



Measurements of Emissions in the Linde-BASF PCC Pilot Units

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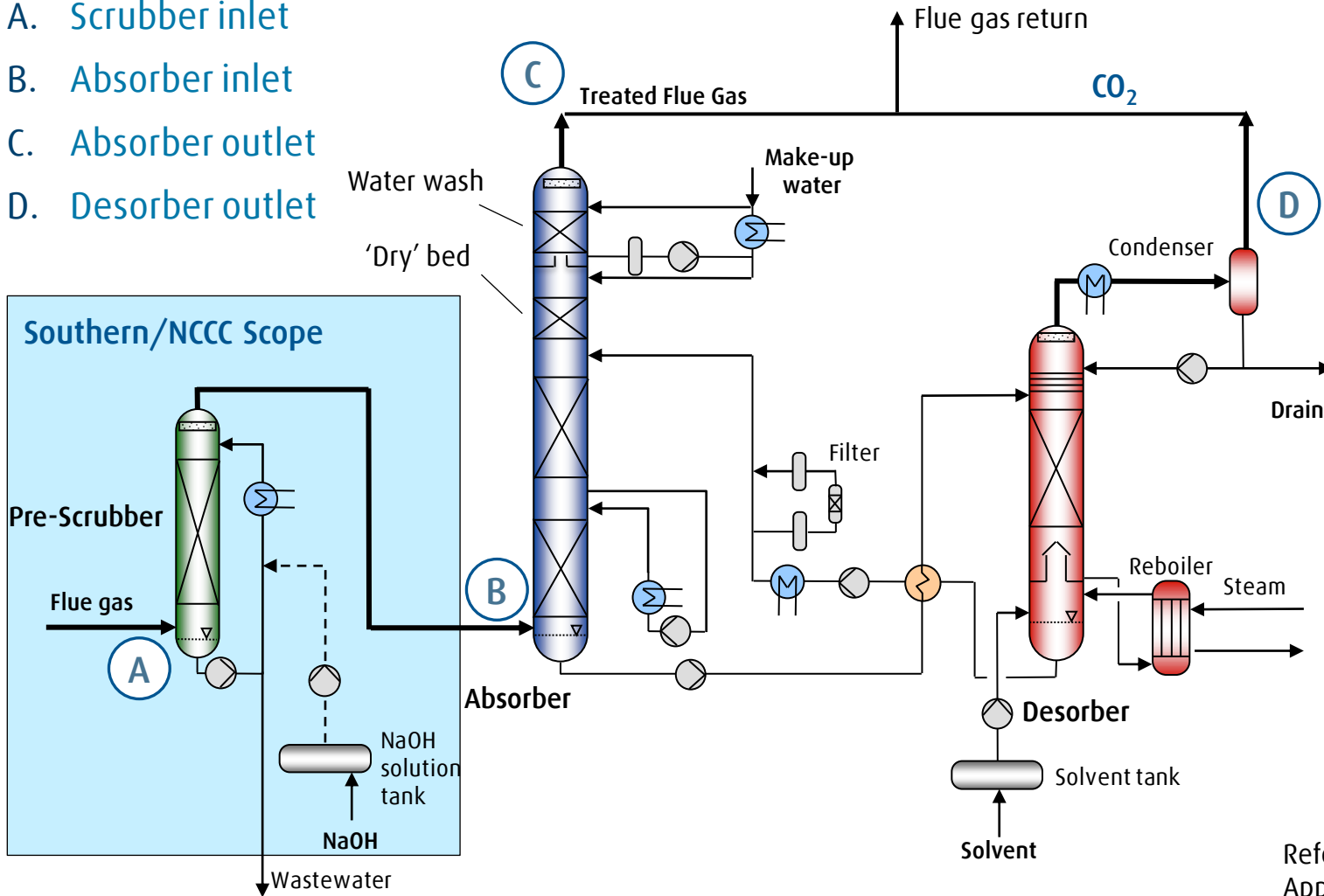
Making our world more productive

Linde/BASF OASE® Blue Post Combustion Capture (PCC) Technology

Emissions Measurements at NCCC by EPRI and Linde.



- A. Scrubber inlet
- B. Absorber inlet
- C. Absorber outlet
- D. Desorber outlet



Summary of gas sampling and analysis plan

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

^a U.S. EPA Methods from 40 CFR 60 Appendix A; Method 8A (SO₃) from NCASI.

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

^c CO₂ CEMs using 0 to 100% scale; Oxygen CEM AMI Model 1000RS-T2 with 0- to 50 ppm range.

