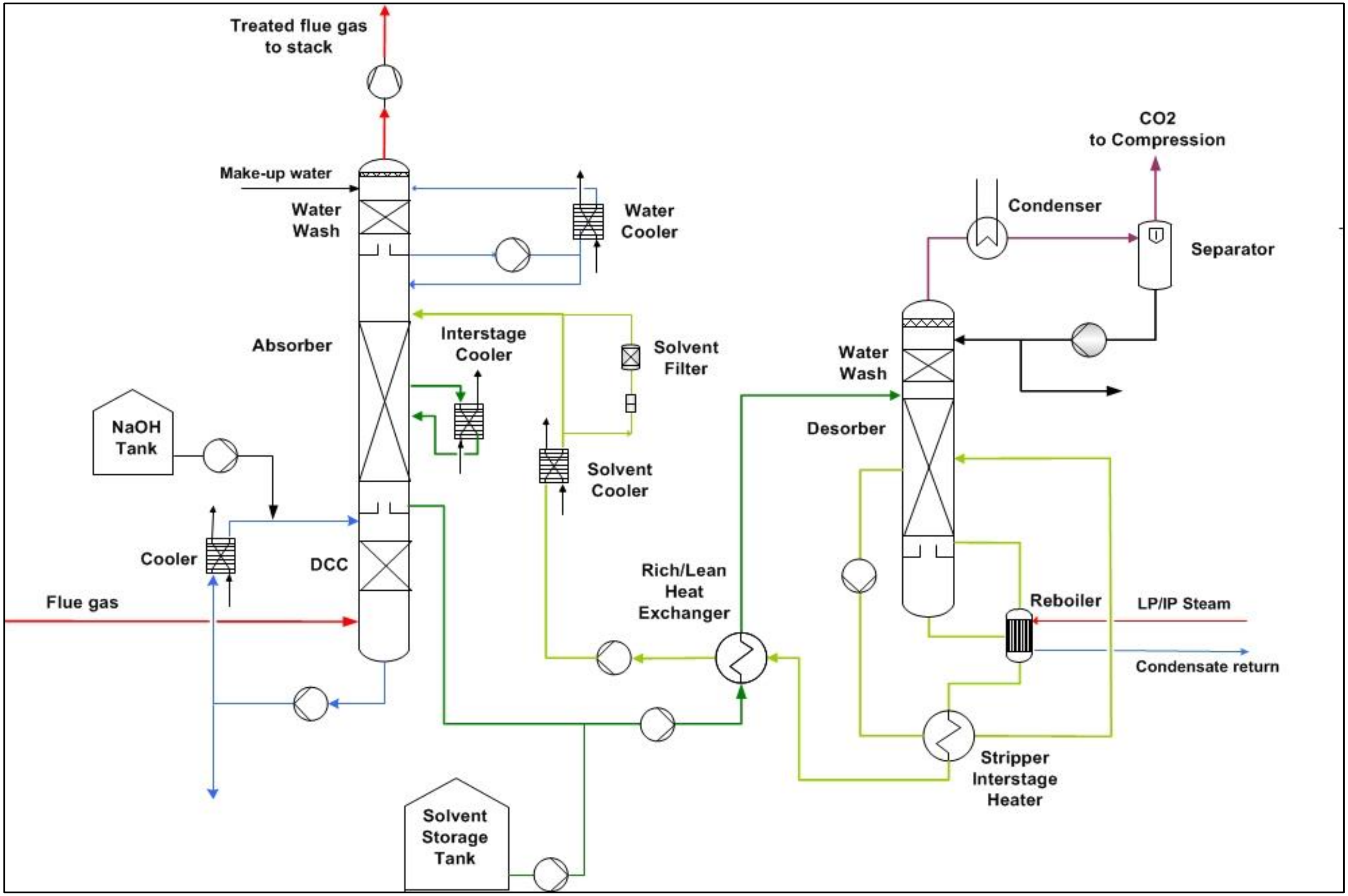
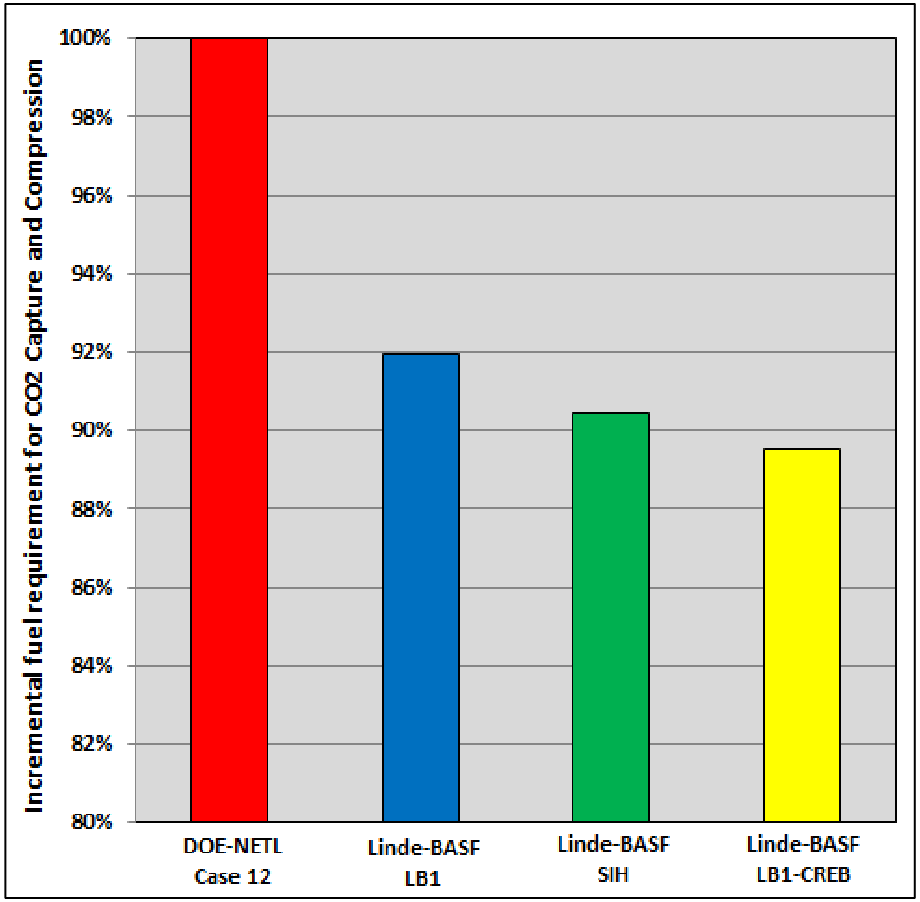


TEA: Incremental fuel requirements

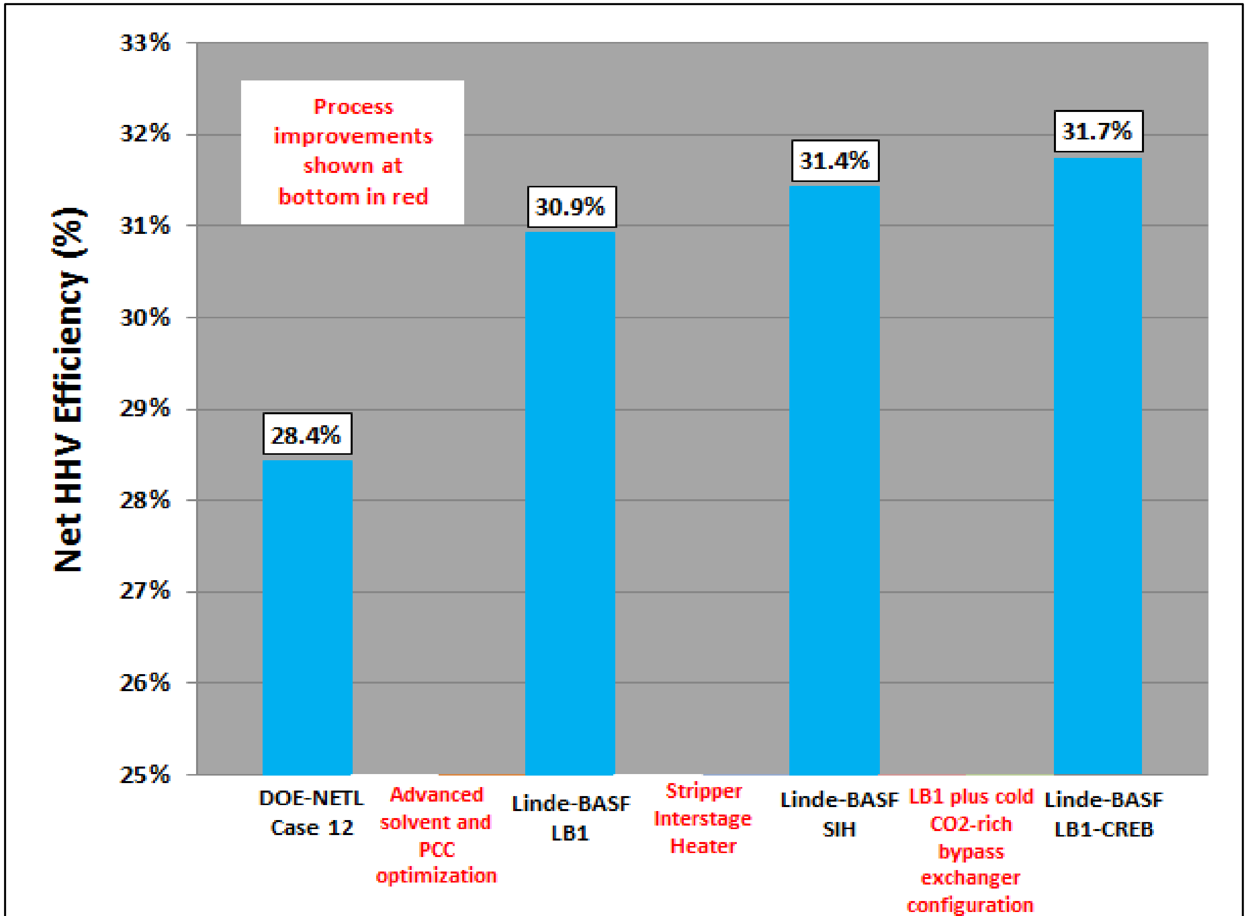
	DOE/NETL Case 12	Linde-BASF LB1	Linde-BASF SIH	Linde-BASF LB1-CREB
Coal fuel requirement (lb/hr)	565,820	520,221	511,899	506,596



