Membrane Technology & Research

Pilot Test Results from a Polaris^{TM} Membrane 1 MW_e CO_2 Capture System

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Carbon Management Technology Conference

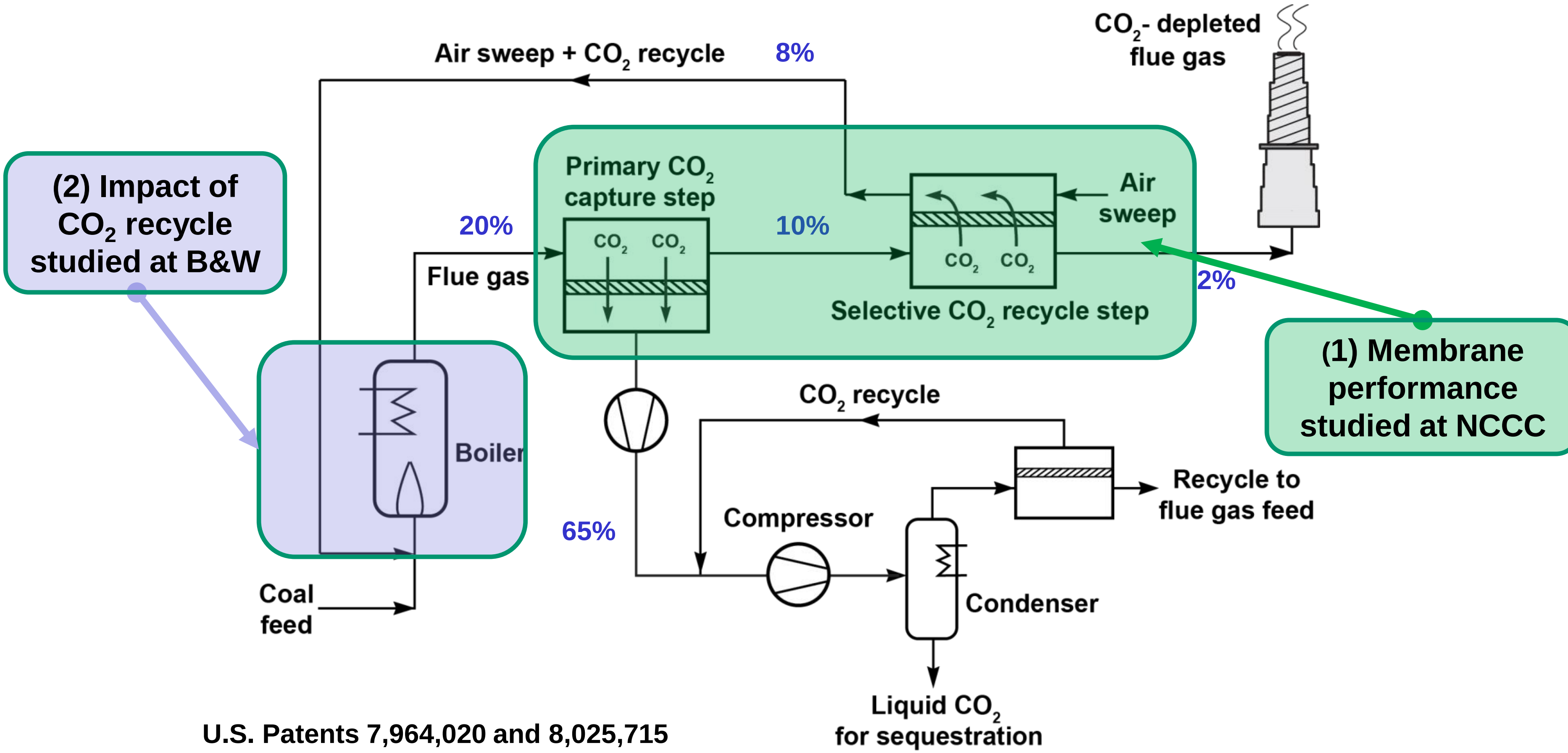
Houston, TX

Wednesday, July 19, 2017

MTR Introduction

- Privately-held, 60 employees mostly located in Newark, California
- Started in 1982 funded by U.S. SBIR grants
- Commercial products in petrochemical, natural gas and refinery industries
- Provides complete turn-key solutions with over 200 membrane systems installed worldwide
- 15 person R&D group with expertise in membrane materials/formation and process design

Background: MTR CO_2 Capture Process



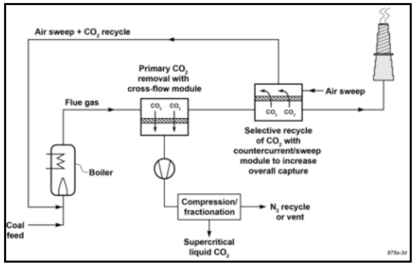
U.S. Patents 7,964,020 and 8,025,715

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

MTR CO_2 Capture Development Timeline

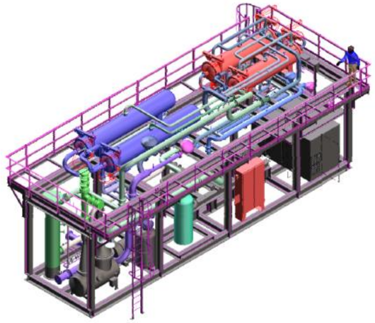
Feasibility study (DE-NT43085)
- Sweep concept proposed
- Polaris membrane conceived



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

APS Cholla 0.05 MW_e Demo (DE-NT5312)
- First Polaris coal flue gas test
- 1 TPD CO_2 captured (50 kW_e)

NCCC 1 MW_e Demo (DE-FE0005795)
- 11,000 hours of 1 TPD system operation
- 1,500 hours of 1 MW_e (20 TPD) system operation



Low Pressure Mega Module (DE-FE0007553)
- Design and build a 500 m^2 optimized module

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

B&W Integrated Test

Future 10 MW_e Large Pilot

2006		2008		2010		2012	2014		2016	2018		2020	
	TRL3		TRL4			TRL5		TRL6			TRL7		TRL8

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Pros and Cons of a Membrane Post-Combustion Capture Process

Benefits:

- No hazardous chemical handling, emissions, or disposal issues
- Not affected by oxygen, SO_x or NO_x
- Water use lower than other technologies (recovers H_2O from flue gas)
- No steam use → no modifications to existing boiler/turbines
- Near instantaneous response; high turndown possible
- Modular and compact; relatively simple installation/operation
- Particularly well-suited for partial capture (40-60%)

Challenges:

- Very low partial pressure driving force favors high permeance membranes
- Unknown impact of real flue gas on membrane-module lifetime
- Module pressure drop and flow distribution issues

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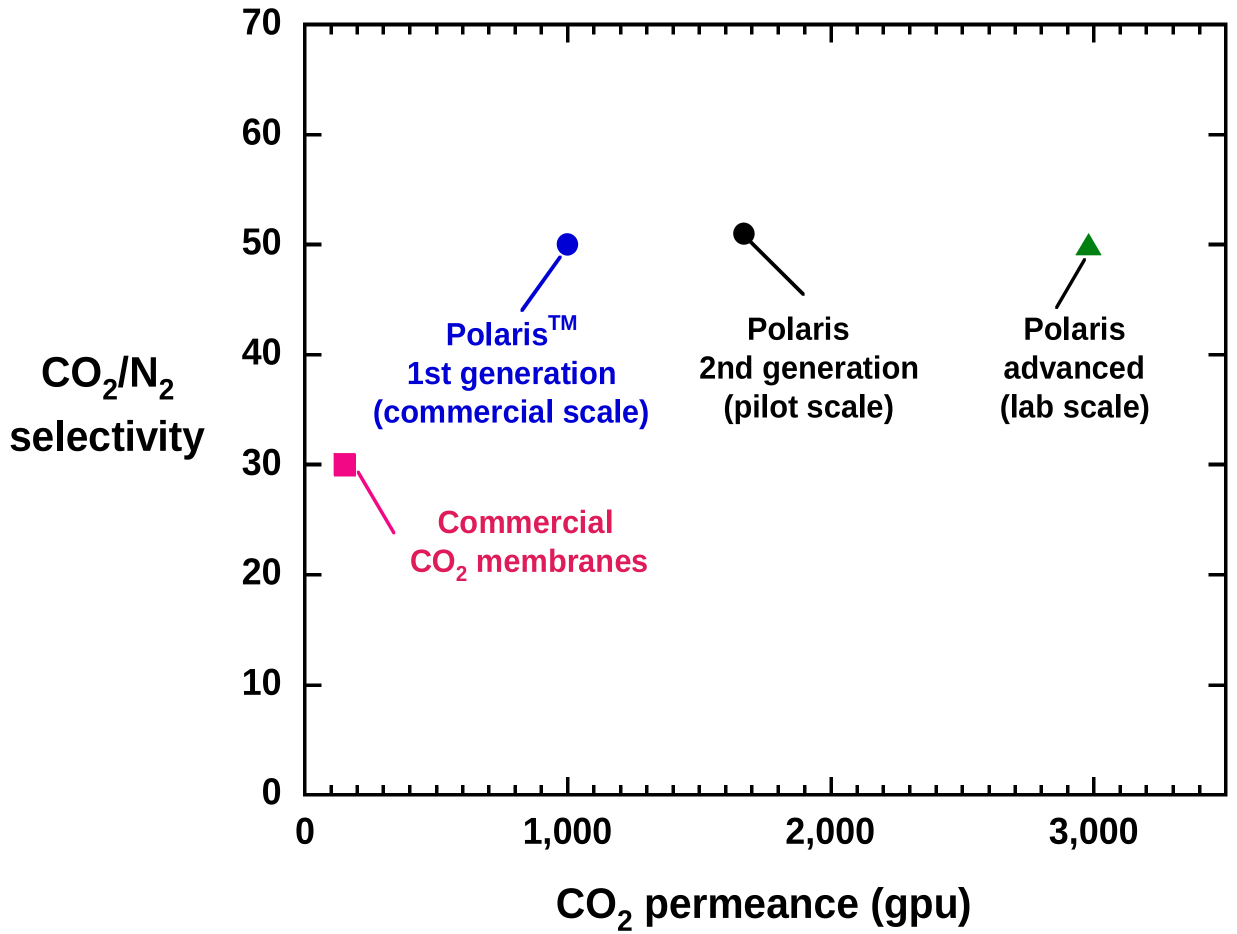
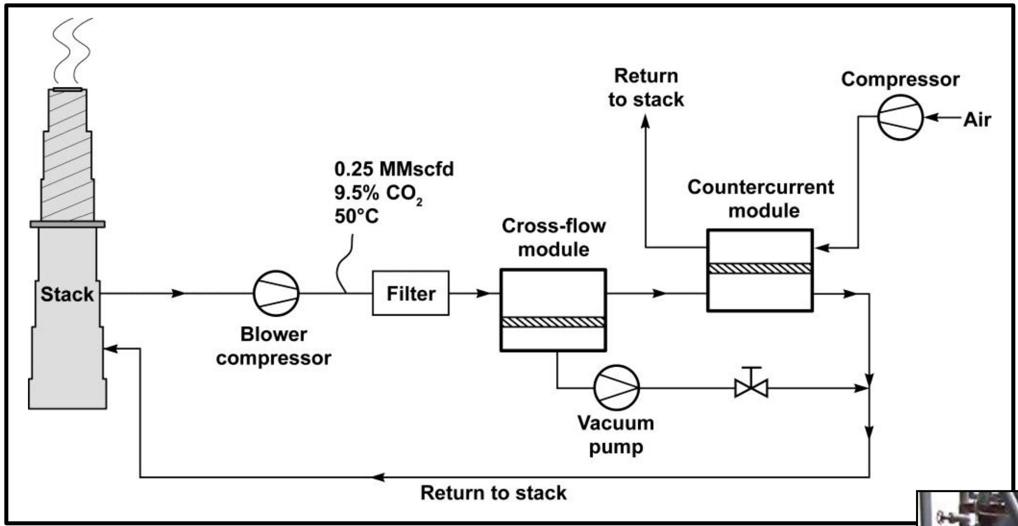
Polaris™ Membranes Continue to Improve



