Pilot Testing of a Membrane System for Post-Combustion CO_2 Capture

DE-FE0005795

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DOE Review Meeting

April 25, 2014

Outline

- Project overview and BP1 background
- Review of BP2 accomplishments and BP3 plans:
  - Membrane development
  - Module testing on 1 TPD system
  - 20 TPD system installation update
  - 2nd Gen sweep module update
  - B&W boiler testing
  - Industrial CO_2 test
- Summary

MTR

Project Overview

Award name: Pilot testing of a membrane system for post-combustion CO_2 capture

Project period: 10/1/10 to 9/30/15

Funding: $15 million DOE; $3.75 million MTR

DOE program manager: José Figueroa

Participants: MTR, Babcock & Wilcox, SCS/NCCC, EPRI, Vectren, Helios

Project scope: Demonstrate a membrane process to capture 20 tons of CO_2/day (TPD) from a flue gas slipstream of a coal-fired power plant.

Project plan: The key project work organized by budget period is as follows:

- BP1 – Membrane optimization though continued slipstream testing on the 1 TPD system and computational evaluation of sweep recycle with B&W
- BP2 – Design and construction of the 20 ton/day system, boiler testing at B&W with CO_2-laden air; membrane/module optimization and durability testing through continued testing on 1 TPD system
- BP3 – 6-month pilot test of the 20 ton/day system; comparative economic analysis; industrial 1 TPD field test

Timeline of Major Project Tasks

FY2011	FY2012	FY2013	FY2014	FY2015
BP1	BP2		BP3	

Optimize Process Design and Complete Systems/Economic Analysis
- In BP1, complete preliminary systems and economic analysis
- In BP2 and 3, evaluate new designs and update economic analysis

Continue Membrane Optimization on 1 TPD System
- Run continuous tests at NCCC
- Improve membrane/module performance
- Collect membrane lifetime data

Boiler Recycle Study
- Evaluate CO_2 recycle with B&W
- Computer modeling in BP1; boiler testing in BP2

Design/Install/Operate 1 MW Demo (20 TPD)
- Design, build, and install the 20 TPD system at NCCC in BP2
- Run 6 month test in BP3, including P&F sweep module developed in project 7553

Industrial CO_2 Capture Test
- Field test CO_2 capture from syngas
- Conduct economic analysis based on test results

Note: all testing to finish by 4/1/15; remaining 6 months for reporting and closeout