PCC Cases for TEA study	PCC Process Innovations and Performance
Linde-BASF LB1	• PCC plant offering 2.61 GJ/MT CO_2 specific regeneration energy* • Employs high-performance structured packing, gravity-drain absorber intercooler, emission control system in absorber wash sections, blower downstream of absorber, novel stripper reboiler design, and elevated regeneration pressure (3.33 bara) • Wilsonville, AL PCC pilot is based off of LB1 design
Linde-BASF SIH	• PCC plant offering 2.30 GJ/MT CO_2 specific regeneration energy* • Employs advanced stripper interstage heater design that improves heat recovery from CO_2-lean solution leaving stripper
Linde-BASF LB1-CREB	• PCC plant offering 2.10 GJ/MT CO_2 specific regeneration energy* • Employs novel cold CO_2-rich solution bypass exchanger and secondary CO_2-lean/CO_2-rich heat exchanger that optimizes heat recovery from hot CO_2 product vapor leaving stripper and hot CO_2-lean solution

*Data based on conceptual modelling results

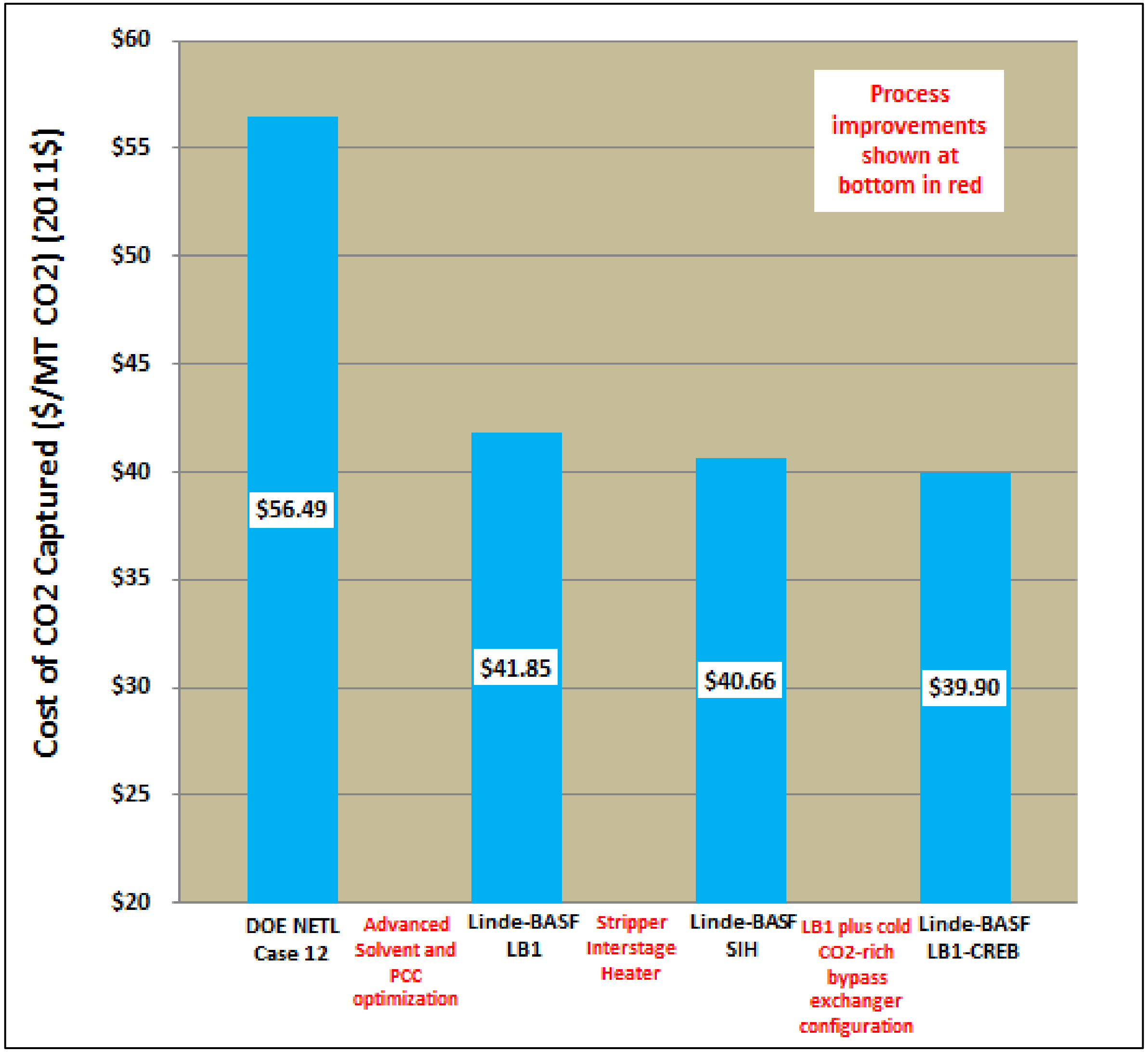
TEA: Net HHV efficiency



	Gross Power (MW)	Net Power (MW)	HHV Efficiency* (%)
Case 12	1702.6	550.02	28.4
LB1	1565.4	549.97	30.9
SIH	1540.4	550.03	31.4
LB1-CREB	1524.4	549.96	31.7

*Assuming 88% boiler efficiency

TEA: Cost of CO2 captured (\$/MT CO_2) 2011\$



Cost of CO_2 Captured =

{COE – $COE_{reference}$}\$/MWh /

{CO_2 Captured} tonnes/MWh

- One major reason the cost of CO_2 captured is significantly reduced in moving from Case 12 to LB1 is due to the higher inlet CO_2 gas pressure for CO_2 compression (48 psia for LB1 vs. 24 psia for Case 12) afforded by elevated regenerator pressure, which reduces downstream compression energy and capital costs
- 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 leads to increasingly smaller incremental reductions in cost of CO_2 captured for each Linde-BASF process improvement

TEA: Cost of Electricity (COE) Breakdown

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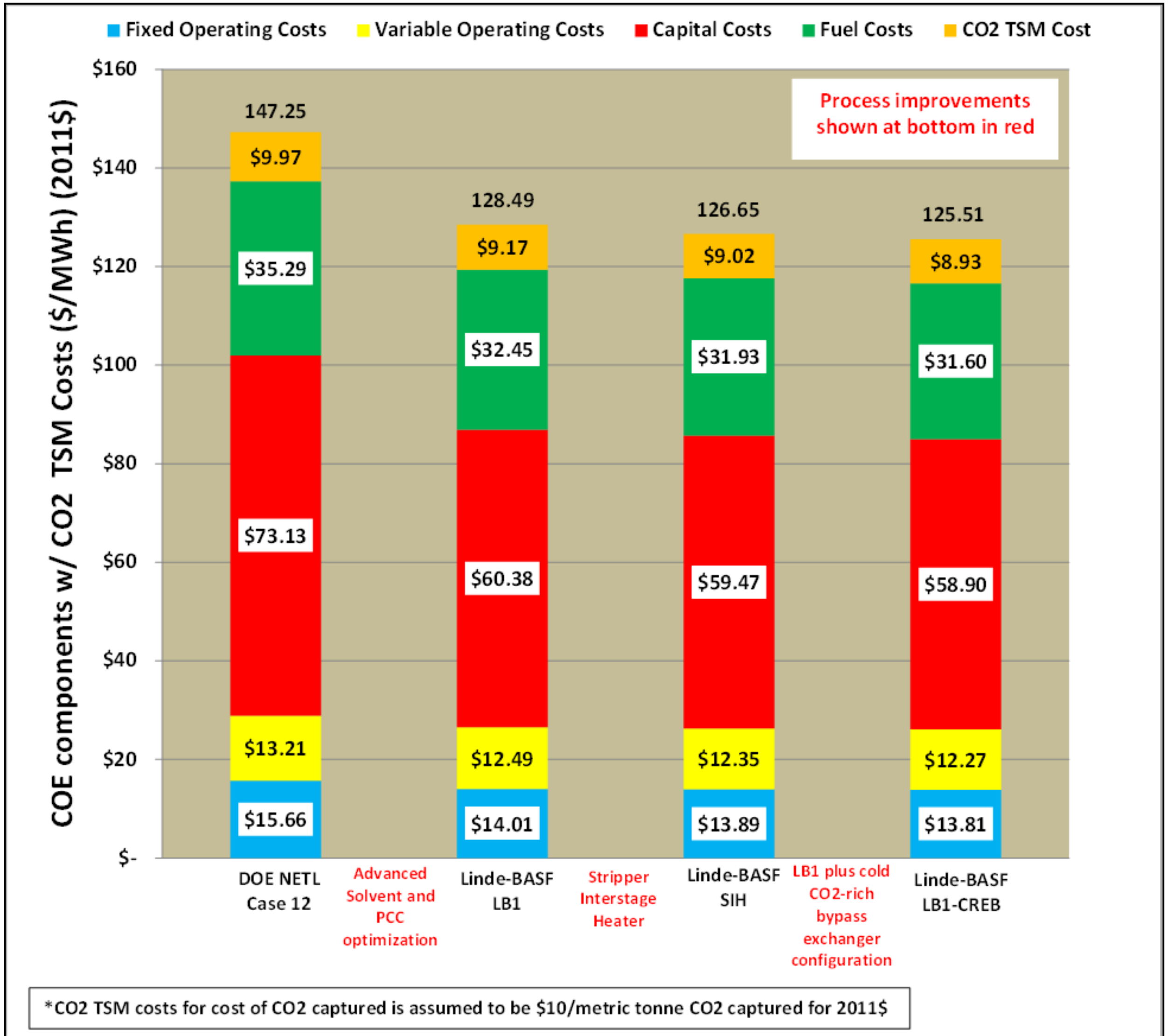