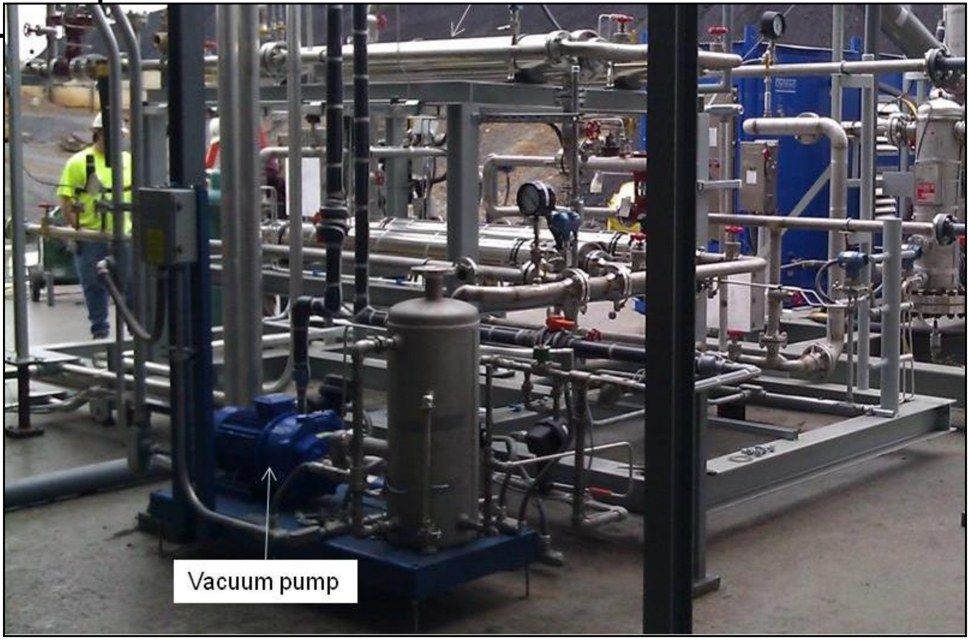
1 gpu = 10^{-6} cm^3(STP)/(cm^2 s cmHg)= 3.35 x 10^{-10} mol/(m^2 s Pa)

- In addition to lowering costs, these improvements are important to shrink the size of the capture system

0.05 MW_e (1 TPD) Testing at NCCC



- Field laboratory that allows lifetime evaluation (>11,000 hours cumulative), and validation testing of new membranes
- Many lessons learned (i.e., ammonium sulfate deposition) applied to scale up



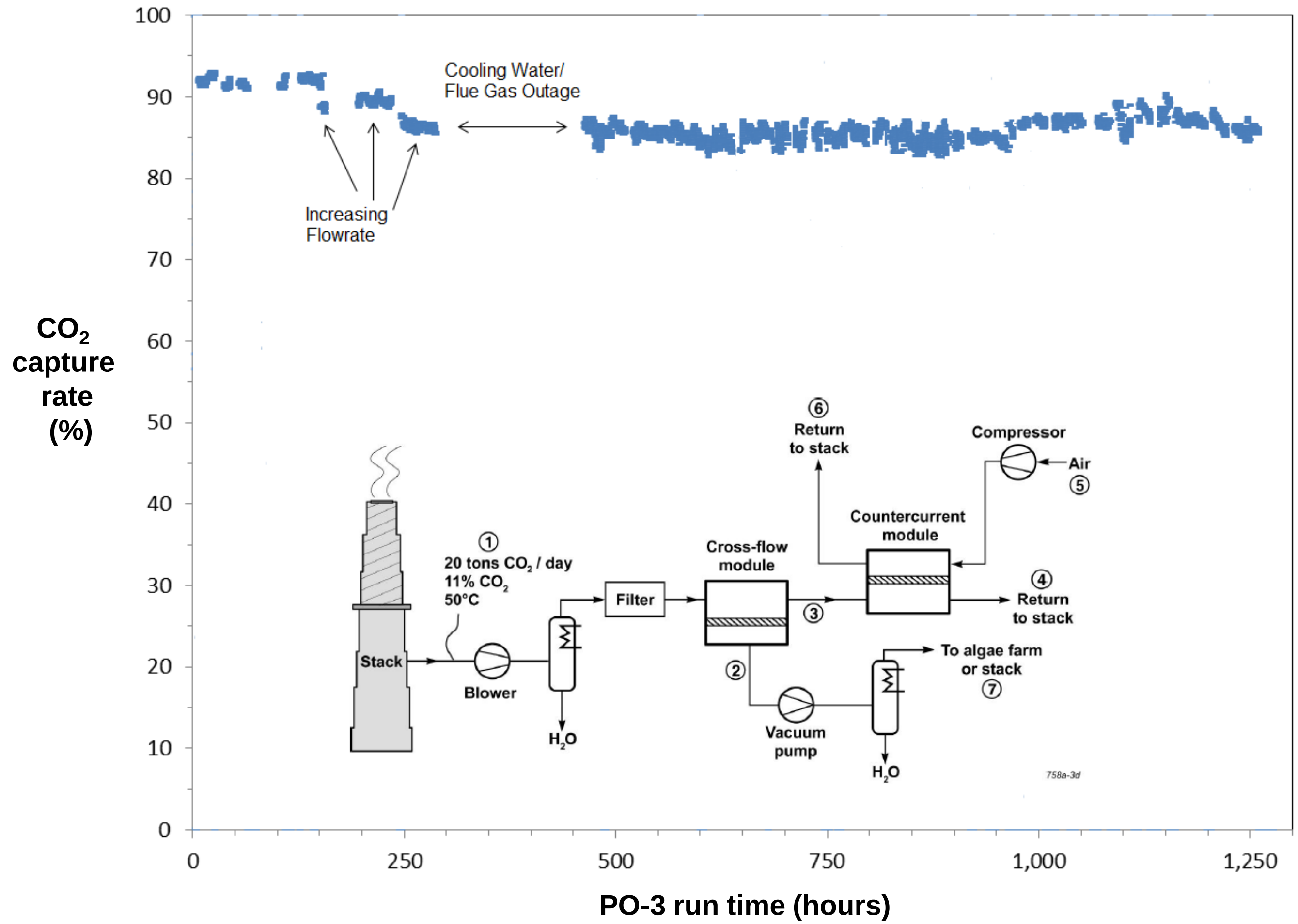
- System is testing vacuum and air sweep membrane steps
- Sized to capture 1 ton CO_2/day using commercial sized module
- System was in operation from Spring 2012 through Summer 2015