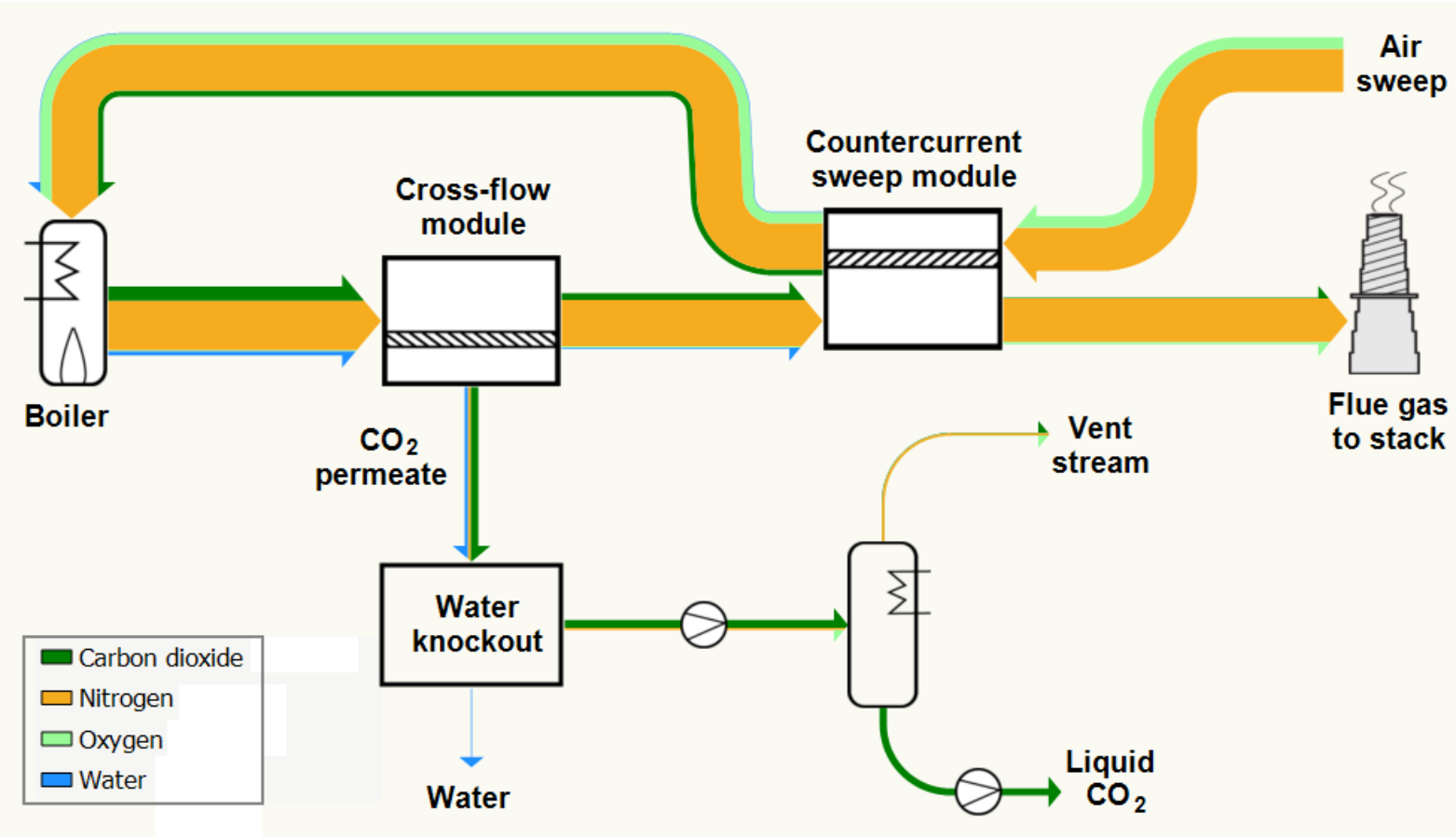
As of 3/31/14, project is 70% complete

Current Status

As of March 31, 2014:

- All budget period 2 milestones achieved except sweep pressure drop target (actual = 0.3 bar vs 0.2 bar target. Lab tests indicate P&F module can reach target)
- A topical report on B&W boiler testing with CO_2-laden air was submitted to DOE in Dec 2013
- Budget period 3 continuation application submitted
- 20 TPD system fabrication completed and installation / commissioning is underway at NCCC
- Industrial CO_2 test site selected and system design finalized
- All BP2 DOE allocation spent ($7,948,502); overall project is 73% costed; cumulative MTR cost share at 22%
- Current TRL = 5; end of project TRL = 6