$$COE = \{(CCF)*(TOC) + OC_{FIX} + (CF)*(OC_{VAR})]\}/ [(CF)*(aMWh)]$$

Where

OC_{FIX} = *Fixed Operating Costs*

OC_{VAR} = *Variable Operating Costs*

CF= Capacity Factor (0.85)

CCF = Capital Charge Factor (0.124)

TOC = Total Overnight Cost

Capital cost components are based on a single parameter scaling methodology using the ratio of the coal feed rates for each process option relative to Case 12 and an exponential scaling factor of 0.669

Summary and concluding remarks

- Linde and BASF are partnering in an advanced PCC technology development incorporating BASF's novel amine-based process, OASE® blue, along with Linde's process and engineering innovations

- This project under cooperation agreement with DOE-NETL (DE-FE0007453) has met all milestones and achieved the targeted success criteria:

  - Nominal 1 MWe pilot plant designed, engineered, constructed and commissioned at NCCC in Wilsonville, AL

  - Parametric and long-duration testing have been completed and have demonstrated stable operation, validation of functional features and achievement of key performance targets.

  - Valuable research data obtained on energy optimization and emissions management for scale-up

  - EPRI independent measurement & analysis performed during long-duration test campaign in June 2016. Results indicate consistency and alignment with Linde data. New information on HAP metal contaminants in flue gas, treated gas and product.

- Technology has been selected by DOE for Phase 1 of the Large Pilot opportunity. Phase 2 proposal has been submitted with Univ. of Illinois as prime and the Abbott coal fired power plant as host site. This will mark the next stage of technology development and evolution.

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Acknowledgements & Disclaimer

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

DOE-NETL Project Manager: Andrew Jones
NCCC host site support: Justin Anthony, Frank Morton and several others
BASF: Sean Rigby, Gerald Vorberg & Gustavo Lozano
Linde: Torsten Stoffregen, Annett Kutzschbach, Stevan Jovanovic, Makini Byron, Luis Villalobos

Thanks for your attention.

Itemized Total Plant Capital Costs ($x1000, 2011$ price basis)

Itemized Capital Cost for Supercritical 550 MWe PC Power Plant with PCC (2011$)				
Capital Cost Element	Case 12 (2011$)	Linde-BASF LB1 (2011$)	Linde-BASF SIH (2011$)	Linde-BASF LB1-CREB (2011$)
Coal and Sorbent Handling	56,286	53,209	52,638	52,273
Coal and Sorbent Prep & Feed	27,055	25,576	25,302	25,126
Feedwater & Misc. BOP Systems	123,565	116,811	115,558	114,755
PC Boiler	437,215	413,317	408,882	406,043
Flue Gas Cleanup	196,119	185,399	183,410	182,136
CO2 Removal	505,963	257,191	247,961	243,415
CO2 Compression & Drying	87,534	63,738	62,401	60,324
HRSG, Ducting & Stack	45,092	42,627	42,170	41,877
Steam Turbine Generator	166,965	157,839	156,145	155,061
Cooling Water System	73,311	69,304	68,560	68,084
Ash/Spent Sorbent Handling Syst.	18,252	17,254	17,069	16,951
Accessory Electric Plant	100,255	94,775	93,758	93,107
Instrumentation & Control	31,053	29,356	29,041	28,839
Improvements to Site	18,332	17,330	17,144	17,025
Buildings & Structures	72,402	68,445	67,710	67,240
Total Plant Cost (TPC)	1,959,399	1,612,170	1,587,748	1,572,255
Preproduction Costs	60,589	53,070	52,476	52,098
Inventory Capital	43,248	39,283	38,753	38,415
Initial Cost for Catalyst and Chemicals	3,782	3,111	3,064	3,034
Land	899	740	729	722
Other Owner's Costs	293,910	241,826	238,162	235,838
Financing Costs	52,904	43,529	42,869	42,451
Total Overnight Cost (TOC)	2,414,731	1,993,728	1,963,801	1,944,814

Summary of Annual Operating and Maintenance (O&M) Costs

Annual O&M Expenses for Supercritical 550 MWe PC Power Plant with PCC (2011$)*				
Cost Element	**Case 12**	**Linde-BASF LB1**	**Linde-BASF SIH**	**Linde-BASF LB1-CREB**
Total Fixed Operating Cost	64,137,607	57,356,056	56,867,612	56,557,758
Maintenance Material Cost	19,058,869	18,017,114	17,823,784	17,700,023
Water	3,803,686	3,595,777	3,557,193	3,532,493
Chemicals	24,913,611	23,551,836	23,299,117	23,137,338
SCR Catalyst	1,183,917	1,119,204	1,107,195	1,099,507
Ash Disposal	5,129,148	4,848,789	4,796,760	4,763,454
By-Products	0	0	0	0
Total Variable Operating Cost	54,089,231	51,132,721	50,584,050	50,232,815
Total Fuel Cost (Coal @ 68.60$/ton)	144,504,012	132,858,628	130,733,327	129,378,772

*O&M costs are based on a single parameter scaling methodology using the ratio of the coal feed rates for each process option relative to Case 12 and an exponential scaling factor of 0.669

EPRI measurements of flue gas contaminant distribution in treated gas and CO_2 product (SOx, NOx and HAP metals)