1 MW_e (20 TPD) System at NCCC

- System installation completed Aug 2014
- Operation during January – June 2015
- Decommissioned in July 2015

- System showed stable performance over 1,500 hours of operation, including demonstration of prototype low-pressure drop plate-and-frame sweep modules

1 MW_e System Shows Stable Performance



- System operated in slipstream mode (no recycle to boiler) with varying ambient conditions (sub-freezing in January to >95°F in June)
- 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)

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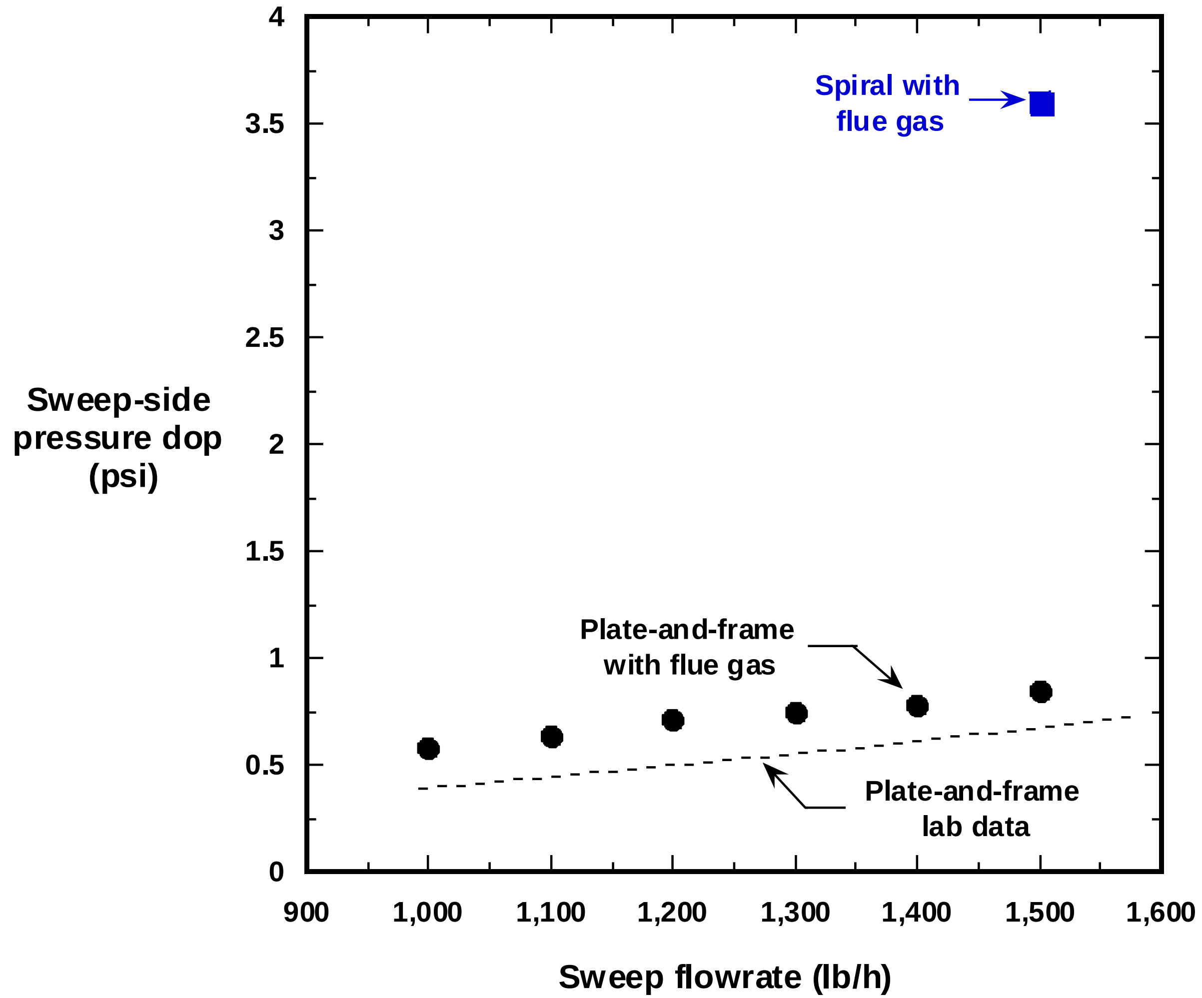
New Modules Demonstrate Improved Pressure Drop Performance

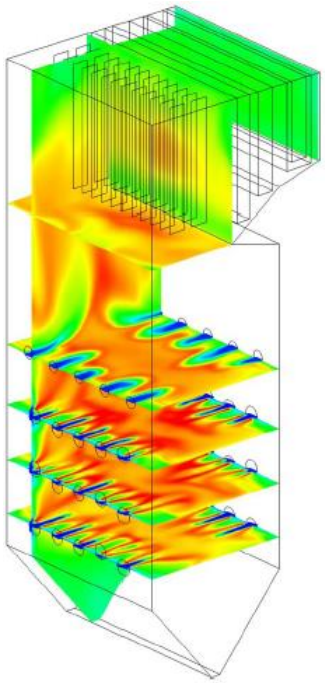


- Field data is consistent with lab results, and confirms much lower air sweep pressure drop in new modules
- At full scale, the difference in pressure drop amounts to savings of about 10 MW_e

B&W Studies of CO_2 Recycle Impact on Boiler Performance

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)
- Main conclusion of modeling study: 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

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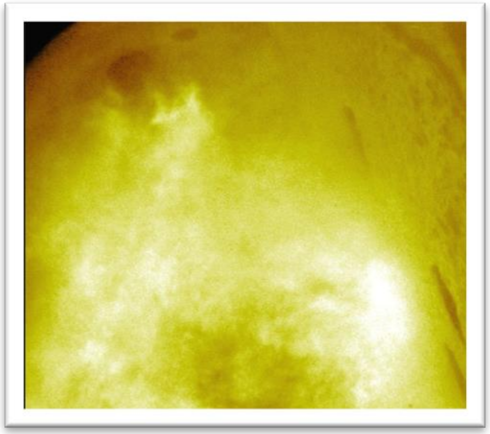
B&W Boiler Study Highlights