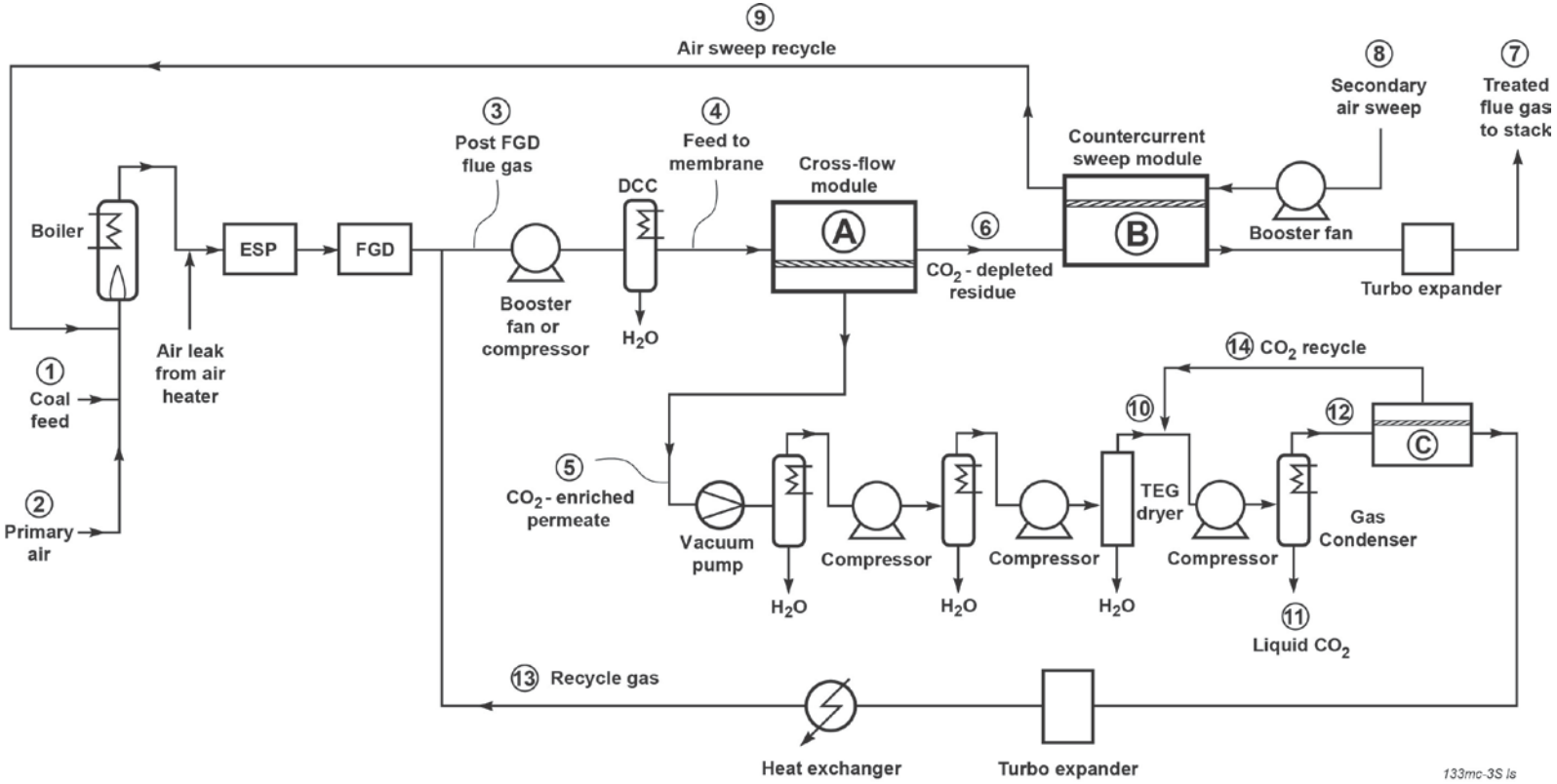
Background: MTR CO_2 Capture Process



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

- Combustion air sweep provides driving force that lowers the capture energy
- Pre-concentrated CO_2 decreases membrane area and power required

