Integrated Testing of a Membrane CO_2 Capture Process with a Coal-Fired Boiler

DE-FE0026414

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Outline

- Background / review of prior results
- Project overview / objectives
- Installation / test plan
- Test results
  - Membrane system performance
  - Boiler performance with sweep
  - Post-test module analysis
- Lessons learned / summary / future work

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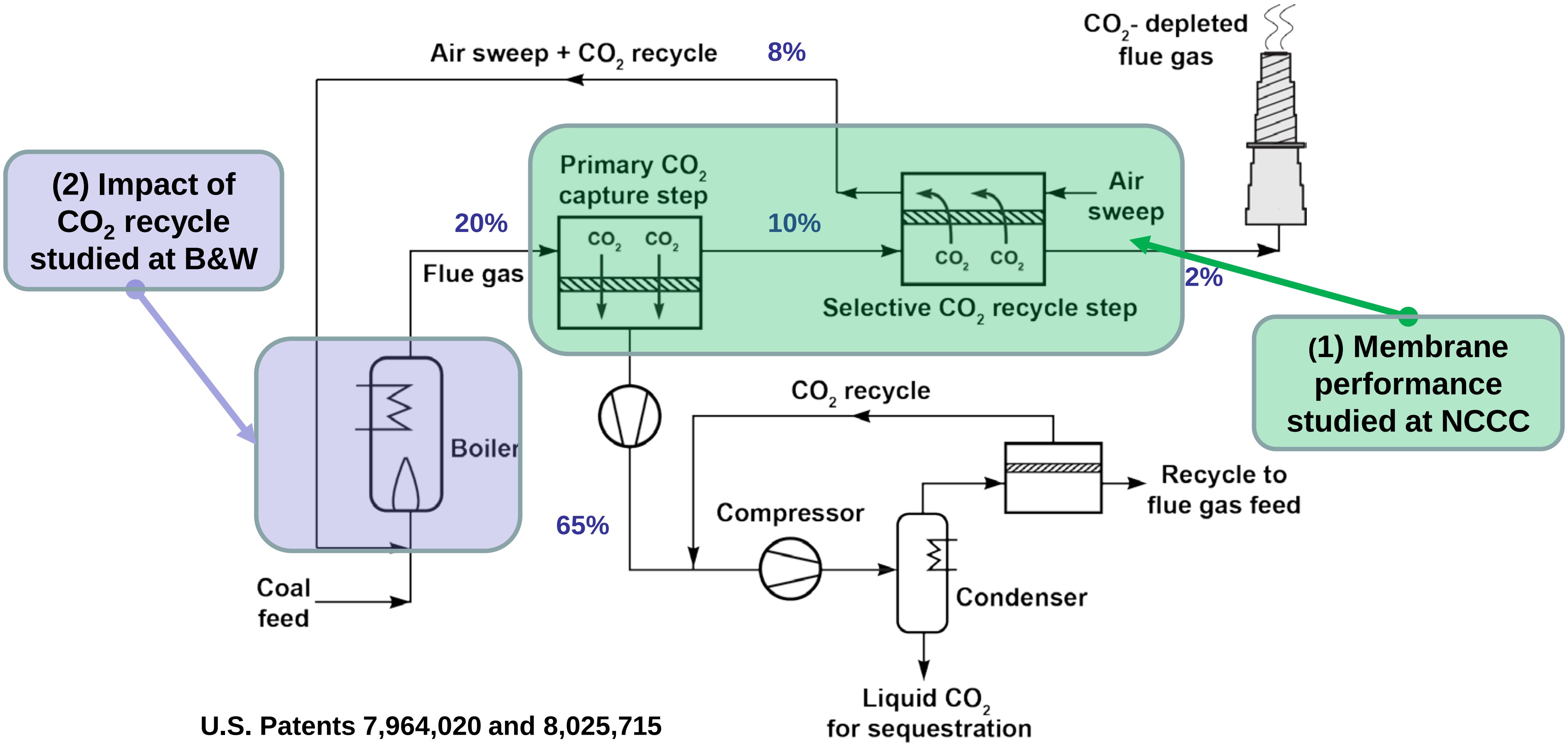
Background: MTR CO_2 Capture Process



U.S. Patents 7,964,020 and 8,025,715

Benefits of selective recycle:

- Increases CO_2 concentration going to the capture step, and
- Reduces the fractional CO_2 removal required by the capture step

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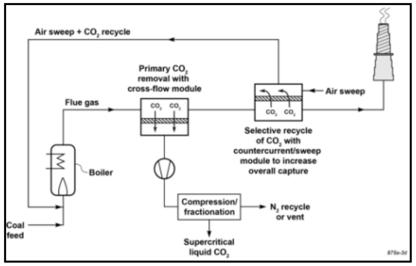
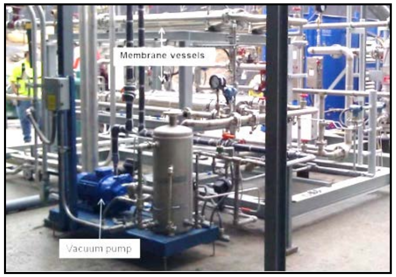
MTR CO_2 Capture Development Timeline

Feasibility study (DE-NT43085)
- Sweep concept proposed
- Polaris membrane conceived

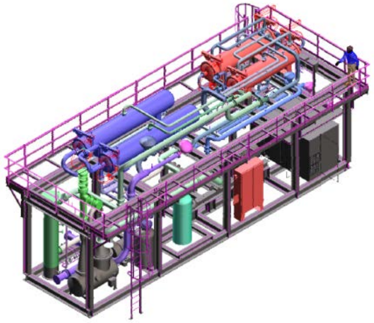


APS Red Hawk NGCC Demo
- First Polaris flue gas test
- 250 lb/d CO_2 used for algae farm

APS Cholla Demo (DE-NT5312)
- First Polaris coal flue gas test
- 1 TPD CO_2 captured (50 kW_e)



NCCC 1 MW_e Demo (DE-FE5795)
- 11,000 hours of 1 TPD system operation
- 1,500 hours of 20 TPD system operation



Low Pressure Mega Module (DE-FE7553)
- Design and build a 500 m^2 optimized module

Hybrid Capture (DE-FE13118)
- Membrane-solvent hybrids with UT, Austin

B&W Integrated (DE-FE26414)

TCM Advanced Polaris

TRL3 | TRL4 | TRL5 | TRL6 | TRL7 | TRL8

2006 | 2008 | 2010 | 2012 | 2014 | 2016 | 2018 | 2020

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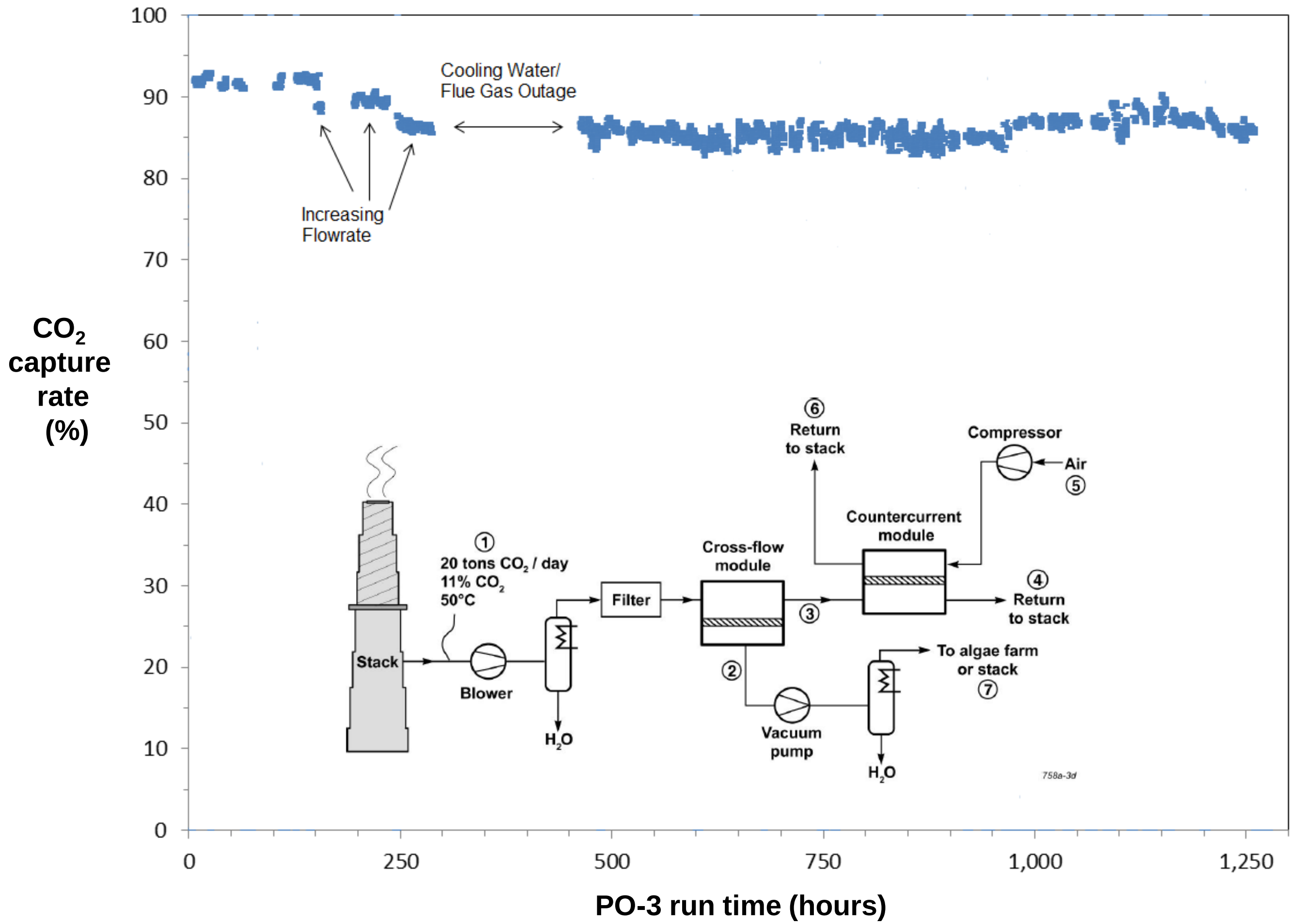
Prior Testing of 20 TPD System at NCCC

- Membranes are simple and compact compared to competing technologies
- In previous 1 TPD testing, Polaris modules completed ~11,000 hours of operation at NCCC

- in June 2015, MTR pilot system completed 1,500 hours of successful operation at NCCC
- System was then moved to B&W in spring 2016 for integrated boiler testing