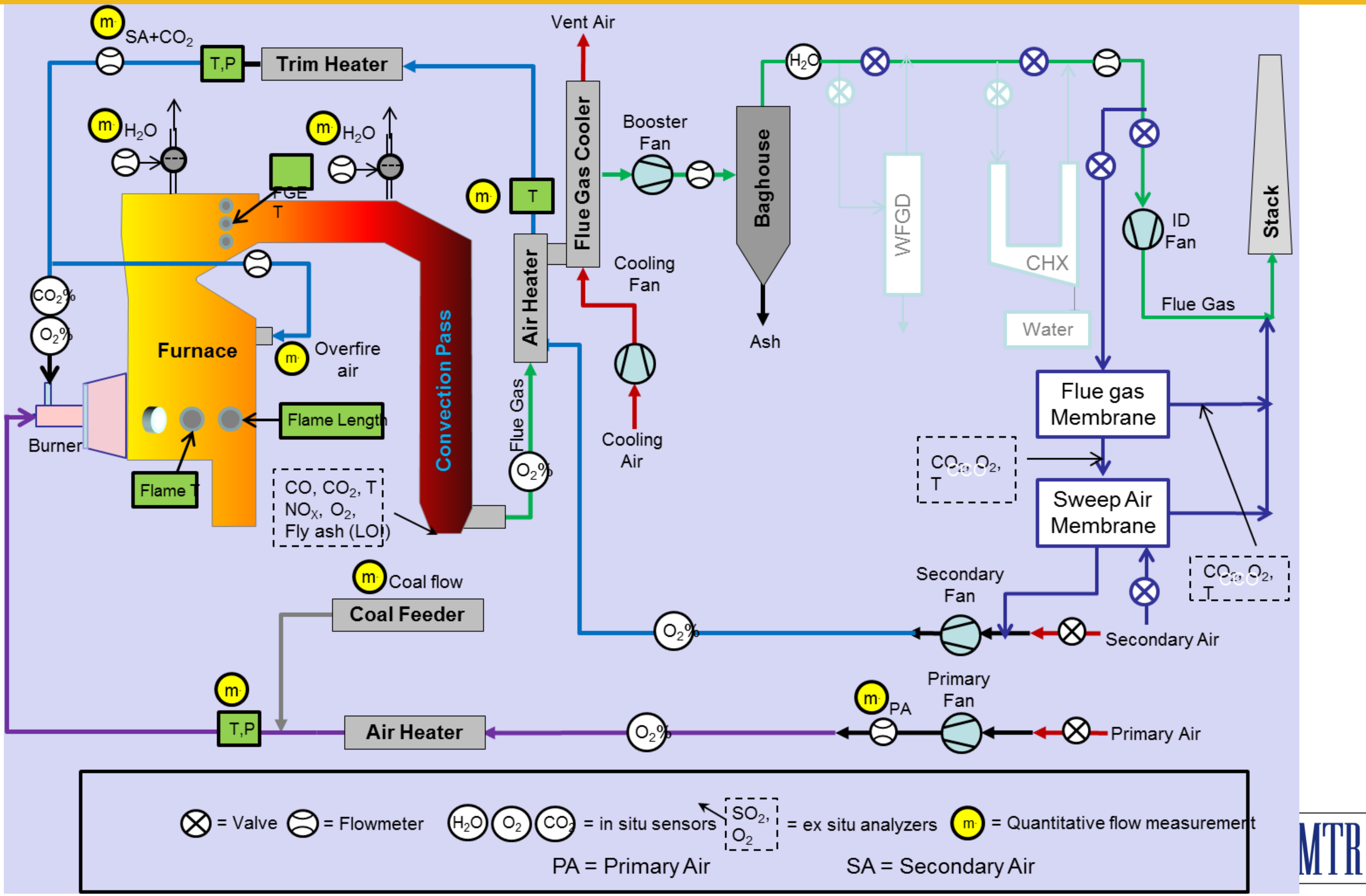
- Stable and attached flames with air (21% O_2) and CO_2-enriched air (16-18% O_2)
- CO_2-enriched flame was less luminous than air-fired case
- Lower furnace heat absorption but higher convection pass/air heater heat transfer for CO_2-enriched operation relative to air
- For bituminous coal, 30% lower 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)