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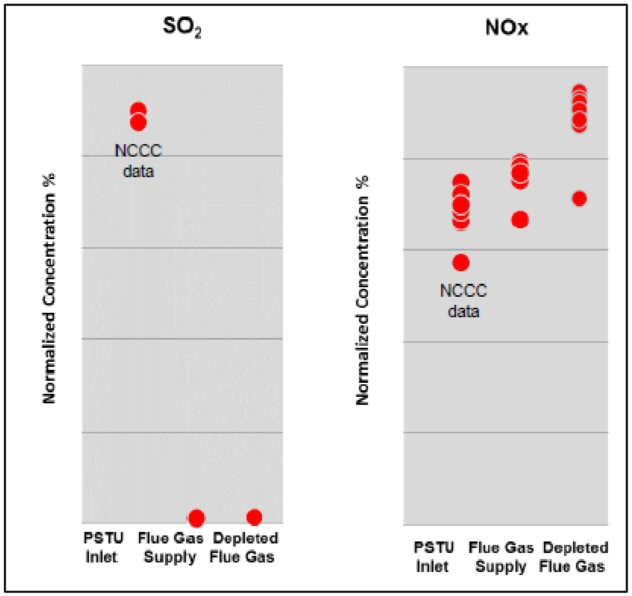
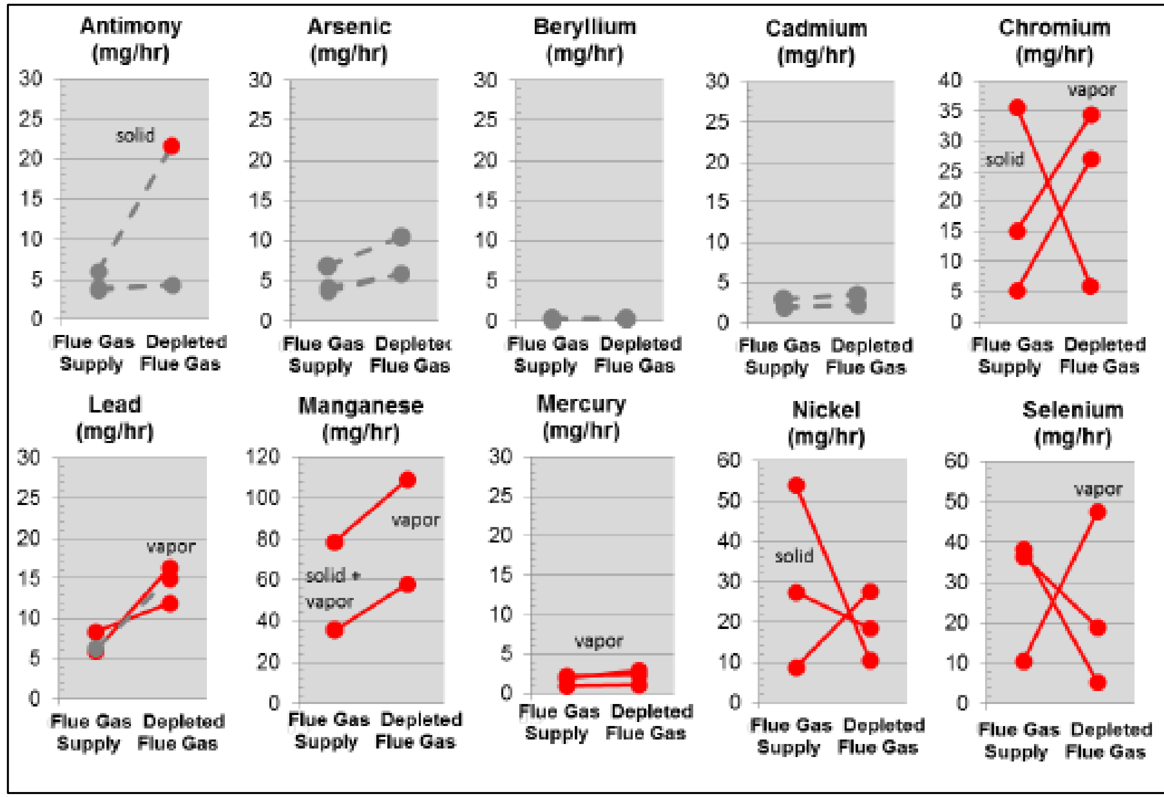
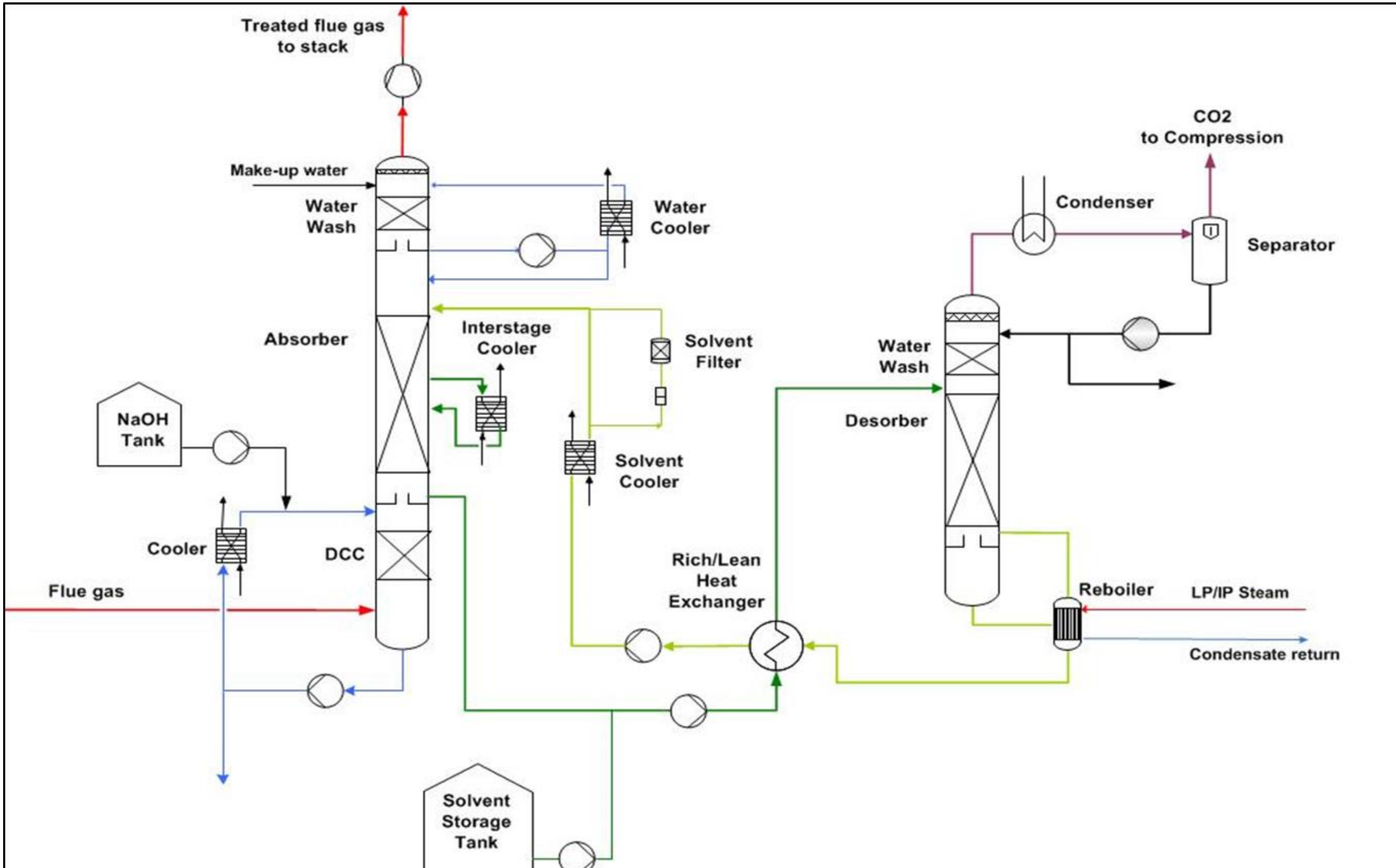




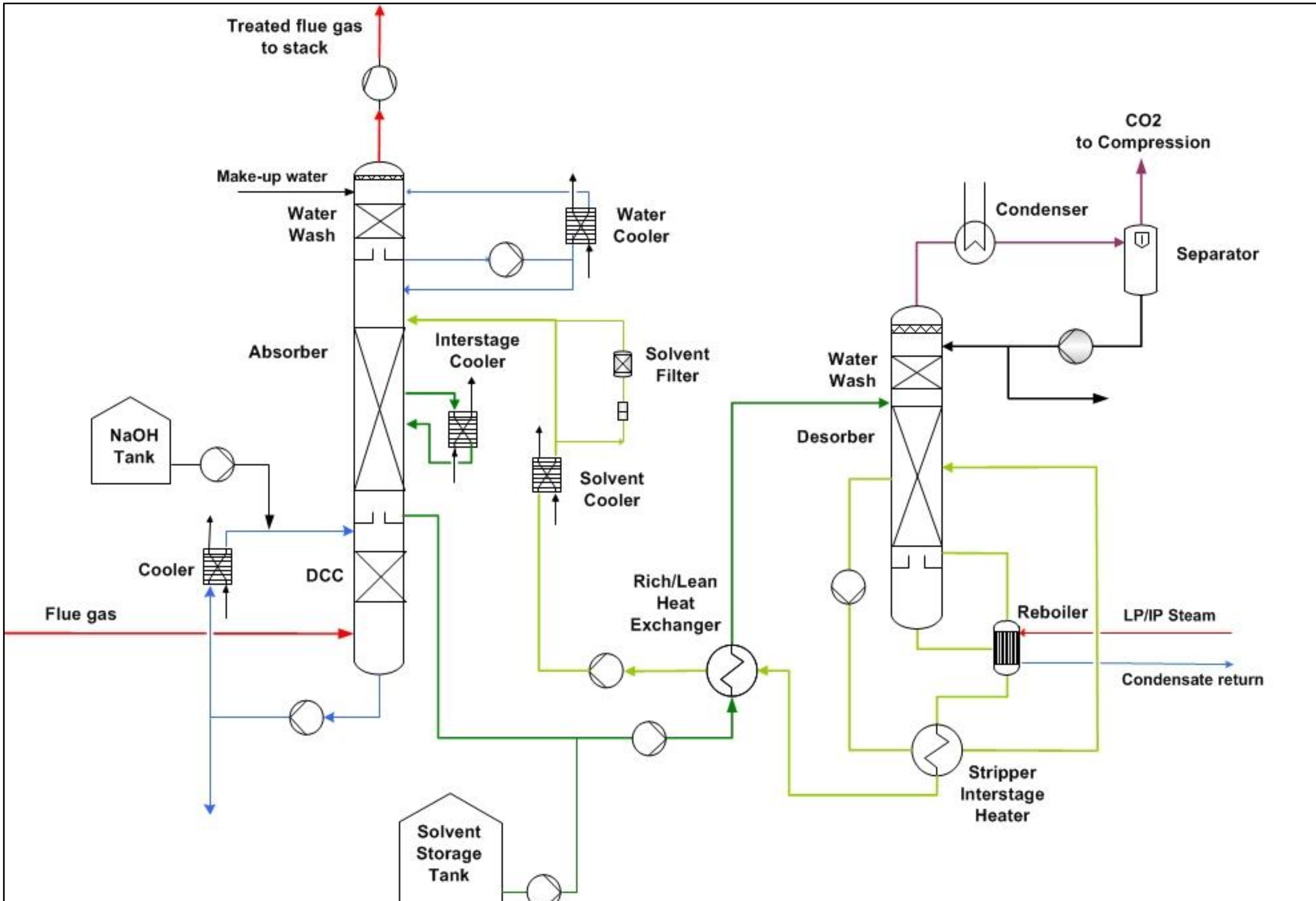
- SO_x removed in DCC ahead of absorber
- NO_x likely not absorbed in solvent and hence goes with treated gas

- Limited measurements suggest that most metal contaminants go with treated gas although Cr, Se and Ni data are mixed.