20 TPD System Shows Stable Performance



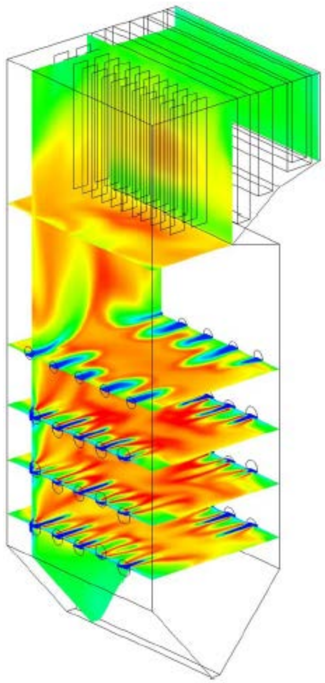
- System operated in slipstream mode (no recycle to boiler)
- Stable performance, reaching up to 90% capture
- System goes from cold start to steady state in ~15 minutes

Figure data from NCCC campaign PO3 (May to July 2015)

Prior B&W Studies of CO_2 Recycle Impact on Boiler Performance (DE-FE0005795)

Phase I – CFD modeling

- B&W modeled 2 boiler configurations (radiant boiler firing bituminous coal and SWUP firing PRB coal) and 2 sweep recycle cases (constant secondary air flow and constant stoichiometry)
- <u>Main conclusion of modeling study</u>: secondary air laden with CO_2 appears feasible as a retrofit in either of the boiler configurations examined if oxygen mass flow to boiler is fixed



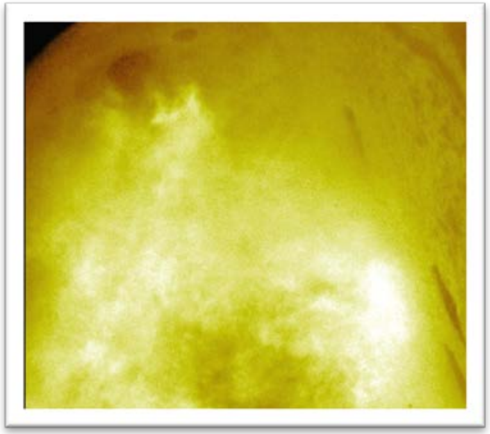
Phase II – Pilot testing

- B&W's SBS-II 1.8 MW_{th} pilot boiler operated with CO_2-laden combustion air
- Two coals evaluated: a western sub-bituminous coal and a highly volatile bituminous coal
- O_2 content of windbox air varied from 21% to 16% through CO_2 dilution
- Monitored flame stability, length, and shape; unburned combustibles in fly ash, and furnace exit gas temperature
- Radiant furnace and convective pass heat absorptions were measured
- Boiler efficiencies for air and sweep firing were determined

Highlights from Testing with CO_2-laden Air on B&W Boiler (DE-FE0005795)

- Stable and attached flames with air (21% O_2) and CO_2-enriched air (16-18% O_2)
- CO_2-enriched flame was less luminous than air-fired case
- Lower furnace heat absorption but higher convection pass/air heater heat transfer for CO_2-enriched operation relative to air
- For bituminous coal, 30% lower NO_x emissions with CO_2-enriched air
- No burner modifications necessary
- Net reduction in plant efficiency of ~0.75% at 18% O_2

Flame image from combustion of PRB coal with air (21% O_2)



Flame image from combustion of PRB coal with CO_2–enriched (18% O_2)

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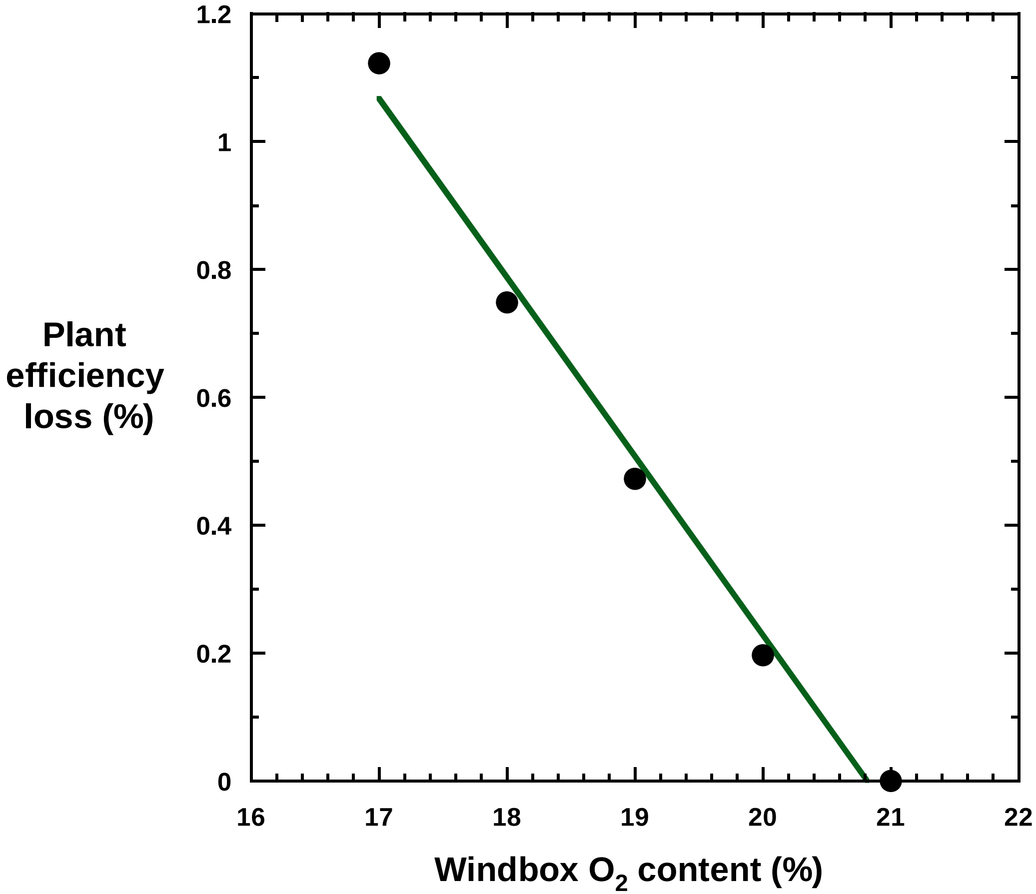
Boiler Efficiency Versus Windbox O_2 (DE-FE0005795)



- Increased CO_2 recycle reduces windbox O_2 content through dilution, which reduces plant efficiency almost linearly
- 18% O_2 appears to be optimum for retrofit; beyond this point tube erosion, abrasion, and slagging may become important
- Because flame is stable to 16% O_2, this level of recycle should be further evaluated for new plants

Project Overview

Award name: Integrated Testing of a Membrane CO_2 Capture Process with a Coal-Fired Boiler

Project period: 7/1/15 to 3/31/18

Funding: $3.6 million DOE; $0.9 million cost share ($4.5 million total)

DOE program manager: José Figueroa

Participants: MTR and Babcock & Wilcox

<u>Project scope:</u> Demonstrate integrated operation of the MTR small pilot capture system with B&W's SBS-II pilot coal boiler.

<u>Project plan</u>: The project is organized in three phases:

- **Phase 1** – Site preparation and system modification/installation
- **Phase 2** – Commissioning, testing, and data analysis
- **Phase 3** – Decommissioning and reporting

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Objectives of Integrated Project (DE-FE0026414)

- Use an existing 20 TPD MTR small pilot membrane system to test integrated operation (with CO_2 recycle to boiler) on an appropriately-sized boiler (B&W SBS-II)
- Validate prior B&W modeling and testing showing modest effect of recycled CO_2 on boiler performance
- Understanding how the various membrane parameters impact performance of a dynamic boiler system
- Reduce risk prior to scaling up to larger demos

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Integrated Project Tasks

1. **B&W Site Preparations**: Prepare process design and engineering drawings, lay foundation at B&W, ready required process connections and utilities infrastructure. (B&W)
2. **Modify and Transport Skid to B&W**: Modify skid as necessary for integrated test, ship skid to B&W. (MTR)
3. **Skid Installation and Shakedown**: Install skid at B&W, including making all process and utility connections, prepare data acquisition and control, and conduct initial shakedown operations. (B&W and MTR)
4. **Integrated Membrane-Boiler Testing**: Conduct parametric studies to validate performance of boiler with varying sweep flowrates; use test to tune system parameters (sweep air flowrate, pressure ratio, boiler O_2 content, CO_2 capture rate, etc) for future scale up. (B&W and MTR)
5. **Site Cleanup and Reporting**: Decommission skid and restore site to original condition; prepare a topical report. (MTR and B&W)

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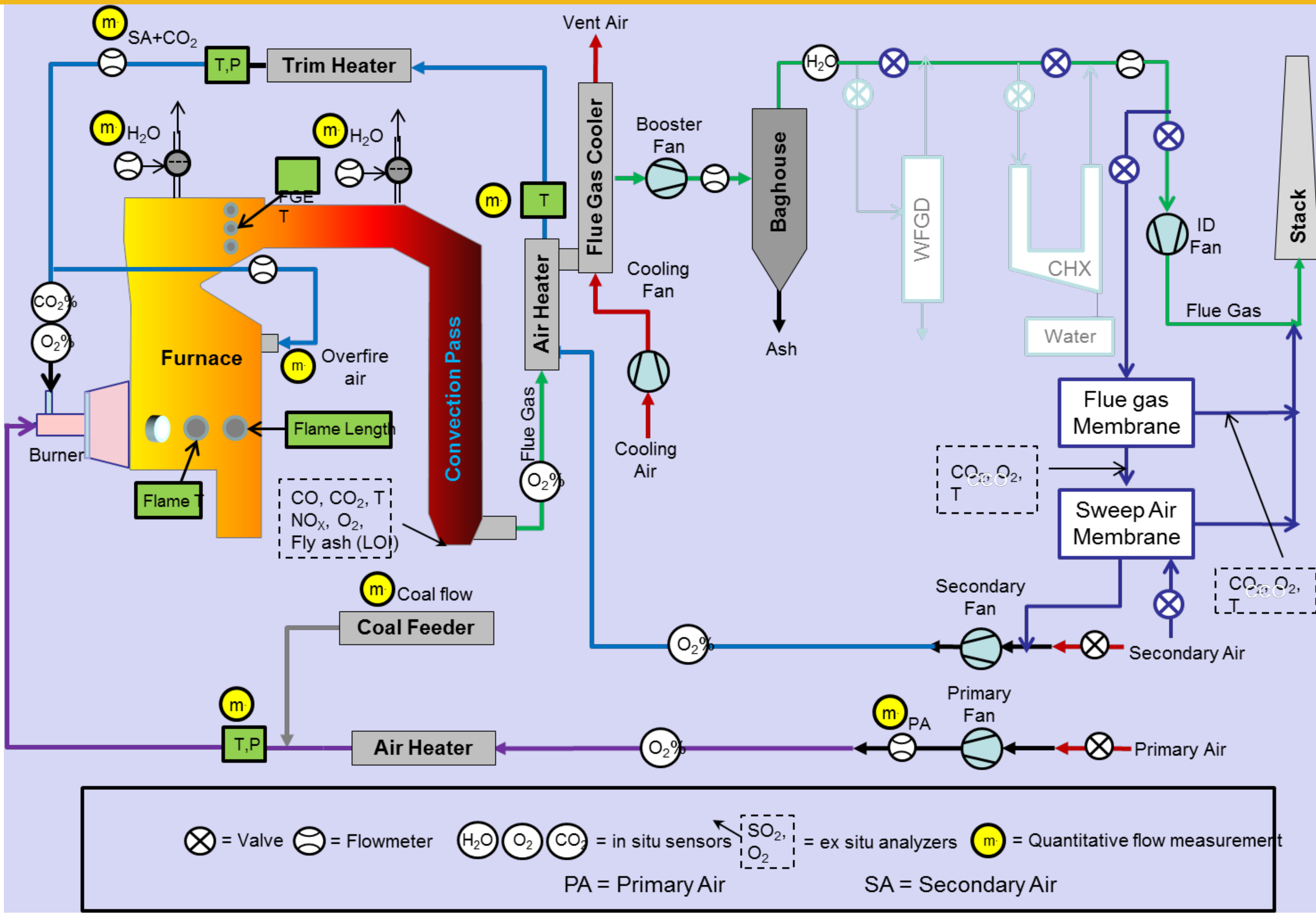
Schematic of Integrated Test