B&W Pilot Boiler / Membrane Schematic



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

Skid arriving at B&W →

← Installation of 2nd floor

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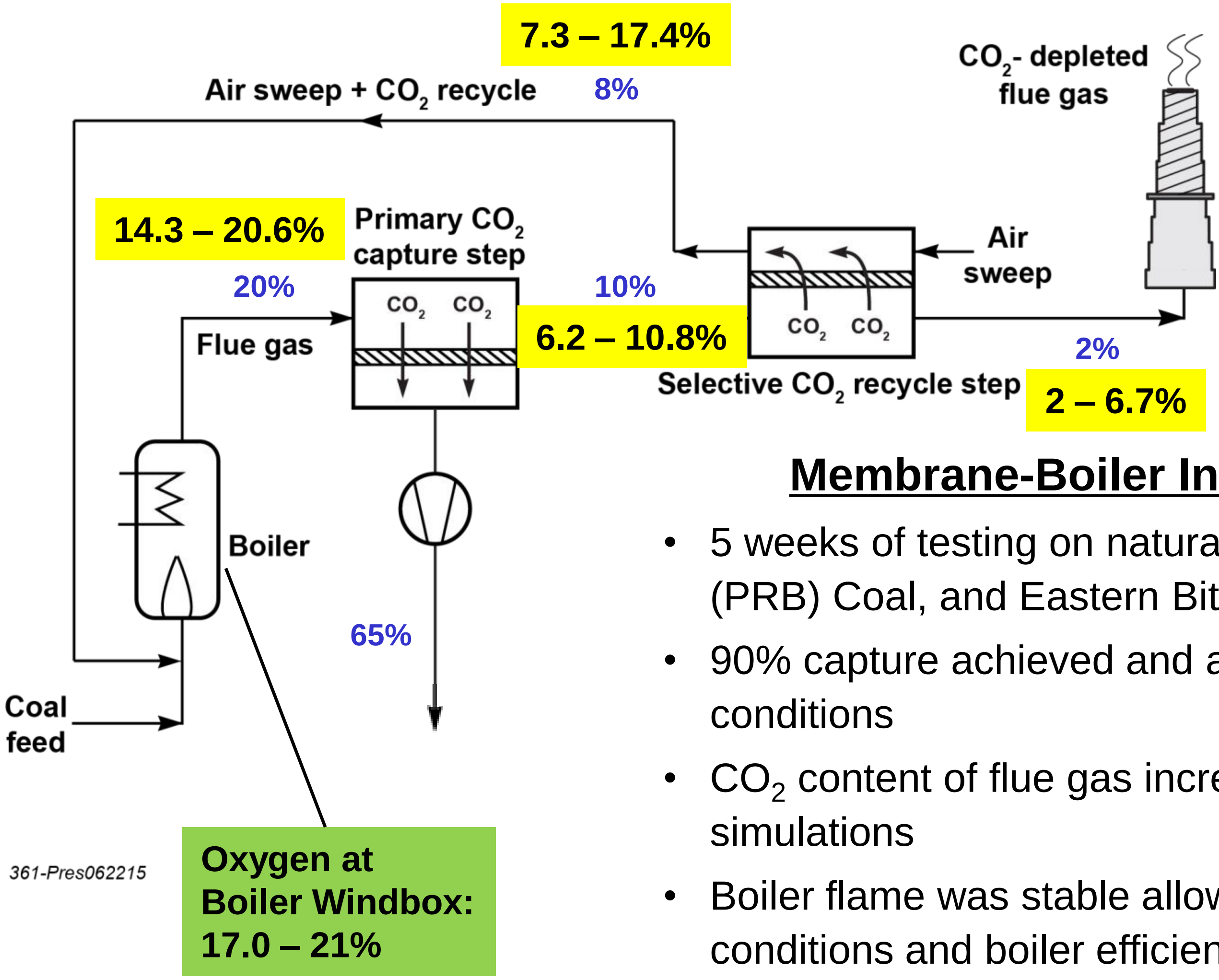
MTR Skids at B&W's SBS-II Research Facility

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

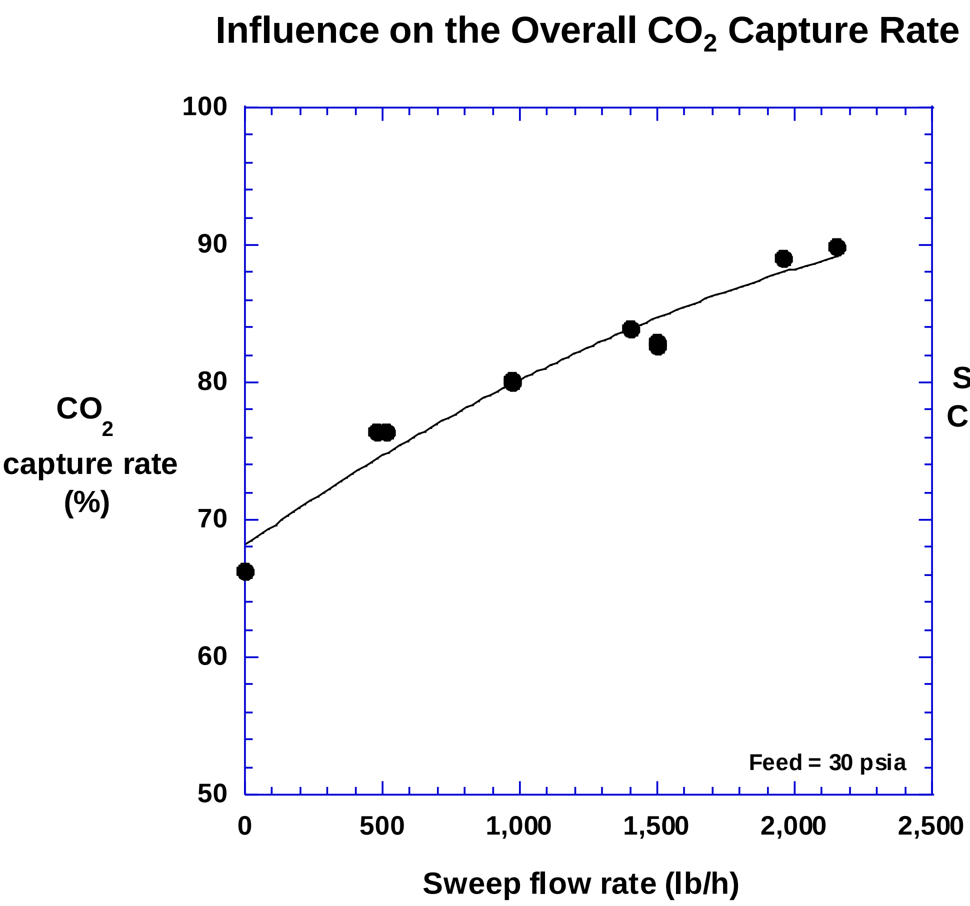
Sample Results from B&W Integrated Tests