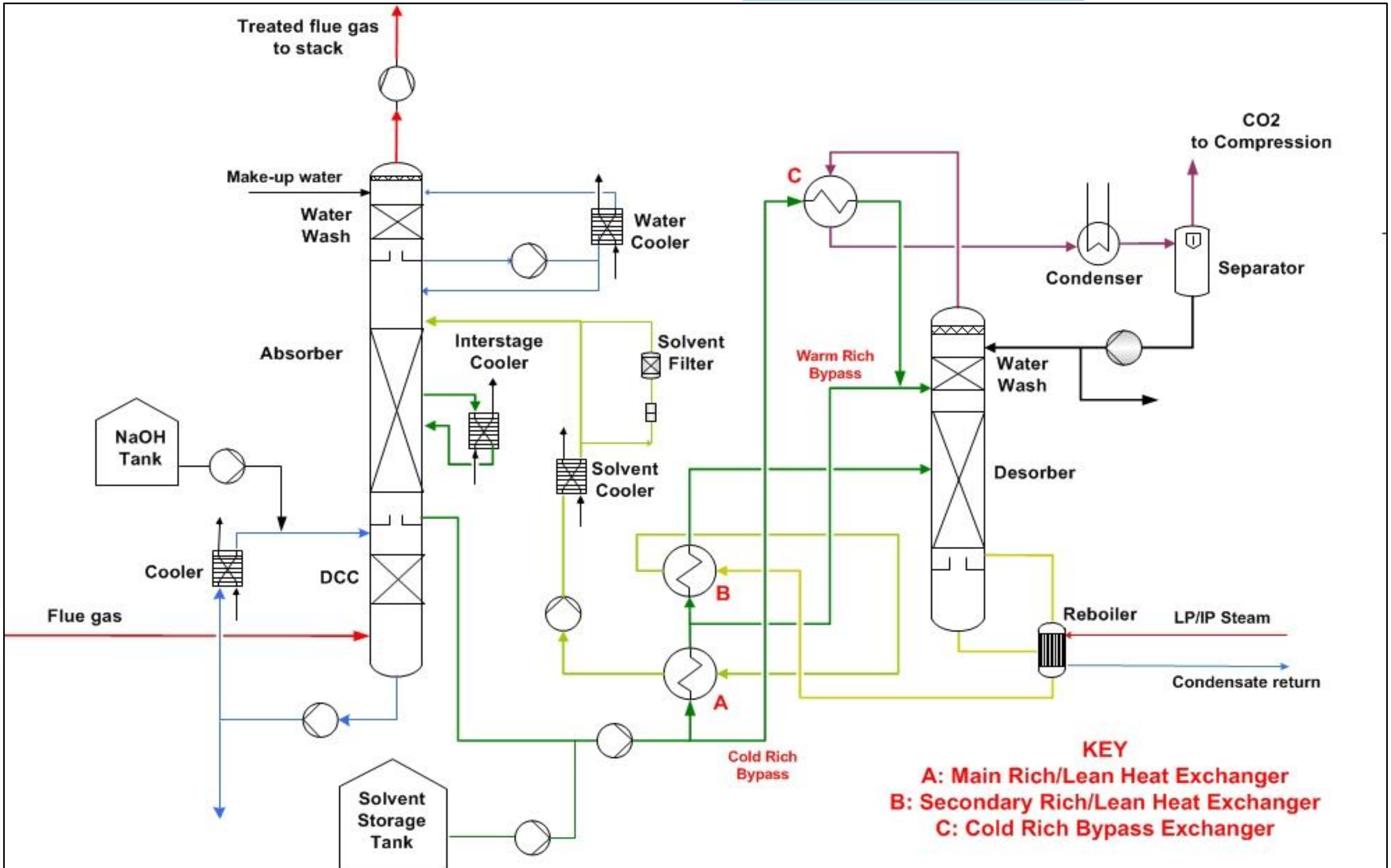
TEA: Linde BASF LB1 PCC Process Option Configuration



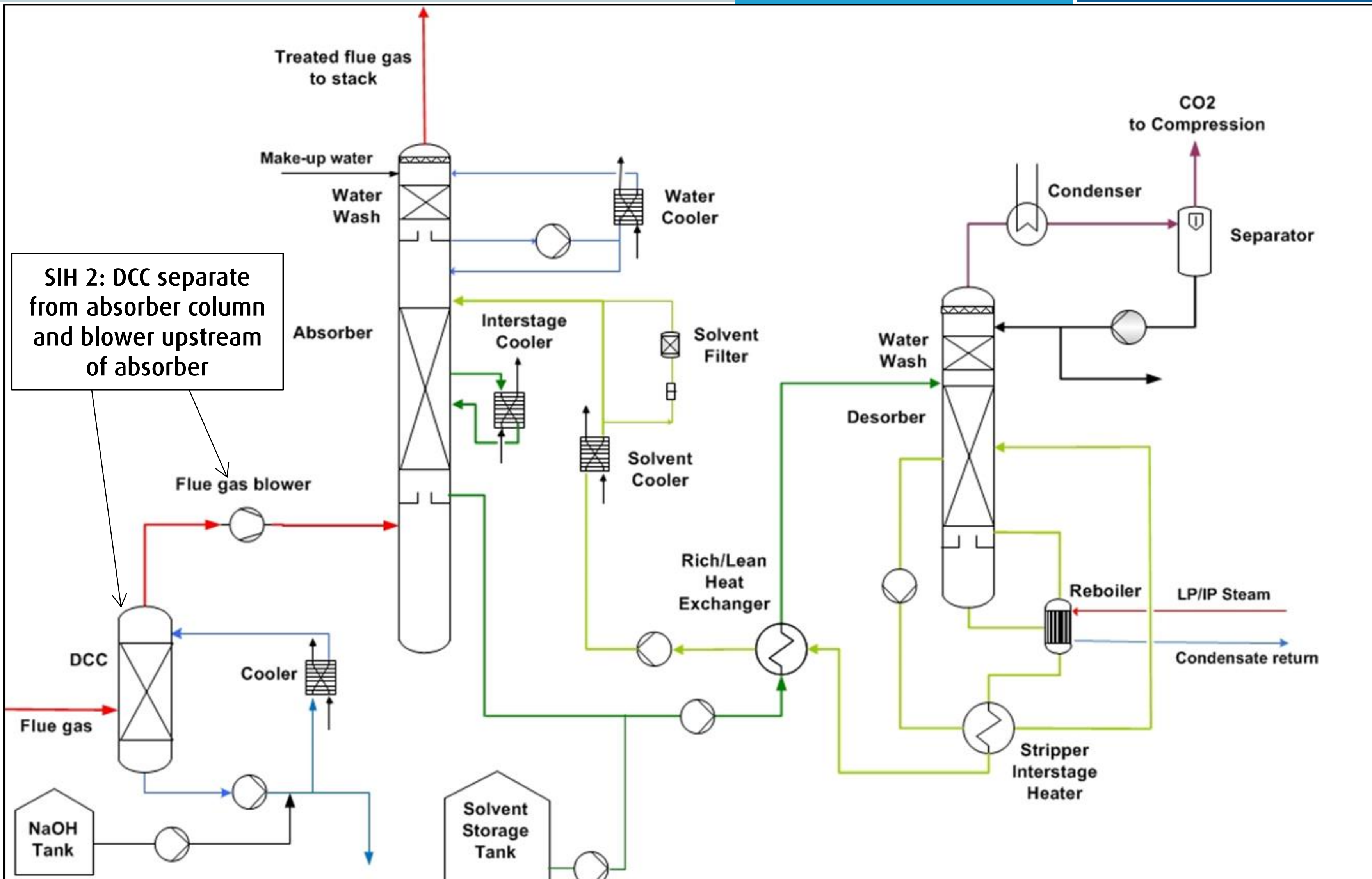
TEA: Linde BASF SIH PCC Process Option Configuration



TEA: Linde BASF LB1-CREB PCC Process Option Configuration



TEA: Cost comparison between two Linde-BASF SIH process cases – blower downstream vs. upstream of absorber



TEA: Cost comparison between two Linde-BASF SIH process cases – blower downstream vs. upstream of absorber

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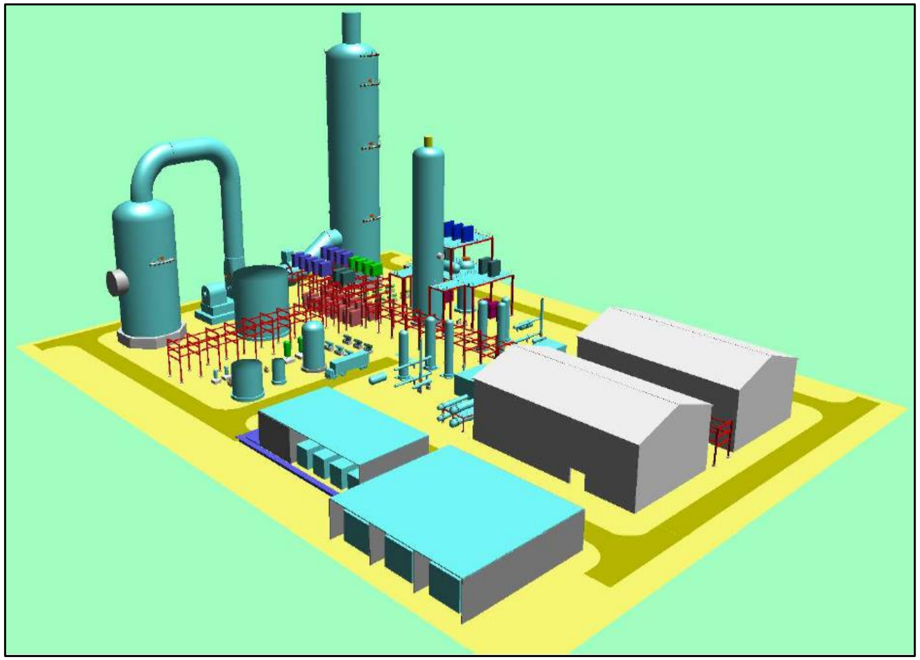
3D model for SIH 1 configuration: blower downstream of absorber column and combined DCC and absorber