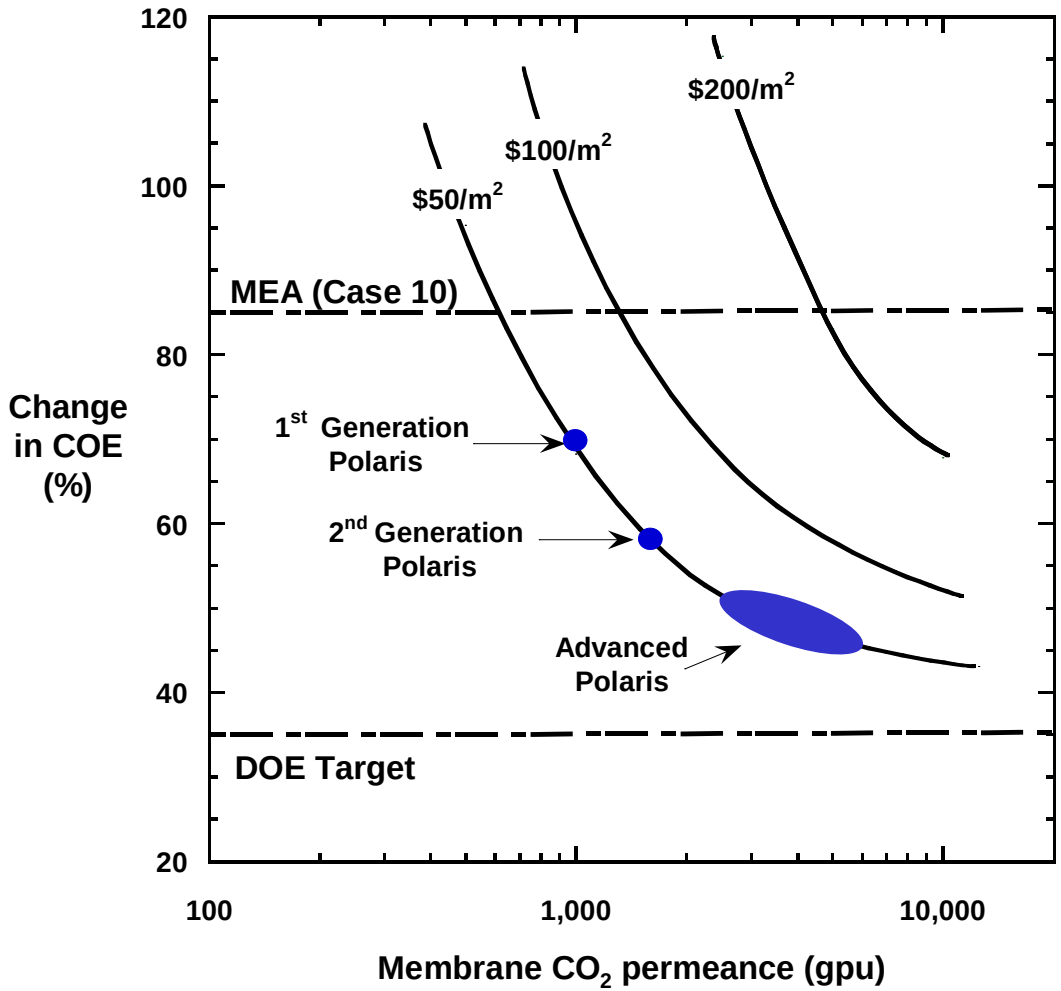
Systems Analysis: Process Flow Diagram



Two cases examined:

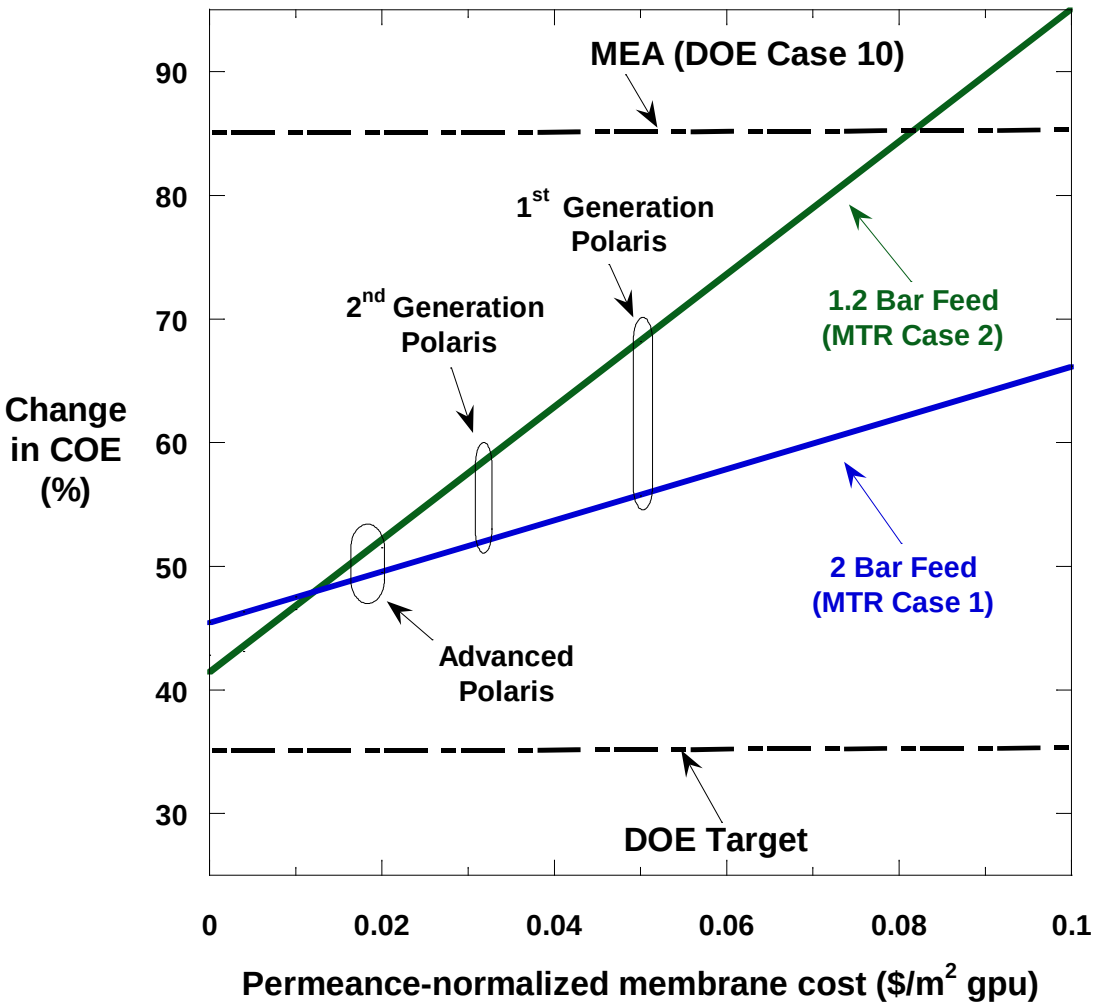
- 1.2 bar feed pressure (booster fan only): simple, but more membrane area
- 2.0 bar feed pressure (single stage compression): less membrane area, but compressor challenges