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B&W Research Facility Site Preparation: Spring 2016

- Skid Foundation
- Upgrade Facility Transformer
- Prepare Process Connections
  - Cooling Water Piping
  - Flue Gas Duct Work
  - Instrument Air Lines
- Refurbish Cooling Tower System

MTR Skid During Transport and Installation at B&W: May 2016

Skid arriving at B&W →

← Installation of 2nd floor

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MTR Skids at B&W Research Facility: May 2016

Main skid and smaller low-pressure drop sweep module anchored to foundation

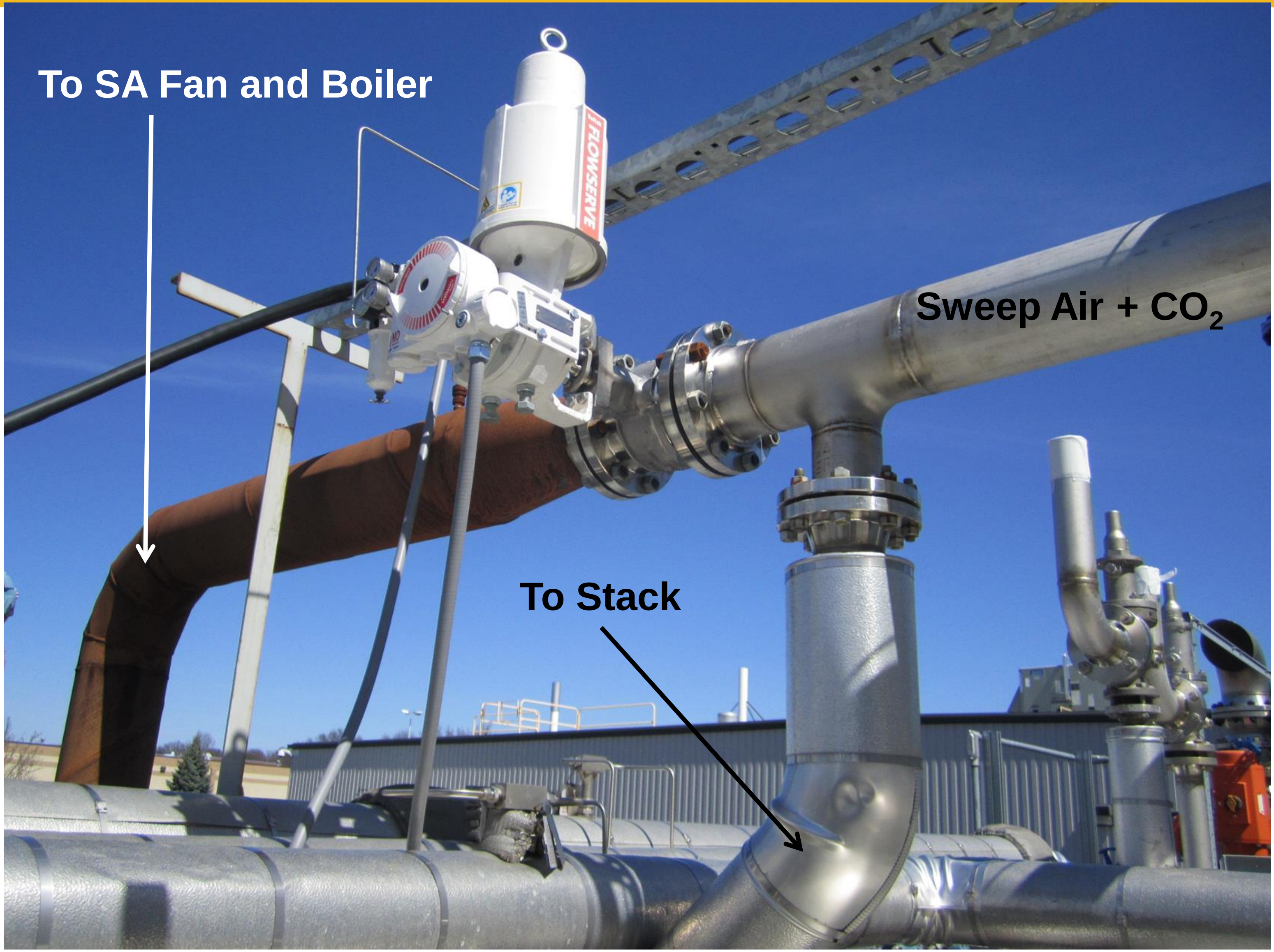
MTR Skids at B&W Research Facility: June 2016

- Skid wiring reconnected
- Skid piping reconnected
- 2nd floor grating and ladders installed
- CW headers and piping installed

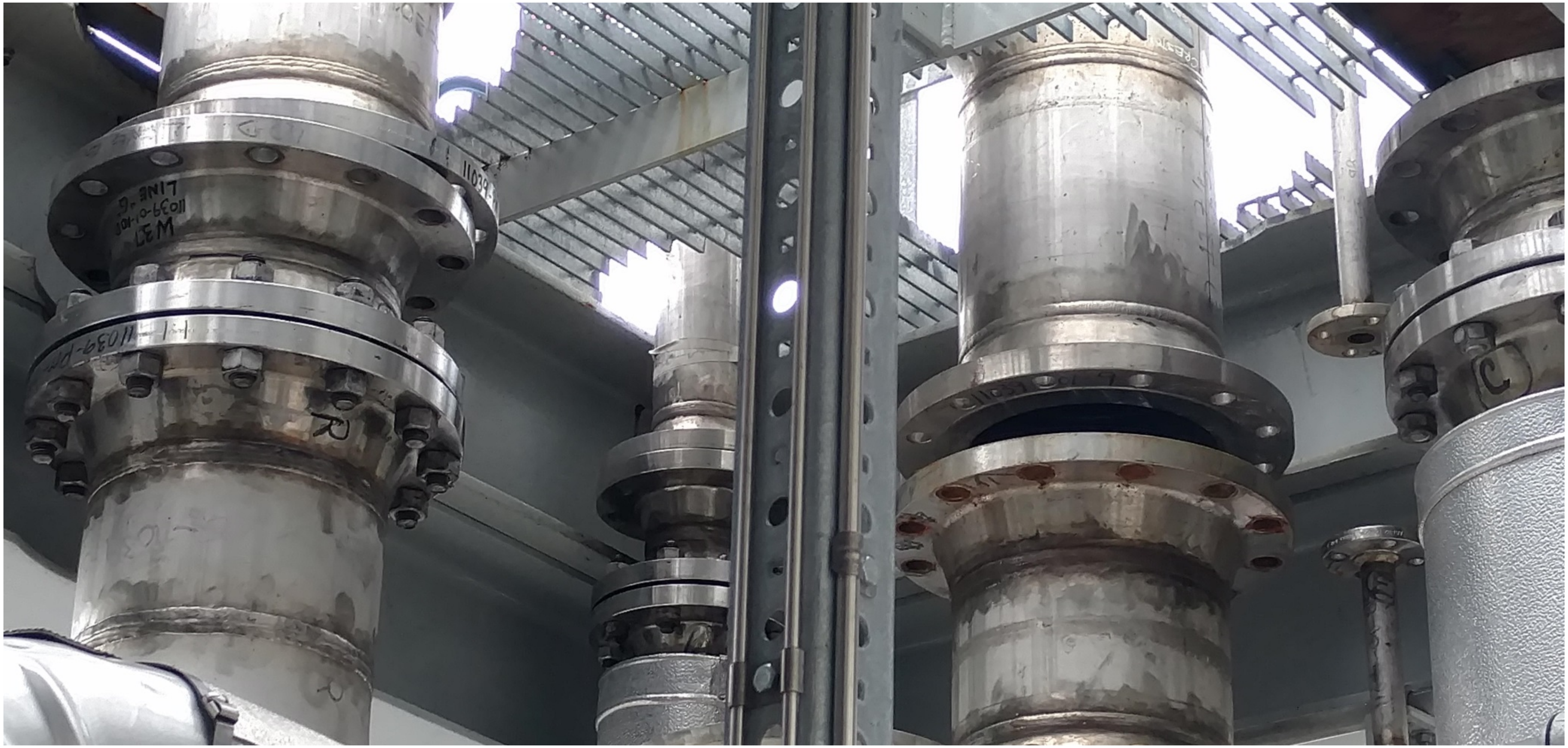
MTR Skids at B&W Research Facility: July 2016

Process and utility lines connected to and from skid

New Control Valve for CO_2 Recycle To Boiler



Lesson Learned: Used Equipment Doesn’t Always Go Back Together As Planned



Lines likely bent during disassembly and shipping from NCCC; B&W team fixed connection issues

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Integrated Membrane-Boiler Field Test Plan Overview