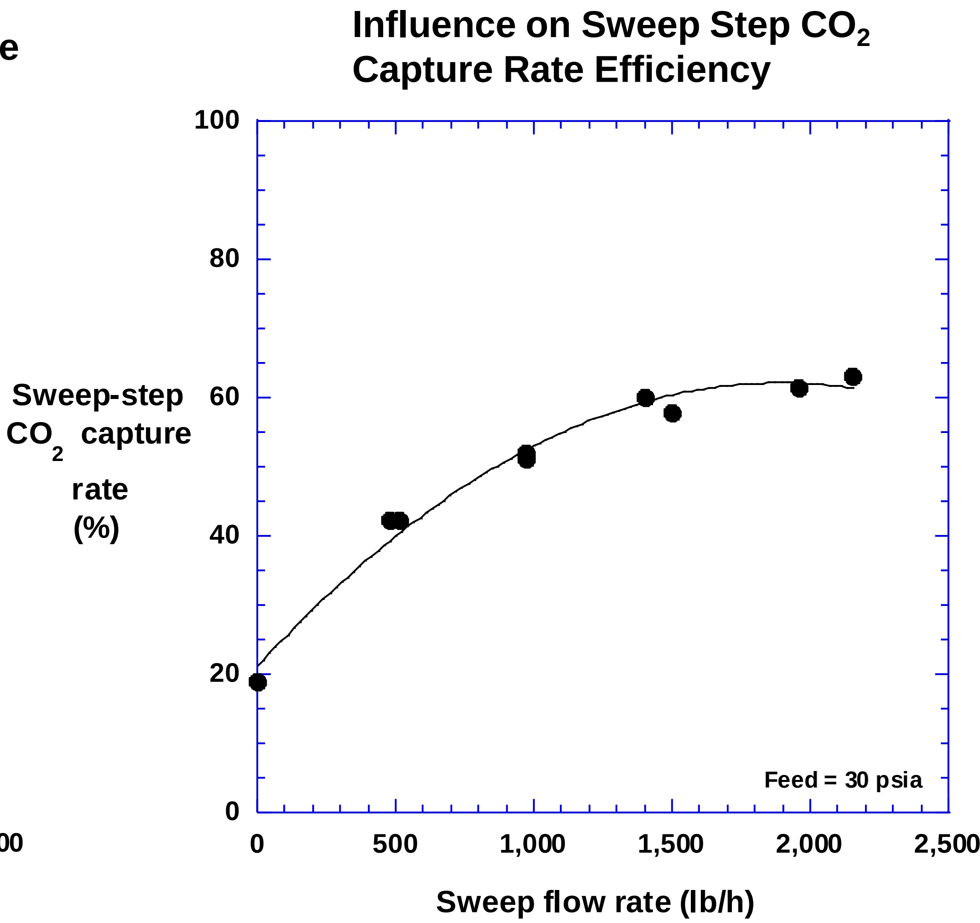


Membrane-Boiler Integrated Test Plan

- 5 weeks of testing on natural gas, Powder River Basin (PRB) Coal, and Eastern Bituminius Coal
- 90% capture achieved and a variety of partial capture conditions
- CO_2 content of flue gas increased as expected in simulations
- Boiler flame was stable allowing a full battery of stream conditions and boiler efficiency measurements to be conducted (analysis is ongoing)

1 MW_e System Sweep Flow Rate Parametric Results from Integrated Tests





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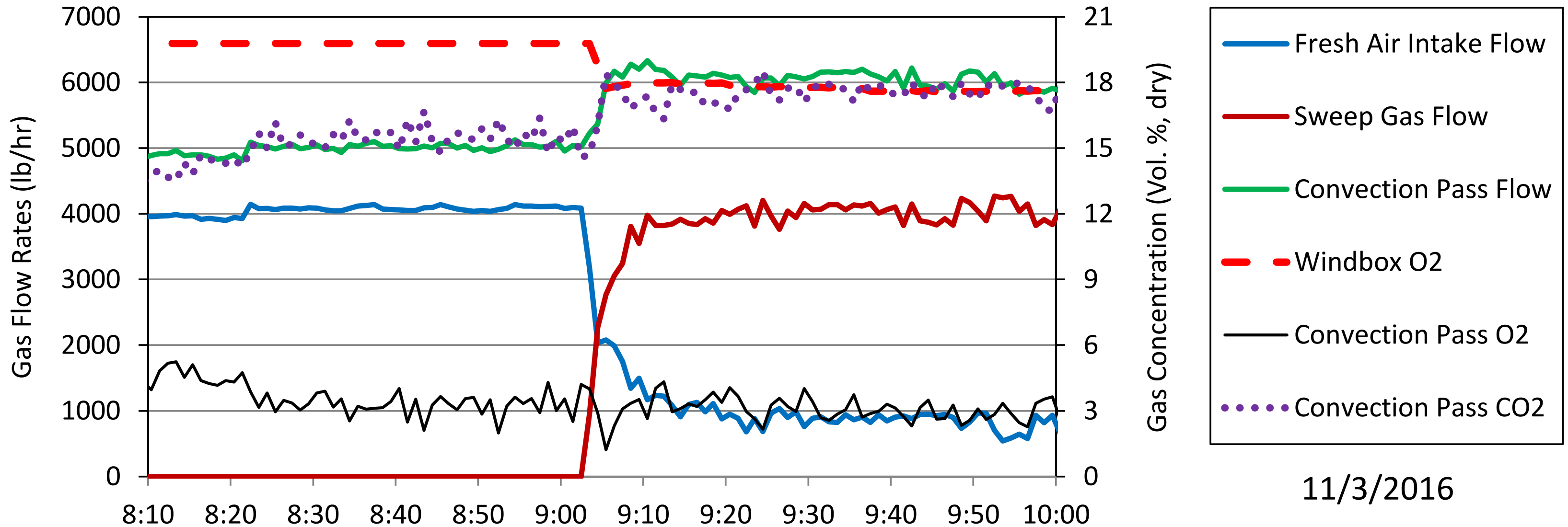
Integrated Boiler/Membrane Systems Transition Response