3D model for SIH 2 configuration: blower upstream of absorber column and separate DCC and absorber



TEA: Cost comparison between two Linde-BASF SIH process cases – blower downstream vs. upstream of absorber

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Total Post-Combustion CO_2 Capture Plant Cost Details ($x1000, 2011$)								
	Equipment Cost	Labor Cost	Bare Erect Cost	Eng. CM H.O. & Fee	Contingencies		Total Plant Cost	
					Process	Project	$x1000	$/kW
Linde-BASF PCC LB1 Option								
CO_2 Removal System	130,475	51,495	181,970	27,194	37,473	10,554	257,191	468
CO_2 Compression & Drying	39,517	18,709	58,226	3,036	0	2,476	63,738	116
Total	169,992	70,204	240,195	30,230	37,473	13,030	320,928	584
Linde-BASF PCC SIH Scenario 1 – Combined DCC and Absorber with Downstream Flue Gas Blower								
CO_2 Removal System	123,824	45,151	168,974	31,322	37,473	10,192	247,961	451
CO_2 Compression & Drying	41,675	13,997	55,672	4,582	0	2,147	62,401	113
Total	165,498	59,149	224,646	35,904	37,473	12,338	310,362	564
Linde-BASF PCC SIH Scenario 2 – Separate DCC and Absorber with Upstream Flue Gas Blower								
CO_2 Removal System	129,166	47,171	176,338	32,063	37,473	10,556	256,430	466
CO_2 Compression & Drying	41,675	13,997	55,672	4,582	0	2,147	62,401	113
Total	170,840	61,169	232,010	36,645	37,473	12,703	318,830	580

Aerosol Particle Number Concentration and Size Distribution Measurements Summary – 2015 (Southern Research)

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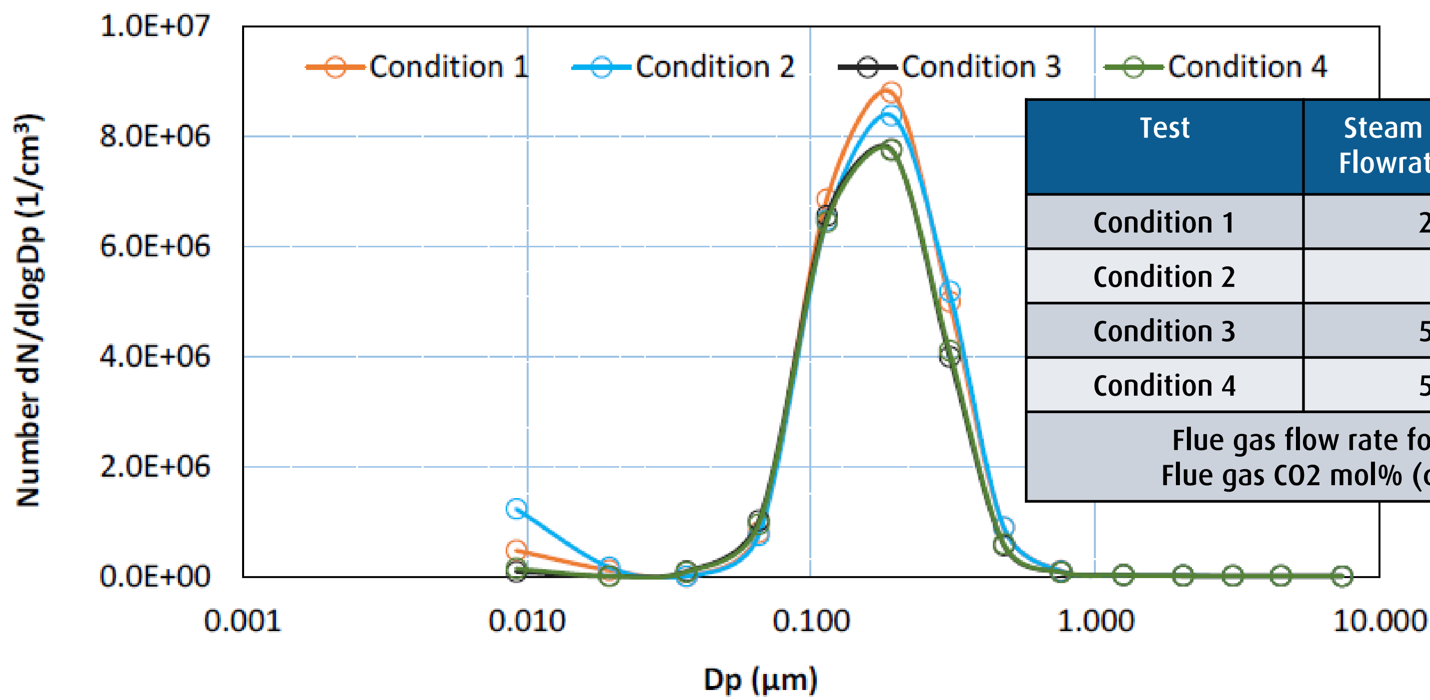
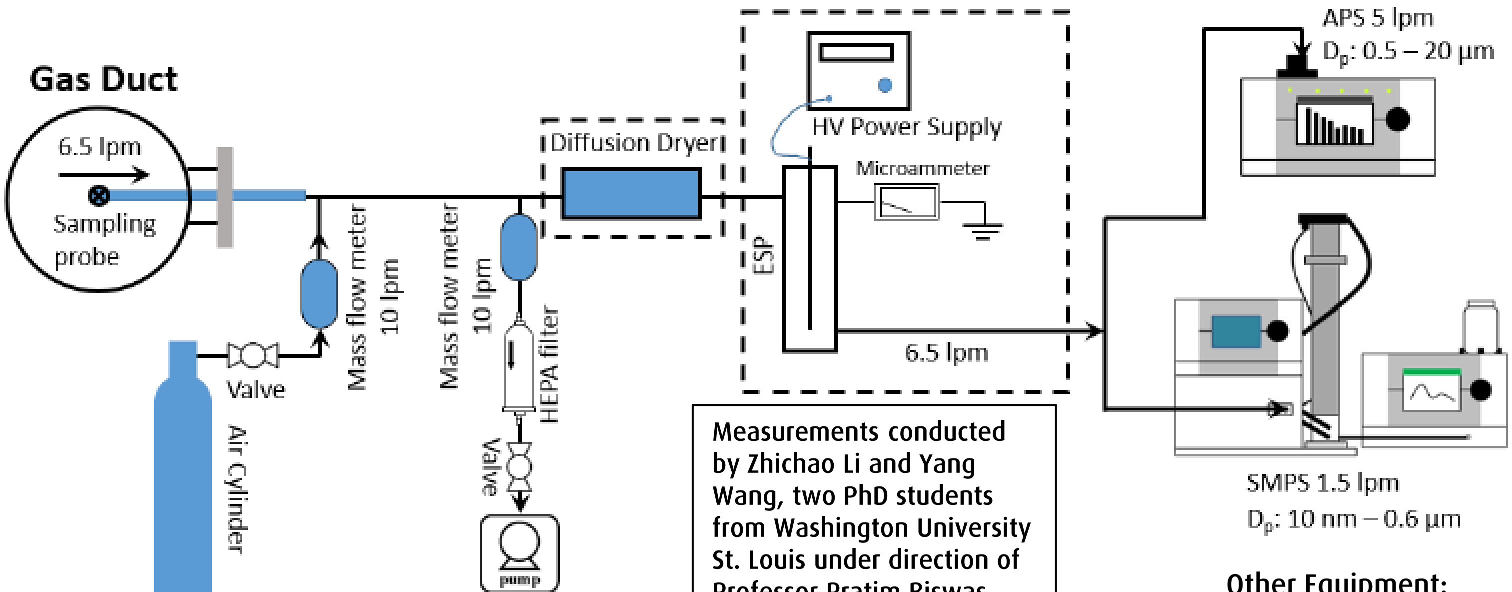


Test	Steam Injection Flowrate (lb/hr)	Flue Gas Temperature (°F)
Condition 1	250	103
Condition 2	0	103
Condition 3	500	95
Condition 4	500	104
Flue gas flow rate for all tests: 9,000 lb/hr Flue gas CO2 mol% (dry) for all tests: 11.4%		

- Tests were conducted by Southern Research (SR) on 12/17/15 and 12/18/15 on flue gas at pilot plant BEFORE baghouse was installed.
- SR tests revealed that very high concentrations of nano-sized aerosol particles (> 8E+06 particles / cm^3 at 200-300 nm diameter) were present in flue gas prior to baghouse installation.
- Steam injection into flue gas had a small effect (~10%) on reducing aerosol particle concentration in flue gas when above 250 lb/hr steam for 9,000 lb/hr flue gas. Varying flue gas temperature within the range tested (95-104 ºF) appears to have little to no measurable effect on particle concentration.
- Significant aerosol-related solvent emissions occurred during parametric test campaign.

Aerosol Particle Number Concentration and Size Distribution Measurements Summary July, 2016 - WashU St. Louis, Equipment Setup



Measurements conducted by Zhichao Li and Yang Wang, two PhD students from Washington University St. Louis under direction of Professor Pratim Biswas

Aerosol particle characterization instruments:

1) **Scanning mobility particle sizer (SMPS, TSI Inc.).** Size distributions of particles from 10-200 nm were measured continuously with SMPS. SMPS uses a differential mobility analyzer (DMA) to classify particles as a function of electrical mobility size, and a condensation particle counter (CPC) to measure particle concentrations. Continuous particle distribution is obtained through data inversion relating particle concentration to neutralizer charging efficiency, CPC detection efficiency, and DMA transfer function.