- A minimum of 4 weeks of boiler operation was planned, including time on both PRB and an eastern bituminous coal
- Parametric testing to focus on varying air sweep flow rate:
  - Initially, no air sweep (regular air firing with 1 step membrane capture)
  - Then, slowly increase air sweep to design condition while monitoring boiler performance and CO_2 capture
- Measurements included:
  - Various membrane and boiler gas compositions
  - Flame stability observations
  - FEGT (Furnace exit gas temperature), temperature profiles
  - UBC (Unburned carbon) and contaminants (SO_x/NO_x)
  - Heat transfer and steady state heat adsorption analysis
- Transient tests to evaluate dynamic operation of integrated system

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Actual Test Schedule Summary

Date	Fuel Source	1st Step Modules On-Line	Notes
9/23 and 9/25	Air	M1 + M2 (Modules from NCCC)	Initial shake down test, duration ~8 hours.
9/27 and 9/28	Natural Gas	M1 + M2, M1, or M2	Commissioning tests, verified M1 and M2 performance
10/10 – 10/20	PRB Coal	M2 or M1+M2	M1+M2 on 10/20 only
10/31 – 11/3	Bituminous Coal	M2 or M1+M2	M1+M2 on 11/3 only
SHUT DOWN TO CHANGE OUT 1ST STEP MODULES IN M1			
11/10 and 11/11	Air	M1	Pressure drop and commissioning tests
11/14 – 11/16	Bituminous Coal	M1	

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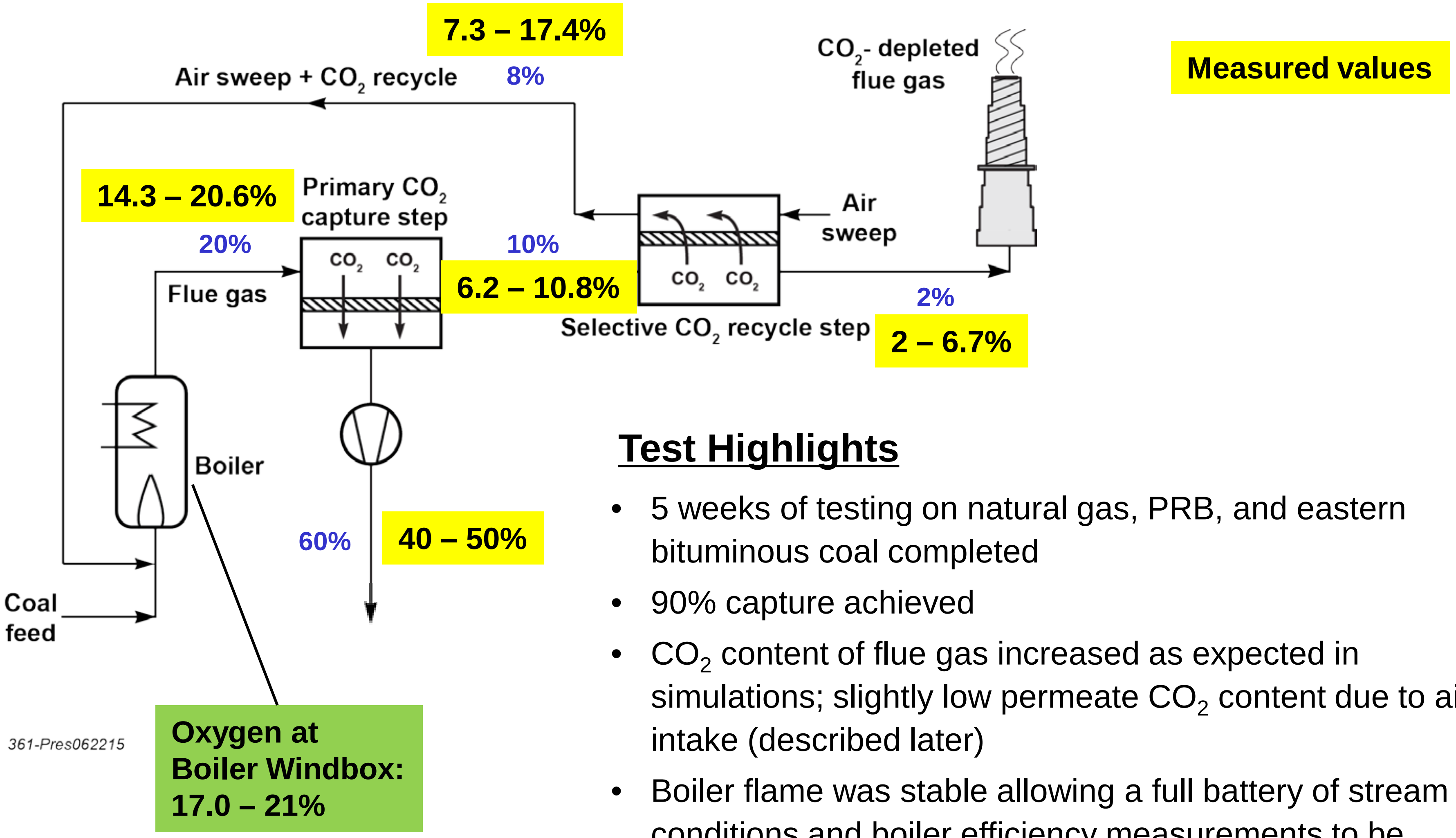
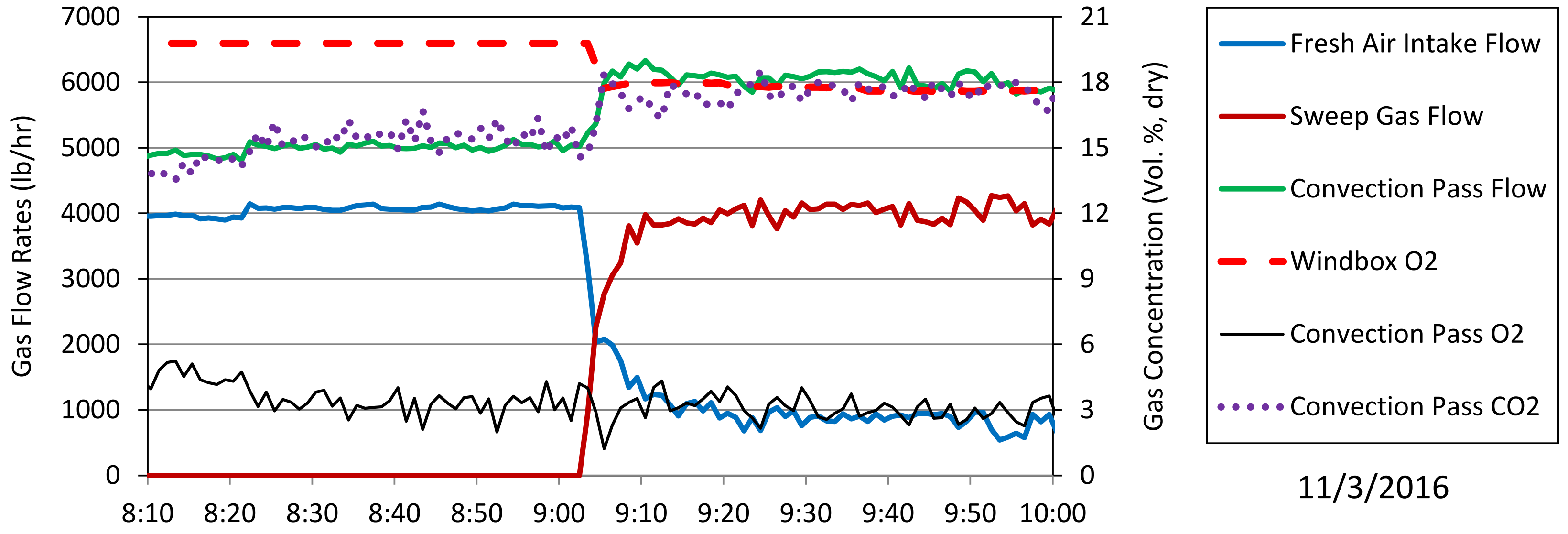
Sample Results from Integrated Membrane-Boiler Field Test

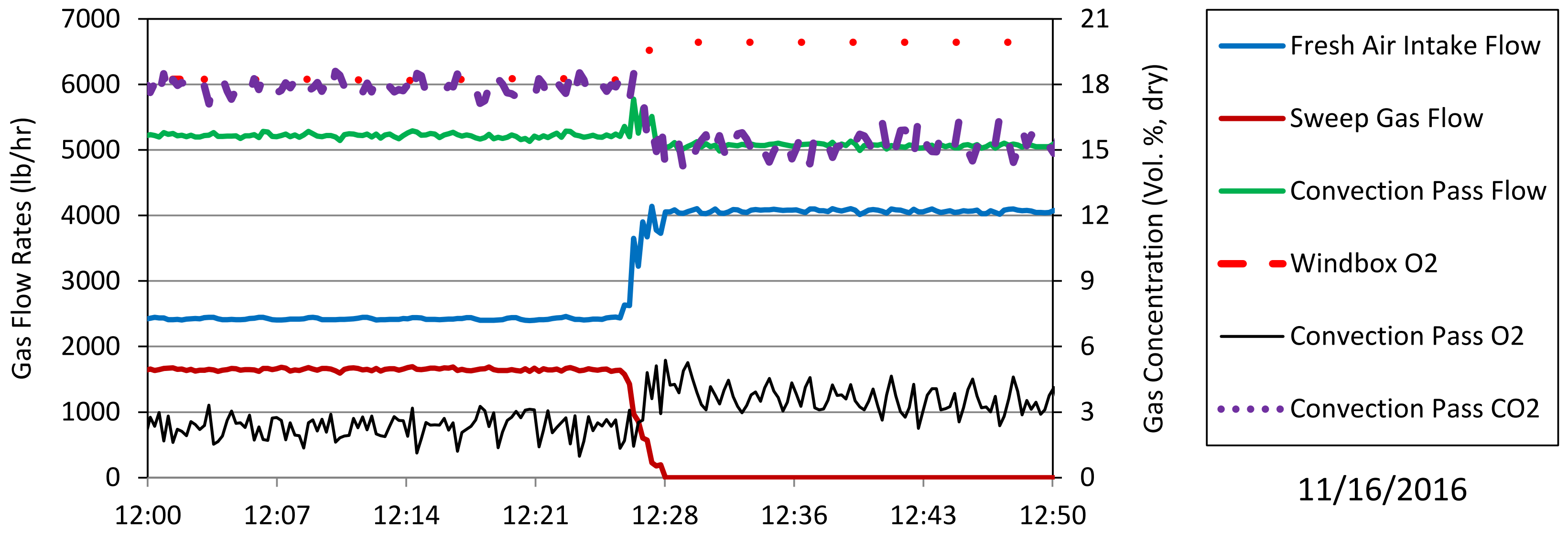


Test Highlights

- 5 weeks of testing on natural gas, PRB, and eastern bituminous coal completed
- 90% capture achieved
- CO_2 content of flue gas increased as expected in simulations; slightly low permeate CO_2 content due to air intake (described later)
- Boiler flame was stable allowing a full battery of stream conditions and boiler efficiency measurements to be conducted