Reference: DE-FE0007453 – Final Scientific/Technical Report to DOE
Appendix – EPRI Test report

Amine Emissions at Linde-BASF PCC 1.5 MW Pilot at NCCC

Impact of Aerosols



- Aerosols were suspected to cause high amine losses during 2015 tests based on learnings in previous pilot tests in Germany
 - Specific amine emissions were in 0.2 to 0.5 kg amine/T CO₂ (measured using isokinetic sampling of treated gas)
 - Aerosols of 100 nm size were estimated at 5×10^6 particles/cm³, which is much higher than safe threshold of $\sim 10^4$ particles/cm³.
- Activated carbon injection baghouse was installed in 2016
- Significant decrease in amine emissions was observed in the subsequent tests
 - Specific amine emissions were in 0.01 to 0.02 kg amine/T CO₂ range
 - Aerosols in 100 to 500 nm range decreased by 100-fold

Reference: DE-FE0007453 – Final Scientific/Technical Report to DOE
Appendix – EPRI Test report

Aerosol Controls Prior to Absorber Key to Minimize Amine Emissions

Emissions Measurements at Linde-BASF PCC 1.5 MW Pilot at NCCC

Results Summary



SO_x/NO_x/PM/THC

- >98% SO₂ removed in pre-scrubber; SO₃ in absorber inlet below detection limit
- NO_x mostly passes through absorber
- PM not measured at scrubber inlet; PM at absorber inlet were below detection limit
- THC was typically <1 ppm for steady state long duration test

HAPs metals

- Most of HAPs metals were below detection limit
- Some of HAPs metals will go from gas phase into liquid phase and thus represents reduction in air emissions

Amine degradation products

- Ammonia at 1 ppm in absorber outlet indicates amine degradation product
- Formaldehyde and acetaldehyde were detected in the absorber outlet at 0.05 ppm and 0.13 ppm, respectively
- Two ketones and one aldehyde were at below detection limits

Reference: DE-FE0007453 – Final Scientific/Technical Report to DOE; Appendix – EPRI Test report

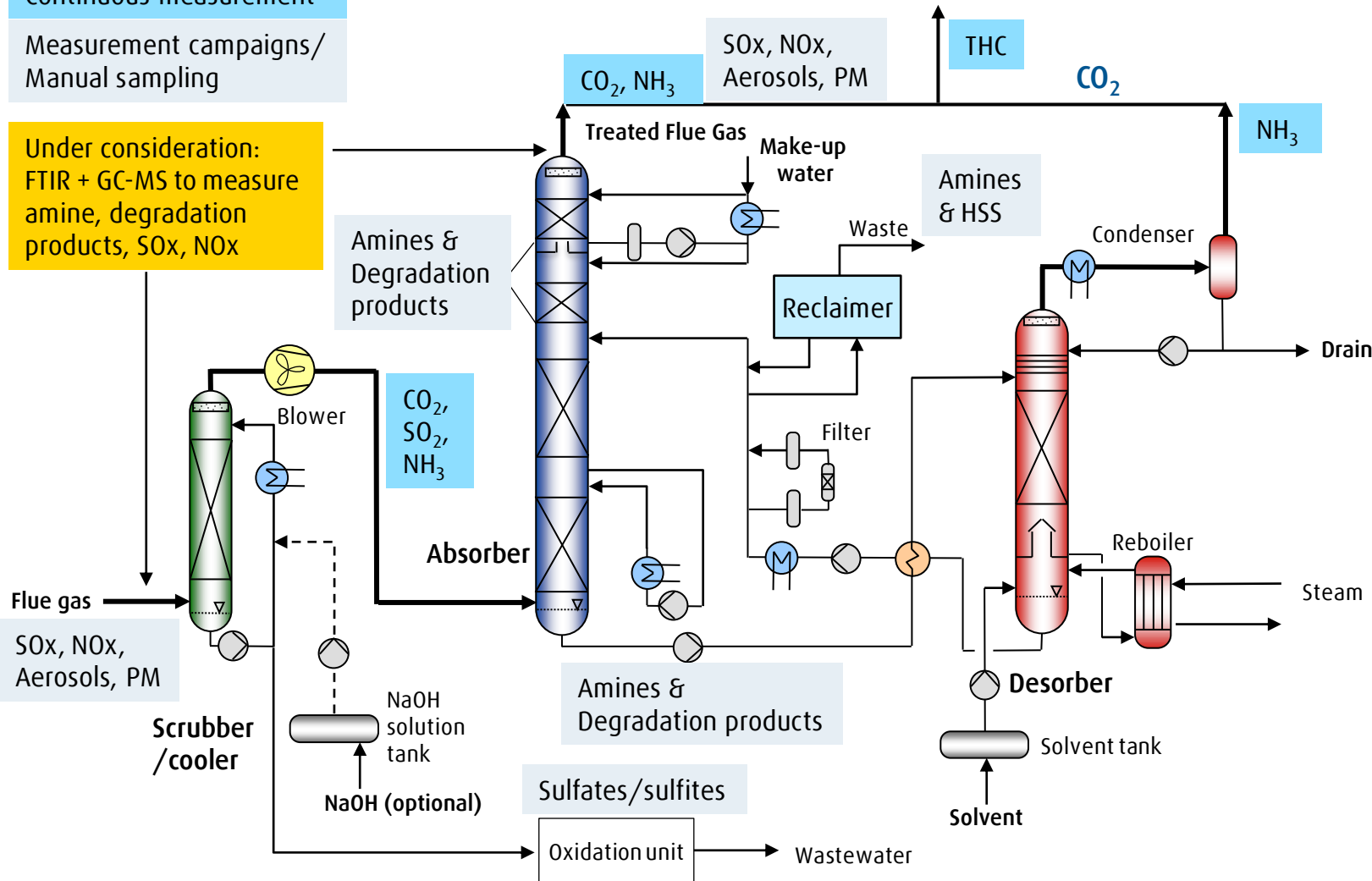
Emissions Measurements at Linde-BASF PCC 10 MW_e Pilot Unit UIUC-Led Large Pilot at CWLP's Coal Plant in Springfield, IL.