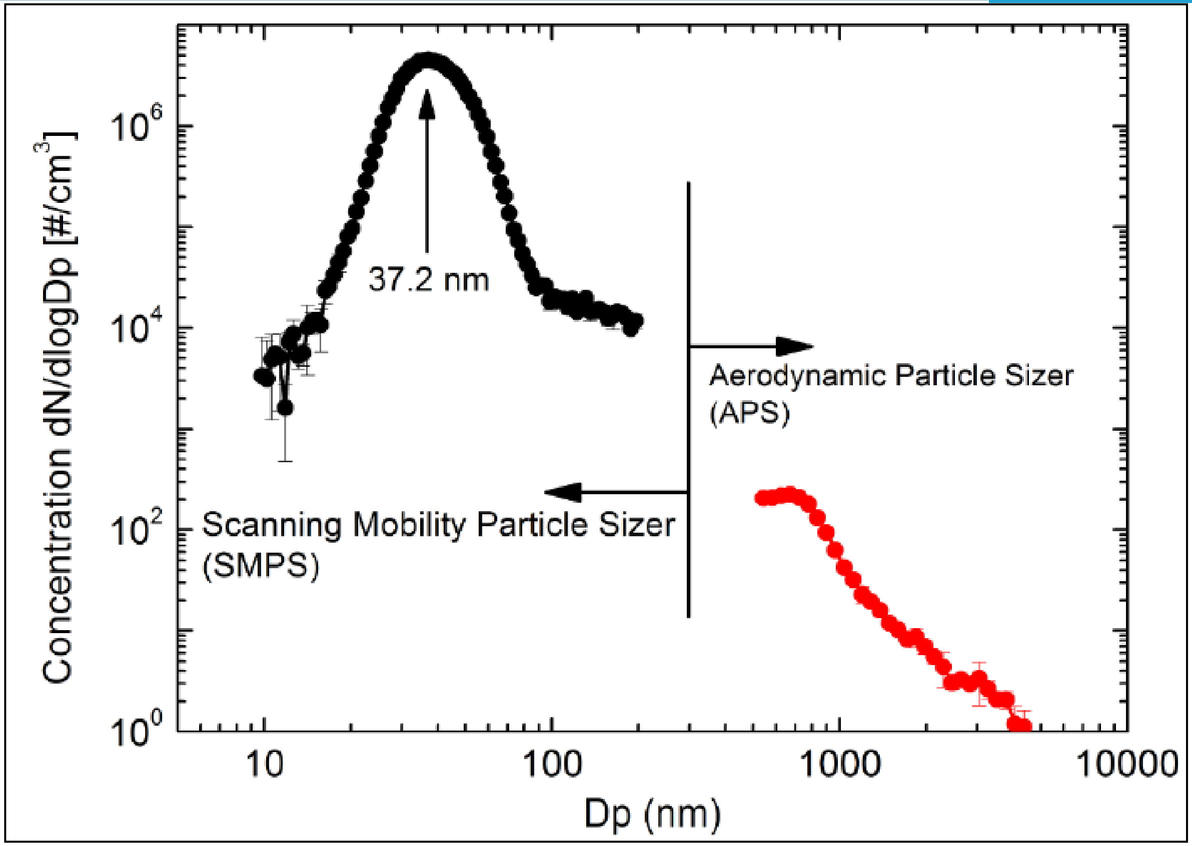
2) **Aerodynamic particle sizer (APS, TSI Inc.).** APS measures aerodynamic size distribution of particles between 0.5 to 20 µm. Sampled particles flow along the centerline of an accelerating flow created by sheath air. A photodetector evaluates the time interval between pulses of scattered light emitted by aerosol particles as they pass through two focused laser beams. The aerodynamic particle size is calculated based on this time interval.

Other Equipment:

1) **Diffusion dryer**: reduces water content of gas supplied to instrumentation, unused for several tests to examine influence of water content on aerosols

2) **Internal pumps** pulled flue gas at a flow rate of 6.5 slpm. Flow rates of dilution air from compressed air cylinder and slipstream going to pump were each maintained at 10 slpm. Resulting dilution ratio of combined air + flue gas flows divided by flue gas flow was 2.54.

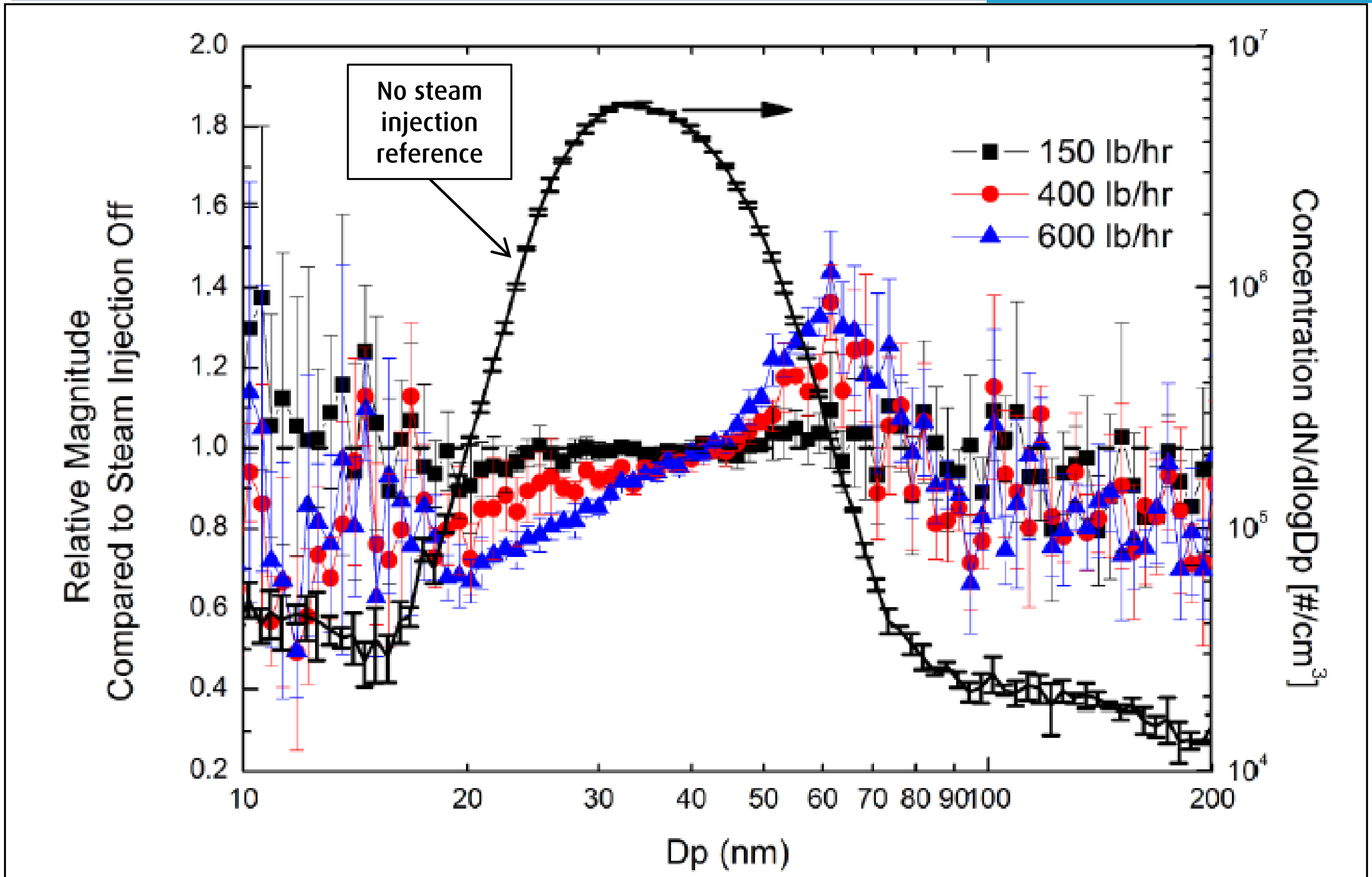
Aerosol Particle Number Concentration and Size Distribution Measurements Summary July, 2016 - WashU St. Louis, Overall Results



1. WashU data was collected on 7/21/16 and 7/22/16 for 10,500 lb/hr flue gas at 95 °F (after baghouse installation).
2. Particle size concentration at 37.2 nm diameter (mode size) was 4.5E+06 particles/ cm^3.
3. Aerosol data between 200 and 500 nm particle diameters was not recorded due to instrumentation error. Interpolation of raw data suggests overall aerosol concentrations for particles above 100 nm diameter are significantly lower compared to results obtained by SR in 2015 before baghouse installation (2E+04 particles/ cm^3 vs. >8.0E+06 particles/ cm^3).
4. Aerosol particles below 100 nm still escape baghouse, and appear to have not been fully measured by SR based on 2015 results.
5. Reduced solvent losses data for 2016 suggests aerosol particles below 100 nm do not have as high of an impact on solvent losses compared to larger particles.