Transient Tests Showed Rapid Response of Integrated System





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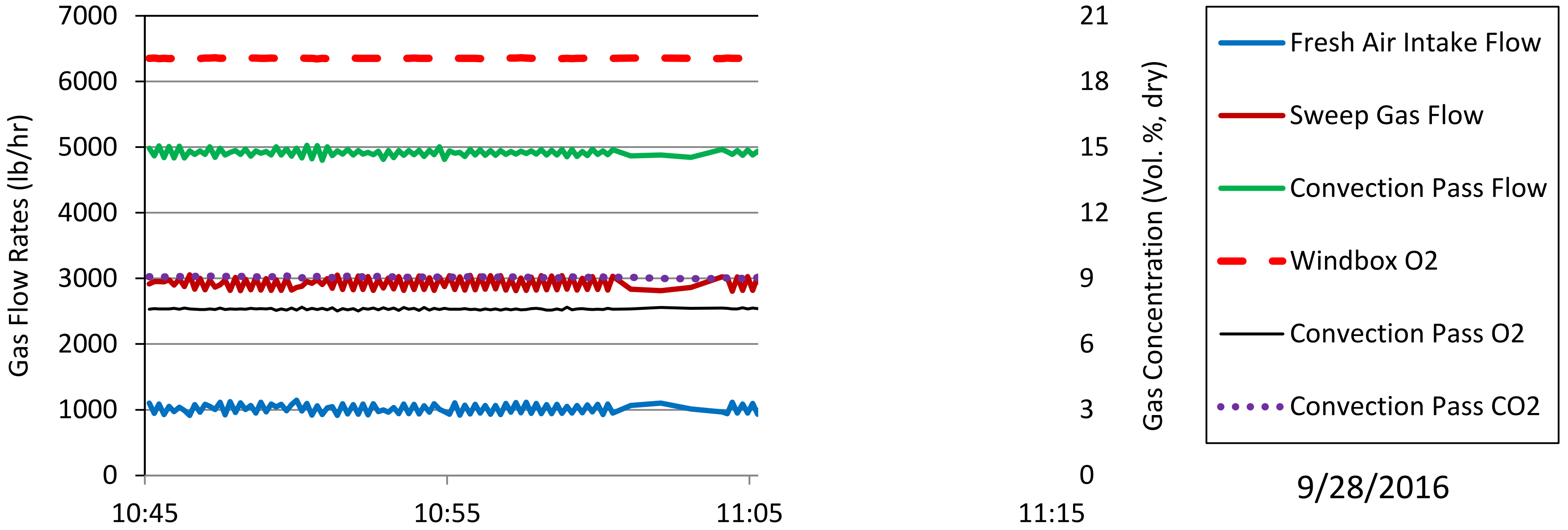
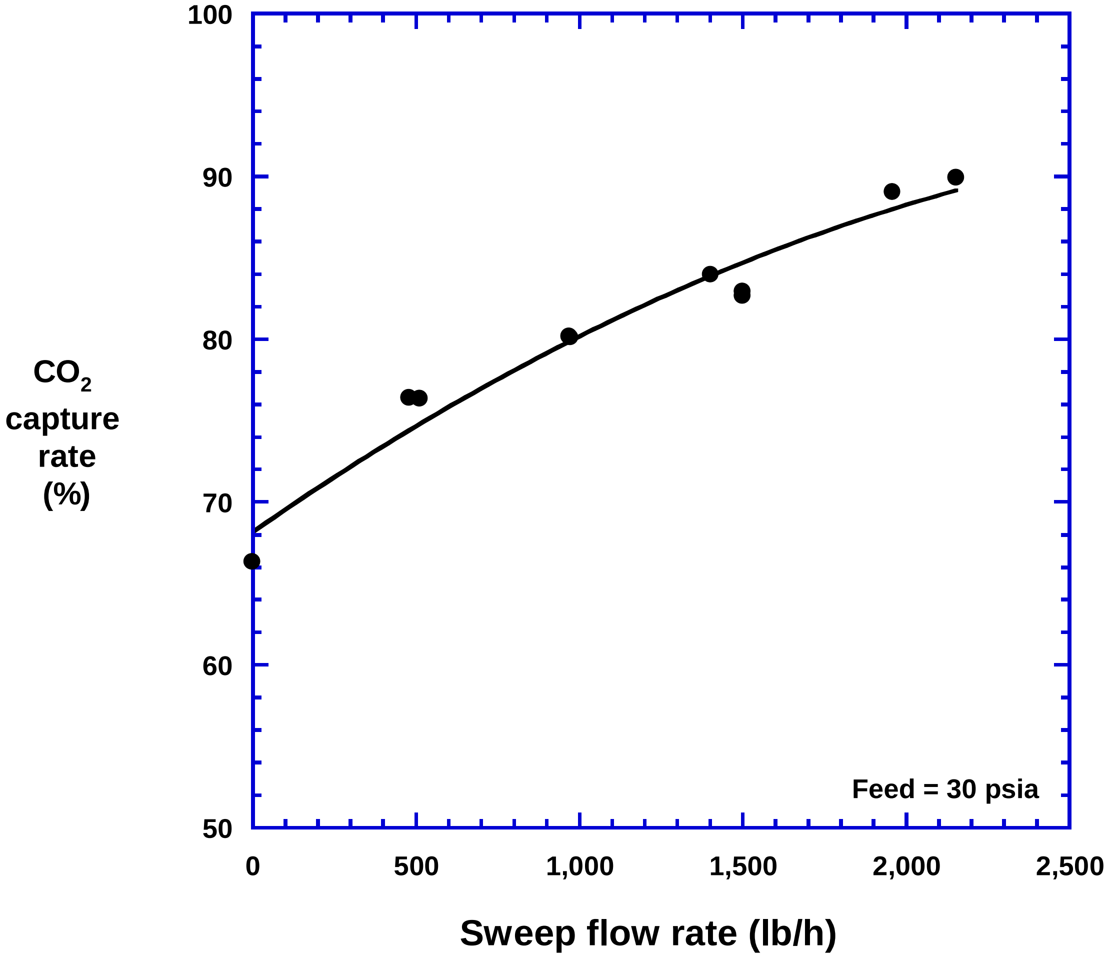
Seamless Transition to Air-Firing After Membrane E-Stop



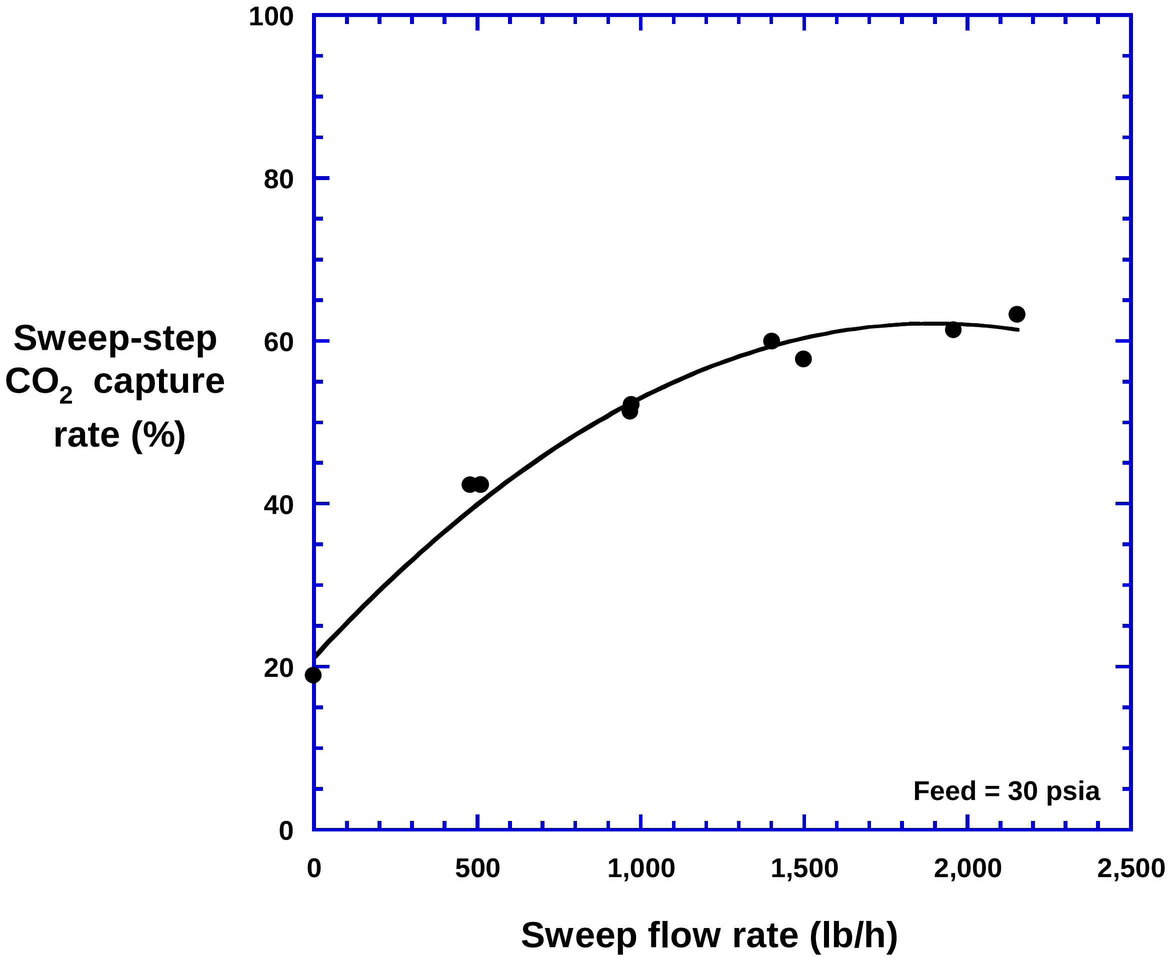
- System controls responded rapidly to allow continuous boiler operation when switching between air-firing and membrane-sweep firing

Results from Parametric Tests: Variation of CO_2 Capture Rate



Highest sweep air flow rate of 2,200 lb/hr corresponds to a Membrane Secondary Air Ratio of ~80%

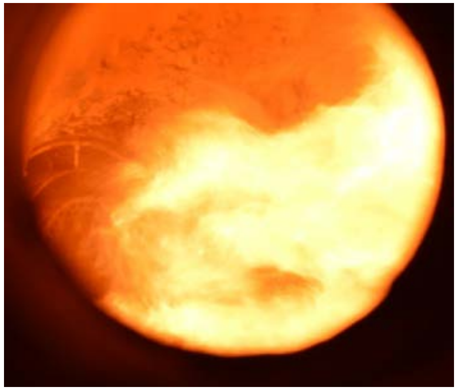
Results from Parametric Tests: Sweep Step CO_2 Capture Rate