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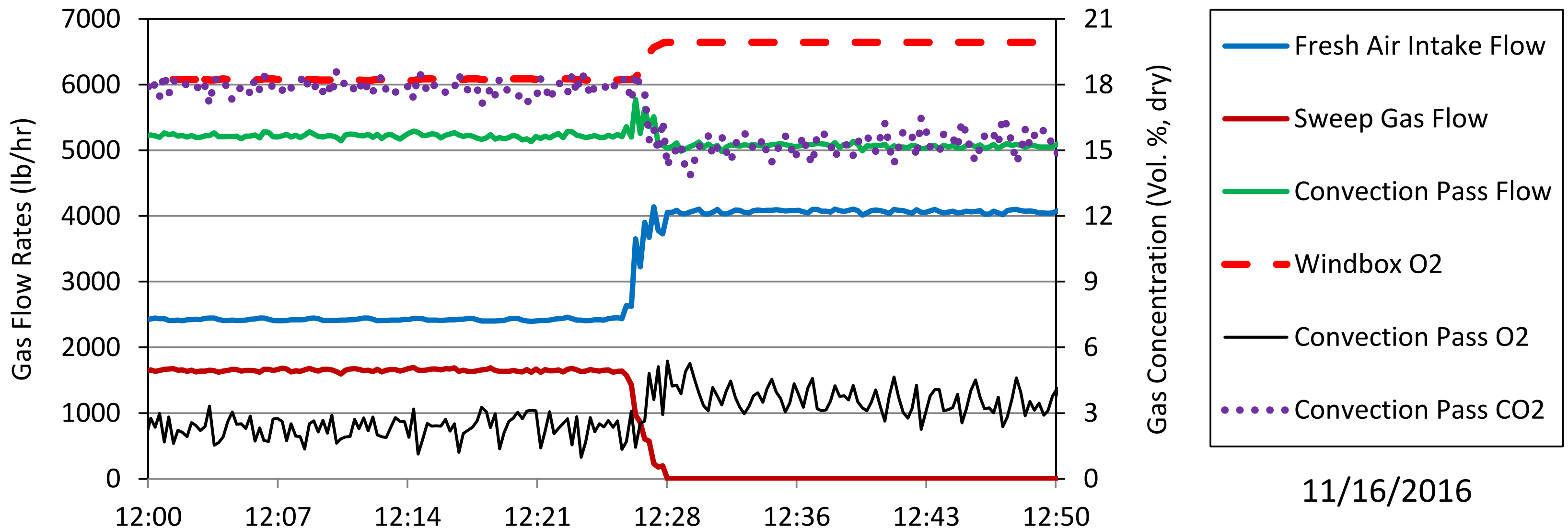

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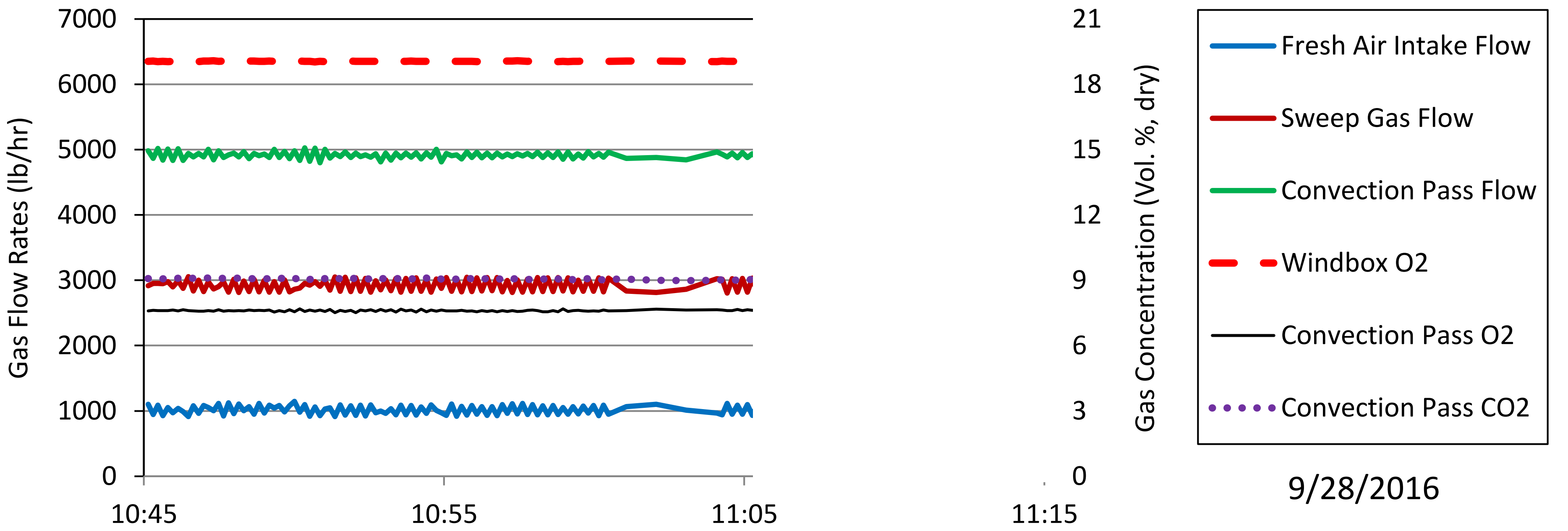
Integrated Boiler/Membrane Systems Transition Response to E-Stop



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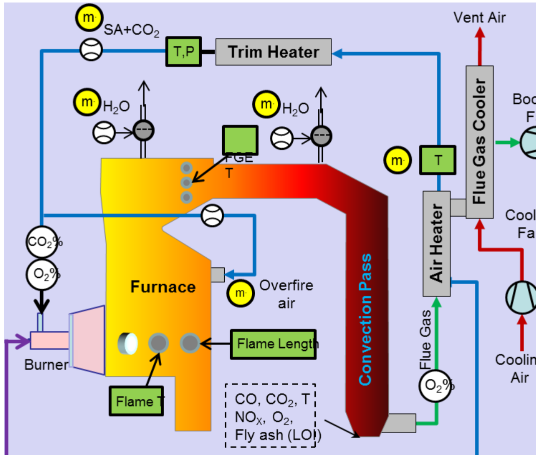
B&W's Analysis of CO_2 Recycle Impact on Boiler Operation

- Furnace heat absorption is lower resulting
- "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

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



Summary

- CO_2 capture membrane performance continues to improve and has been validated on the 0.05 MW_e slipstream system with over 11,000 hours of runtime at NCCC
- 1 MW_e small pilot operation at NCCC was completed in 2015. Testing successfully demonstrated optimized modules (low Δp, low cost) with over 1,500 hours of runtime
- 1 MW_e small pilot was successfully integrated with the B&W research boiler for five weeks of integrated testing with CO_2 recycle to the boiler in late 2016
- The integrated membrane-boiler field test experimentally validated simulated system performance
- Boiler flame was stable throughout parametric testing allowing a full battery of stream conditions and boiler efficiency measurements

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Acknowledgements

- **U.S. Department of Energy,**

National Energy Technology Laboratory

  – José Figueroa
  – Mike Mosser

- **Southern Company Services (NCCC)**
  – Tony Wu

- **Babcock & Wilcox**
  – Hamid Farzan
  – Jennifer Sivy
  – Andrew Mackrory