Parameter	SR (before baghouse)	WashU St. Louis (after baghouse)
Mode Particle Size	200 nm	37.2 nm
Concentration at mode size (#/ cm^3)	8.2E+06	4.5E+06
> 100 nm and < 500 nm particle concentration (#/ cm^3)	4.0E+06 to 8.2E+06 (max)	1E+04 to 2E+04 (max)
> 1 µm particle concentration (#/ cm^3)	0	1 to 25

Aerosol Particle Number Concentration and Size Distribution Measurements Summary July, 2016 - WashU St. Louis, Steam Injection



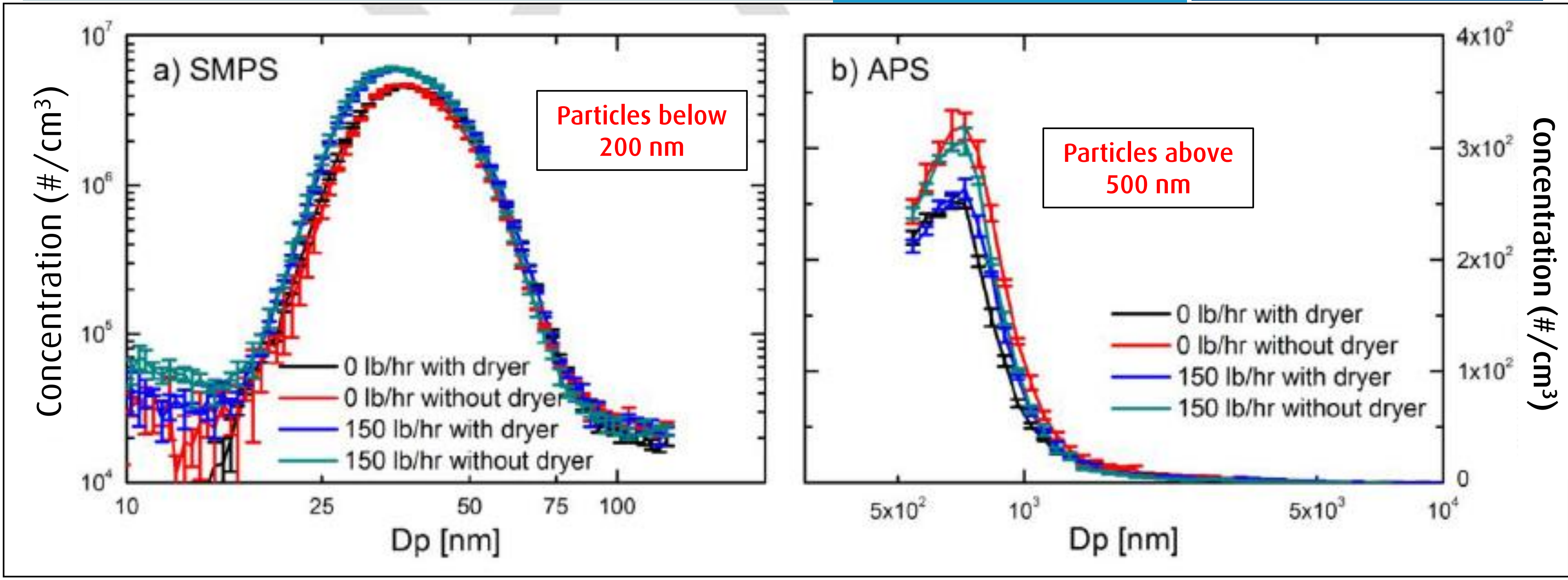
Relative magnitude < 1.0 indicates removal of particles, > 1.0 indicates generation of particles.

In size range outside 20-60 nm, relative magnitude fluctuated around 0.8, indicating overall particle removal effect with steam injection. However, since most particle sizes are between 20-60 nm, this removal effect is relatively insignificant, as shown in relative magnitudes > 1.0 between 40 and 60 nm particles with steam injection.

Steam Injection Flowrate (lb/hr)	Integrated Particle Number Concentration (#/cm^3)
0	1.47E+06
150	1.46E+06
400	1.39E+06
600	1.35E+06

Results indicate a minor reduction (~8%) in overall aerosol particle concentration caused by steam injection into flue gas

Aerosol Particle Number Concentration and Size Distribution Measurements Summary July, 2016 - WashU St. Louis, Diffusion Dryer

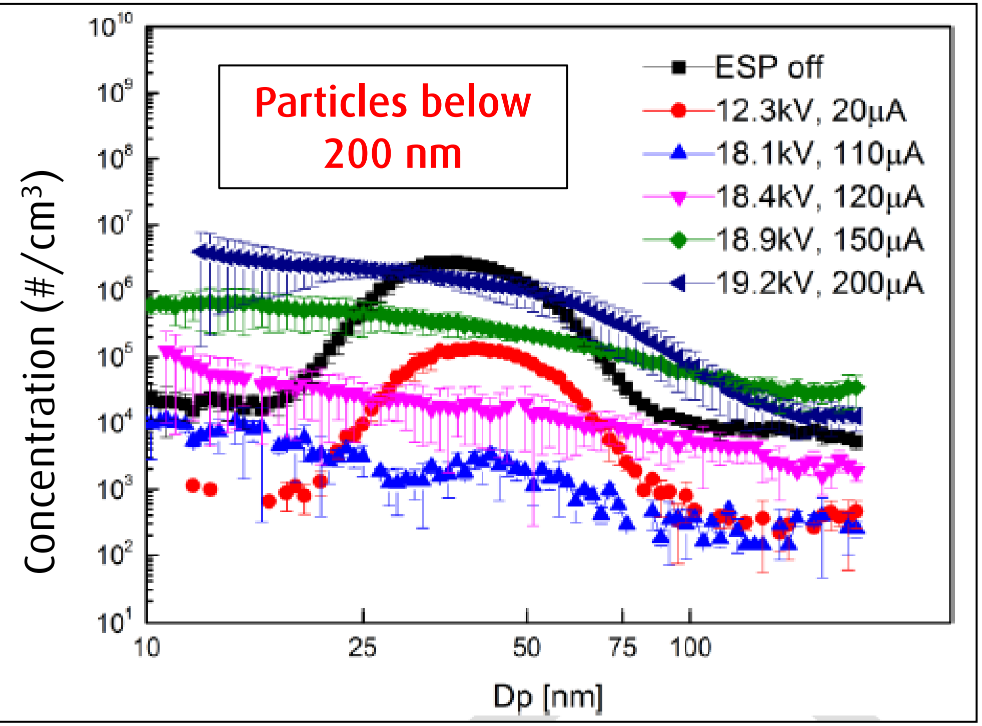


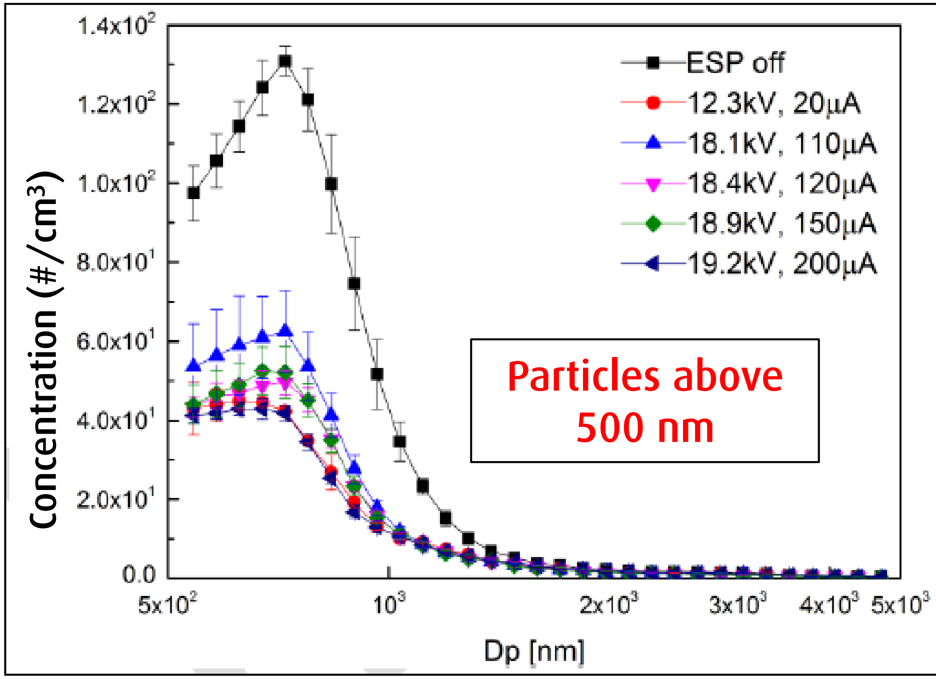
Effects of adding diffusion dryer:

1. Particle concentrations measured with 150 lb/hr steam were slightly higher than those with no steam injection -> most likely attributed to experimental aerosol particle property fluctuation during power plant operation since experiments were conducted in two separate days (7/21/16 and 7/22/16).

2. Adding diffusion dryer did not significantly reduce particle size for both SMPS and APS results, indicating that water content in particles was relatively low.

Aerosol Particle Number Concentration and Size Distribution Measurements Summary July, 2016 - WashU St. Louis, ESP





Effects of applying an electrostatic precipitator (ESP) to flue gas:

1. Even with small current of 20 µA at 12.3 kV supplied by ESP, the number concentrations of most aerosol particles decreases by ~2 orders of magnitude.

2. When voltage is increased above 18.1 kV starting from 12.3 kV, the particle concentration begins to increase. When voltage increases from 18.4 kV to 19.2 kV, 10-100 nm particles showed higher concentration compared with 18.1 kV case. This phenomenon can be most likely attributed to secondary particle generation inside ESP since it has been shown that some small amount of SO_2 in the flue gas can be oxidized by radicals in the ESP and react with water to form H_2SO_4 aerosols that contribute to aerosol concentrations.

3. Right plot shows significant decrease in number concentrations of particles larger than 500 nm in diameter for all tested voltages, indicating that more large particles were removed rather than generated by the ESP.