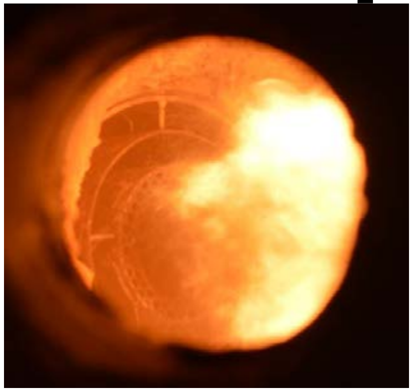
Highest sweep air flow rate of 2,200 lb/hr corresponds to a Membrane Secondary Air Ratio of ~80%

Influence of CO_2 Recycle on the Boiler Flame

PRB Air



PRB 18% O_2



Eastern Bituminous Air

Eastern Bituminous 17% O_2

- Flame was attached and stable for all test conditions
- Flame slightly less luminous for recycle cases due to additional diluent

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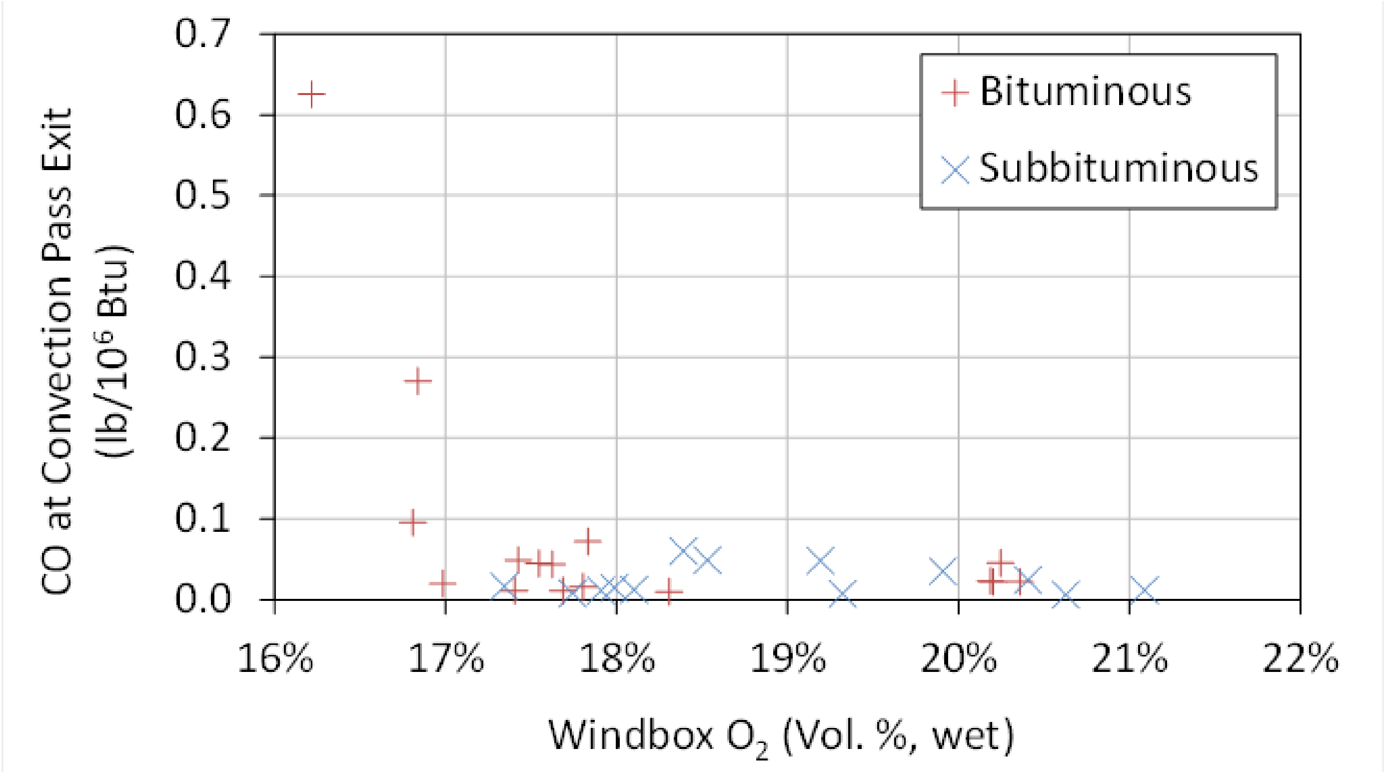
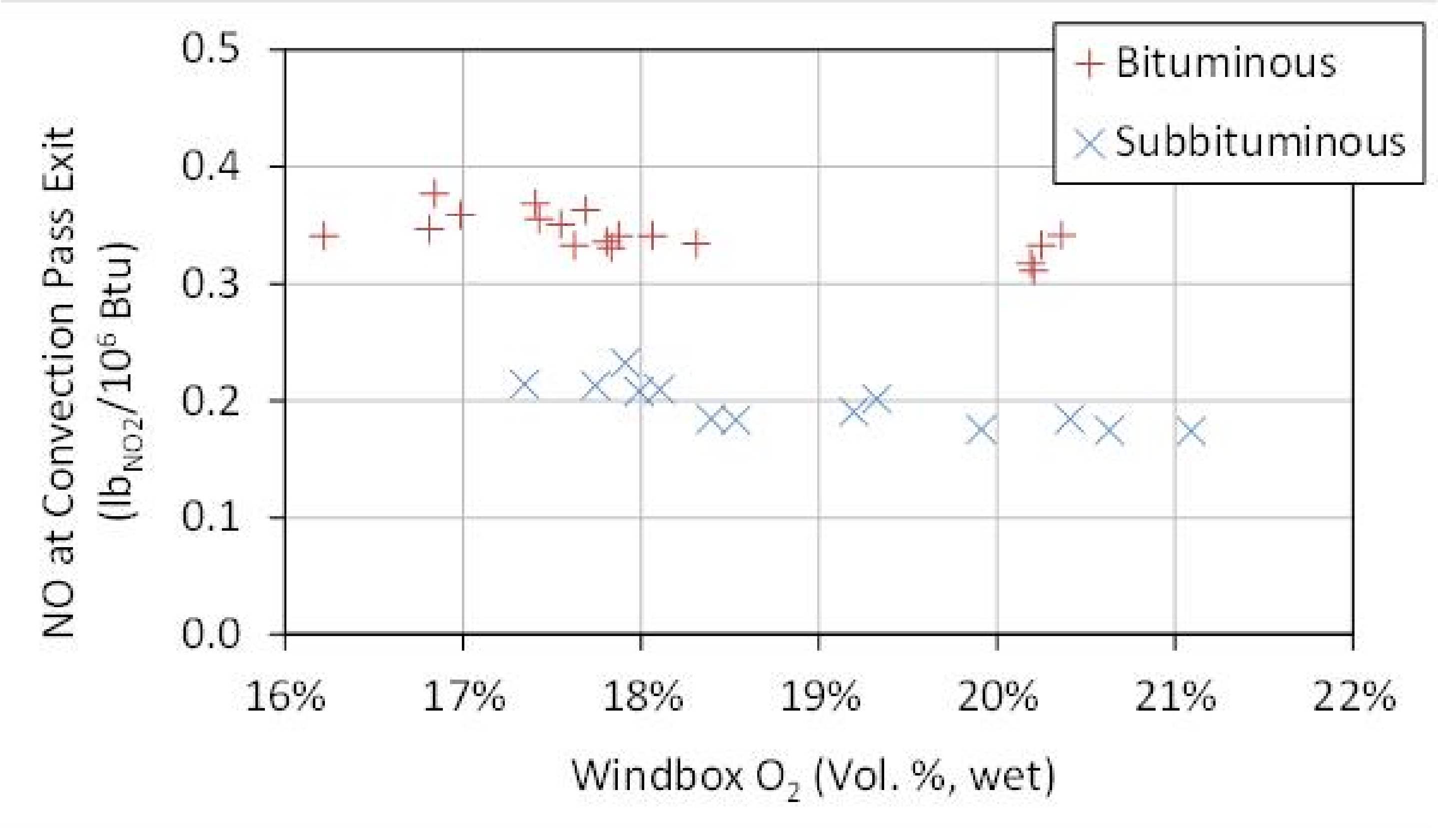
Influence of CO_2 Recycle on Pollutant Concentration: Carbon Monoxide



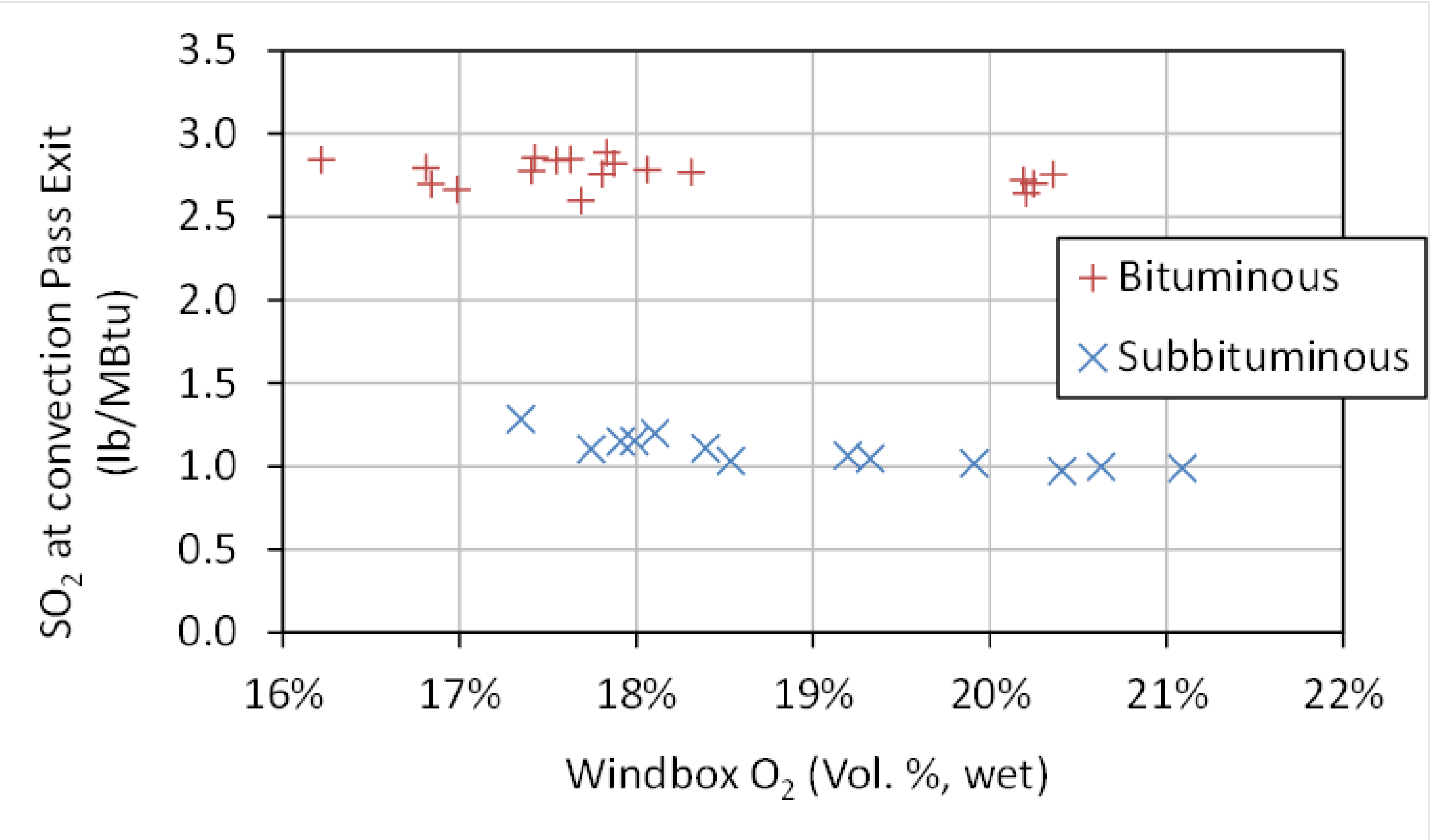
- Carbon monoxide levels at convective pass exit increased only at the lowest O_2 levels examined for bituminous coal
- At design levels of 18% O_2, CO levels were always acceptable for both coals