Continuous measurement

Measurement campaigns/
Manual sampling

Under consideration:
FTIR + GC-MS to measure
amine, degradation
products, SO_x, NO_x



- Current design includes
 - Continuous analysis for SO₂, NH₃ and THC
 - Batch analysis to measure SO_x, NO_x, aerosols and PM in raw and treated flue gas
- Under consideration to install
 - FTIR + GC-MS for detailed analysis of amine and degradation species
- CWLP plant has both electrostatic precipitator and baghouse filter
 - Aerosols are below safe threshold not requiring further upstream measures
 - Design includes high velocity spray tower on stand-by in case needed



- SO_x removal by scrubber is included in PCC to protect amine solvent; PM removal occurs naturally in the scrubber
 - SO_x/PM emissions reduction is a co-benefit of CO₂ capture
- Aerosol controls essential to minimize secondary amine emissions into air
 - Measures within absorber can manage aerosols up to 10⁵ particles (50 to 200 nm size)/cm³
 - Higher aerosol particle concentration requires upstream removal
- Current large pilot includes plans for analyzing SO_x, NO_x, NH₃ and THC emissions
 - FTIR + GC-MS is under consideration to more comprehensively quantify both co-benefits of CCS and secondary emissions from amine solvent

Back-Up



SOX/NOx/PM Measurements at NCCC



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

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

| Test No. | NOx Emissions | | | | | | % Overall Removal |
|---------------|-------------------------|---------------------|-------------------------|---------------------|--------------------------|----------------------|-------------------|
| | Scrubber Inlet ppmv dry | Scrubber Inlet lb/h | Absorber Inlet ppmv dry | Absorber Inlet lb/h | Absorber Outlet ppmv dry | Absorber Outlet lb/h | |
| Test 1, PM-1 | 28.6 | 0.55 | 33.3 | 0.65 | 35.7 | 0.58 | -4.7 |
| Test 2, PM-2 | 37.4 | 0.73 | 39.5 | 0.77 | 47.4 | 0.77 | -6.1 |
| Test 3, PM-3 | 34.9 | 0.68 | 38.1 | 0.75 | 46.1 | 0.70 | -3.7 |
| Test 4, SO3-1 | 33.0 | 0.64 | 38.3 | 0.75 | 45.1 | 0.68 | -6.9 |
| Test 5, SO3-2 | 33.4 | 0.64 | 39.7 | 0.77 | 44.5 | 0.69 | -7.3 |
| Test 6, SO3-3 | 33.2 | 0.64 | 39.5 | 0.77 | 46.7 | 0.76 | -18.0 |

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

Reference: DE-FE0007453 – Final Scientific/Technical Report to DOE
Appendix – EPRI Test report

HAPS Metals Measurements at NCCC



Summary of HAPs metals and mercury concentrations during performance tests

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

values below detection limit of method

Reference: DE-FE007453 – Final Scientific/Technical Report to DOE
Appendix – EPRI Test report

Ammonia, Aldehydes and Ketones Measurements at NCCC



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

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

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