Influence of CO_2 Recycle on Pollutant Concentration: NOx



- NOx levels at the convective pass exit increased slightly over the O_2 range examined
- The slight NOx increase at low O_2 (high recycle) likely results from permeation of the sweep membrane and recycle to boiler

Influence of CO_2 Recycle on Pollutant Concentration: SO_2



- SO_2 levels at the convective pass exit increased slightly over the O_2 range examined
- Again, this is likely the result of permeation of SO_2 in sweep membrane and recycle to boiler

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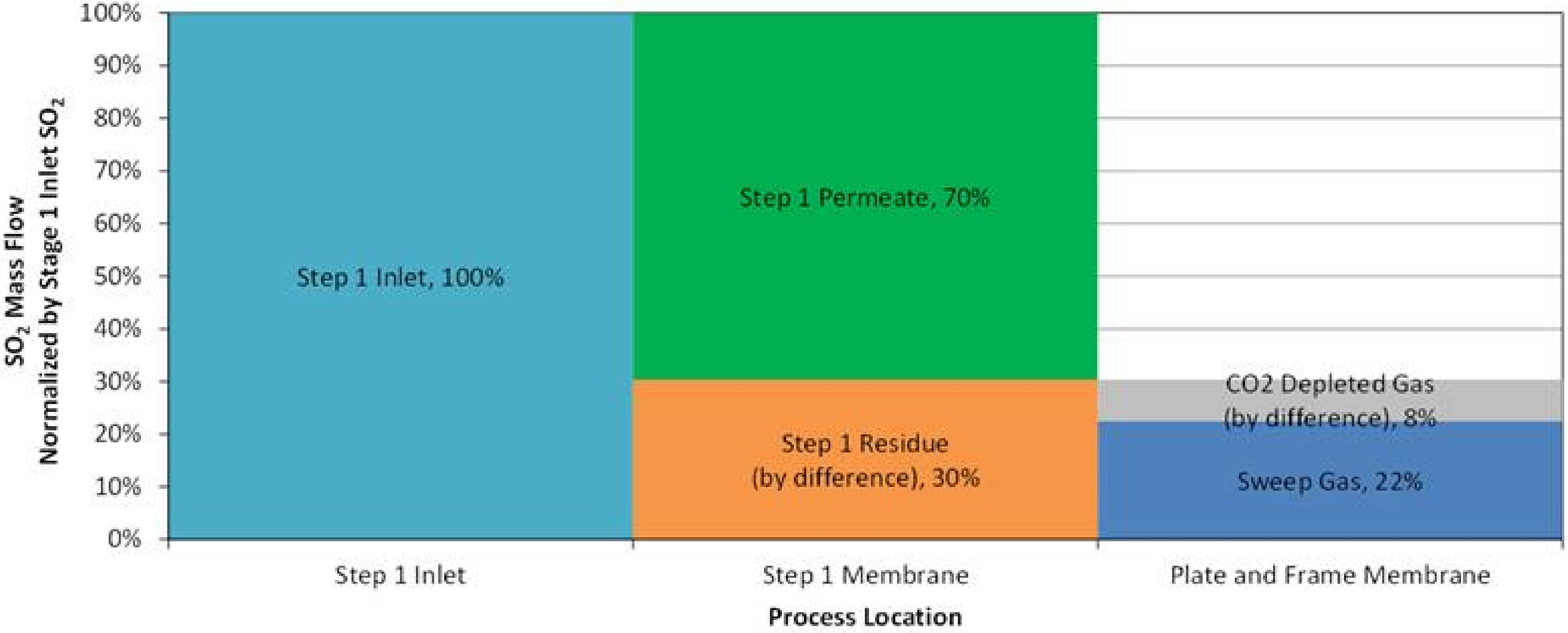
SO_2 Balance During Testing

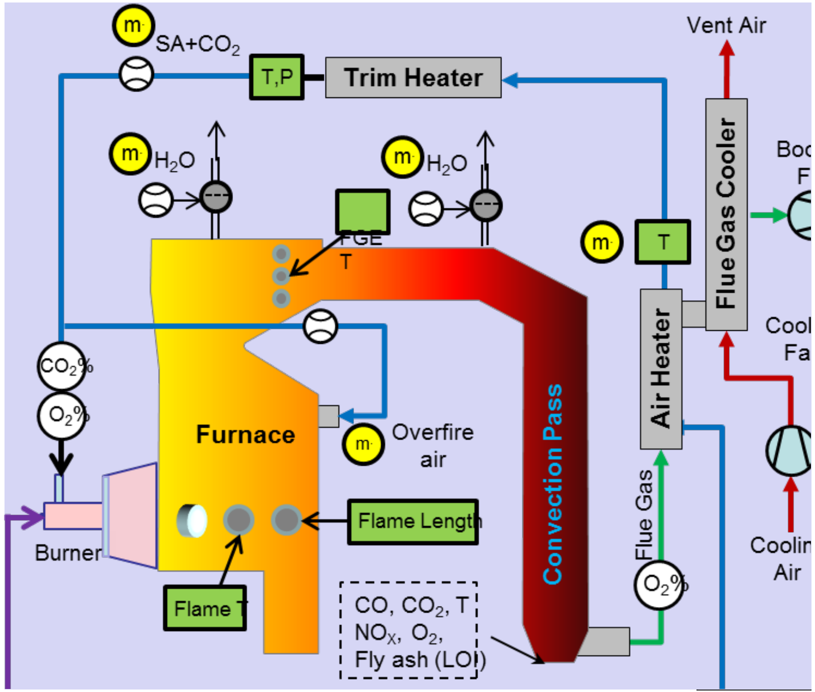


- Overall SO_2 removal by the membrane process is higher than CO_2 removal → co-capture?
- If not scrubbed in FGD, SO_2 cleanup from CO_2 is required in CPU (much like oxy-combustion)

Summary of CO_2 Recycle Impact on Heat Absorption

<u>Higher mass flow due to recycle results in the following observations:</u>

- Furnace heat absorption is lower with recycle
  - "Furnace" refers to the radiant heat transfer section of the boiler upstream of the tube banks in the convection pass.
- Convection pass heat absorption is higher
- Convection pass outlet heat flux is higher
- Air heater heat absorption is higher
- Air heater flue gas outlet heat flux is higher
- Total heat absorption is slightly reduced
- (numerical details on next slide)



Summary of CO_2 Recycle Impact on Heat Absorption

		Recycle	No Recycle
Test Name		Coal 30P M1 & M2	Coal 27P M2 Only
Date		20-Oct-16	18-Oct-16
Test Duration	(h:mm)	7:00	7:15
Fuel		PRB	PRB
Load	(MW)	1.5	1.4
FEGT	(°C)	1,179	1,259
Convection Pass Exit Temperature	(°C)	397	380
Air Heater Exit Temperature (Flue Gas)	(°C)	217	210
Membrane Secondary Air Ratio		**53%**	**0%**
Furnace Absorption	(MW)	0.52	0.66
Convection Pass Absorption	(MW)	0.96	0.91
Convection Pass Outlet Heat Flux	(MW)	0.50	0.43
Total Heat Absorption	(MW)	1.62	1.68
Air Heater Absorption	(MW)	0.19	0.16
Air Heater Outlet Heat Flux (Flue Gas)	(MW)	0.31	0.27

- For retrofit with no changes to absorption equipment, total heat absorption is lower for recycle cases (more heat leaves system in flue gas)
- This will cause a lower boiler efficiency (see next slide for details)

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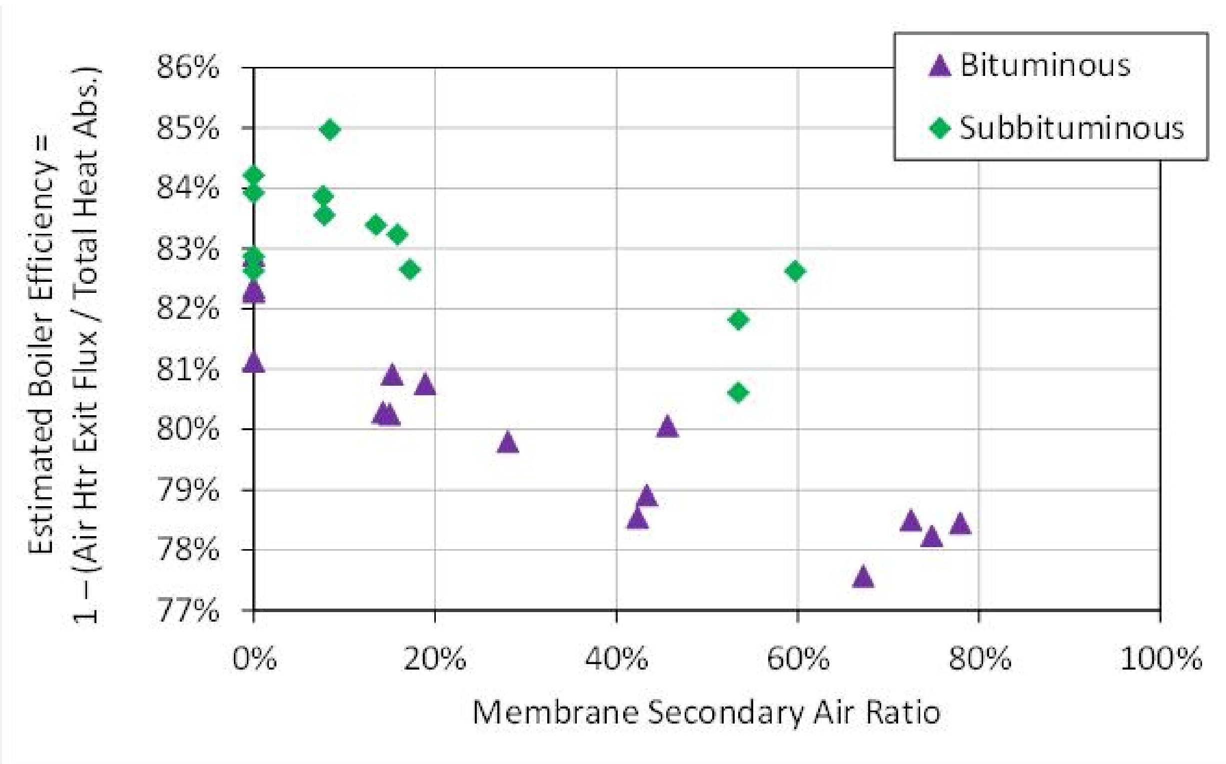
Impact of CO_2 Recycle on Boiler Efficiency



~2 to 4% boiler efficiency reduction at 90% capture for a retrofit

Corresponds to a 0.75 to 1.5% overall plant efficiency loss at 90% capture for a retrofit

Consistent with 0.75% overall plant efficiency loss used in MTR 90% capture TEA

Efficiency loss could be minimized with partial capture, modified boiler design, or higher selectivity membrane on sweep step

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Decommissioning and Site Restoration Activities: Summer 2017

- MTR visited in March and April to coordinate decommissioning activities
- All skids decommissioned and removed from site by June 2017

- Skids currently located at Canton Erectors in Canton, OH (indoor storage)

Final Decommissioning and Site Restoration Activities

- Site Restoration Activities at B&W:
  - Skid foundation tapered
  - Coal clean-up and removal
  - Clean-out of furnace
  - Furnace refractory inspection and patching

Analysis of Membrane Modules

Polaris Plate and Frame Sweep Modules

- The plate and frame sweep modules tested at NCCC were removed prior to testing at B&W; their post-test performance is summarized below and is consistent with "as-made" Gen 2 Polaris
- Autopsies of these modules showed them to be in pristine condition; sweep step is "protected" by the capture step, so no obvious fouling or contaminants
- New plate and frame modules tested at B&W are now being installed at UT Austin for Hybrid project testing

Membrane Stamp	CO_2 permeance (gpu)	α CO_2/N_2
1	1480	53
2	1500	46
3	1720	48
4	1670	48
5	1640	49
6	1540	44
Average	**1600**	**48**

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Post-Test Analysis of Membrane Modules

Polaris Spiral Wound Modules from B&W and NCCC

- Module faces showed more fouling than plant-and-frame modules
- Nevertheless, relatively clean compared to commercial returns

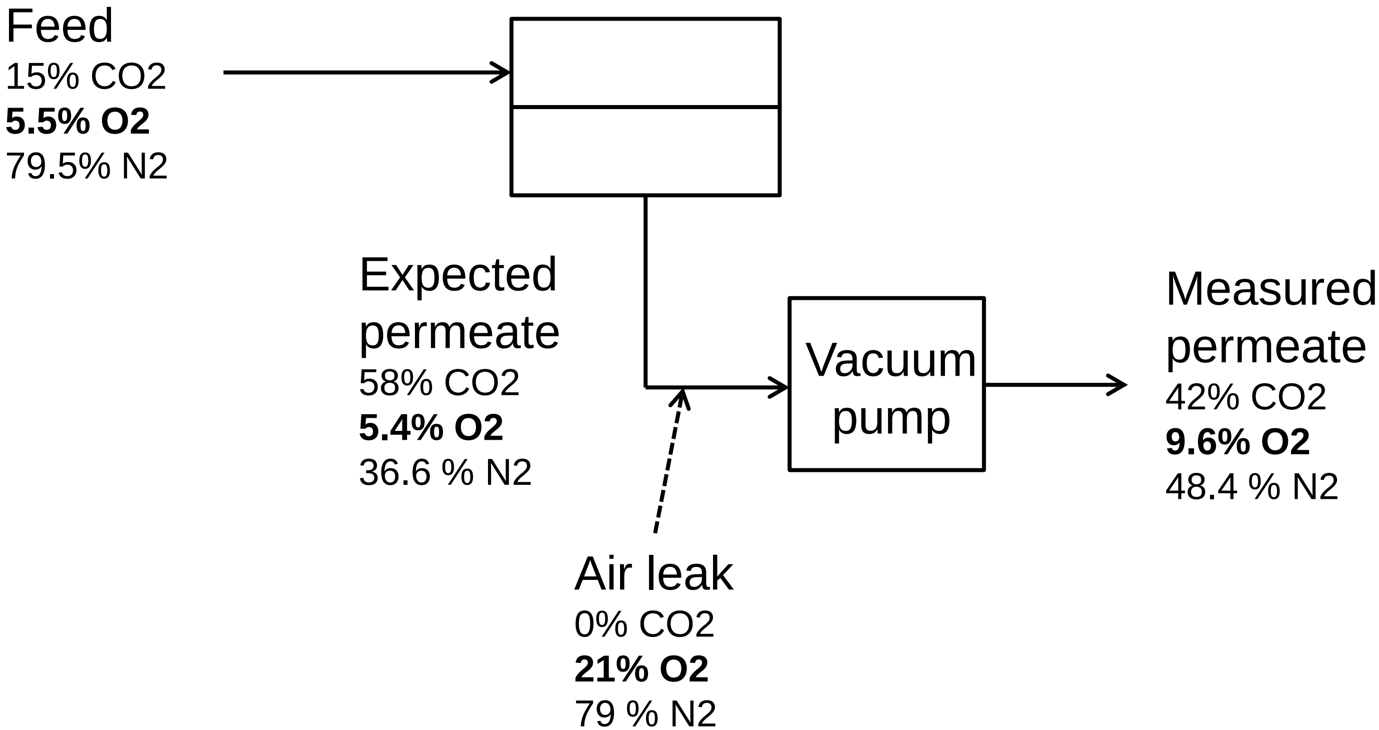
Post-Test Analysis of Membrane Modules

Polaris Spiral Wound Modules from B&W Field Test

Module Location	Before Field Test		After Field Test		After Field Test and 1 week Under Vacuum at 50°C	
	CO_2 (gpu)	CO_2/N_2	CO_2 (gpu)	CO_2/N_2	CO_2 (gpu)	CO_2/N_2
1A	820	58	670	60	770	57
6A	780	54	690	59	810	61

- After testing at B&W, Polaris modules showed lower permeances, but still good selectivities
- CO_2 permeance was mostly recovered after vacuum treatment at MTR to remove condensables (water vapor) in microporous membrane support
- This water condensation issue did not affect performance at B&W, it is an artifact of shutdown conditions often seen in commercial returns
- Good performance indicates modules did not develop leaks at NCCC or B&W and they are not the source of relatively low CO_2 content in permeate

Post-Test Analysis: Air Infiltration



- The measured permeate CO_2 concentration was lower than expected based on NCCC performance; also, O_2 concentration was much higher than expected
- The measured O_2 permeate concentration cannot be explained by permeation or even a direct leak of feed to permeate; most likely explanation is infiltration of air into the vacuum line
- Mass balance suggests air leak flowrate of ~15% of permeate flow

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Project Summary

- The MTR small pilot membrane system was successfully integrated with the B&W SBS-II boiler and operated with CO_2 recycle to the boiler
- The integrated system responded almost immediately to changes in operating set points or shutdowns, demonstrating the simplicity and flexibility of membrane-based CO_2 capture
- A stable combustion flame was obtained for all windbox oxygen concentrations examined (17 – 21%)
- Compositions of windbox oxygen and convection pass CO_2 during CO_2 recycle with a membrane were generally consistent with process simulations
- There was minimal impact of CO_2 recycle on combustion pollutant formation (CO, SO_2, NO_x). The membrane system removed SO_2 from flue gas at a greater rate than CO_2, offering a co-capture possibility

Project Summary (Cont)

- CO_2 capture rates of 65% to 90% were achieved by varying the percentage of secondary air sent to the sweep membrane
- With CO_2 recycle, heat absorption was shifted from the furnace to the convective pass/air heater
- For retrofits, heat absorption is slightly reduced when using recycle
- As a result, at the highest sweep rates examined, corresponding to 90% capture, there is a 2 – 4% reduction in boiler efficiency due to CO_2 recycle
- This is equivalent to a 0.75 to 1.5% overall plant efficiency loss, with the lower value being consistent with prior TEA studies of the MTR process
- As sweep flowrate (and capture rate) is decreased, the efficiency loss decreases in a roughly linear manner

Project Summary (cont)

- Post-test analysis of returned Polaris modules showed them to be in good condition, although build-up of contaminants had started on the front face of the first step spiral modules.
- This type of contaminate collection will need to be monitored in future tests for potential flow obstruction (and pressure drop increase).
- Module performance was consistent with initial values confirming that relatively low permeate CO_2 purity measured at B&W was not due to module leaks
- Module results and modeling indicate that air infiltration into the vacuum line was the source of low permeate CO_2 content; piping and connections under vacuum in future test systems should be minimized to prevent dilution of purified CO_2.

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Recommendations for Future Work

- A site-specific engineering study is recommended to evaluate the potential benefits of changing pressure parts on existing boiler to minimize efficiency losses and the risk of increased tube erosion with increased gas velocity through the boiler
- Update TEA with measured boiler efficiency as a function of capture rate (subtask in TCM Advanced Polaris project)
- At capture rates <90%, existing fans might be able to move sweep gas through the system; evaluate possible cost savings and optimal sweep flow/capture rate (subtask in TCM Advanced Polaris project))
- Purification requirements for the captured CO_2 should be evaluated due to membrane system's ability to capture SO_2 along with CO_2 (task in TCM Advanced Polaris project)

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Acknowledgements

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  - Jennifer Sivy
  - Andrew Mackrory

DOE-NETL Visit to B&W – Oct. 20, 2016