Systems Analysis: Importance of Membrane Improvements



- Study completed in BP1 to meet a project milestone
- All calculations for 90% CO_2 capture use Bituminous Baseline report methodology
- Higher permeance (lower cost) membranes are key to approaching DOE goals
- Results are generally consistent with independent findings reported in DOE report "Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture" (DOE/NETL-2012/1557)

Systems Analysis: Effect of Membrane Performance and Pressure



- For expensive and/or low permeance membranes, some feed compression is beneficial to reduce COE
- For high permeance, low cost membranes, no compression (fan only) is preferred
- the lowest COE is achieved with minimal feed compression and high performance membranes

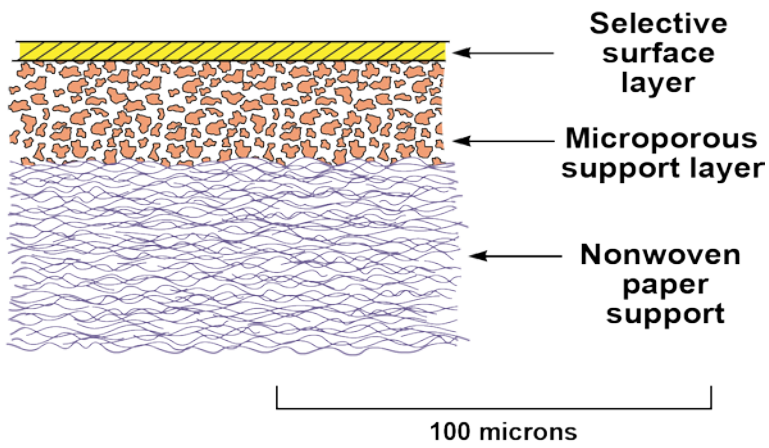
At $50/m^2, $0.1/(m^2 gpu) = 500 gpu, $0.02 /(m^2 gpu = 2500 gpu

Membrane Development

Why is higher membrane permeance important?

- Higher permeance means less membrane area is required, so system cost is reduced
- For low feed compression cases, membrane costs are a significant fraction of overall system cost and increase in LCOE
- Membrane permeance also has a direct effect on system footprint – a parameter not captured by LCOE; Double the permeance → halve the footprint
  - High permeance, relatively expensive membrane (say 2,000 gpu and \$100/m^2) is better than low permeance, cheap membrane (1,000 gpu and \$50/m^2); Membrane cost will be similar for this example, but high permeance membrane will have smaller footprint

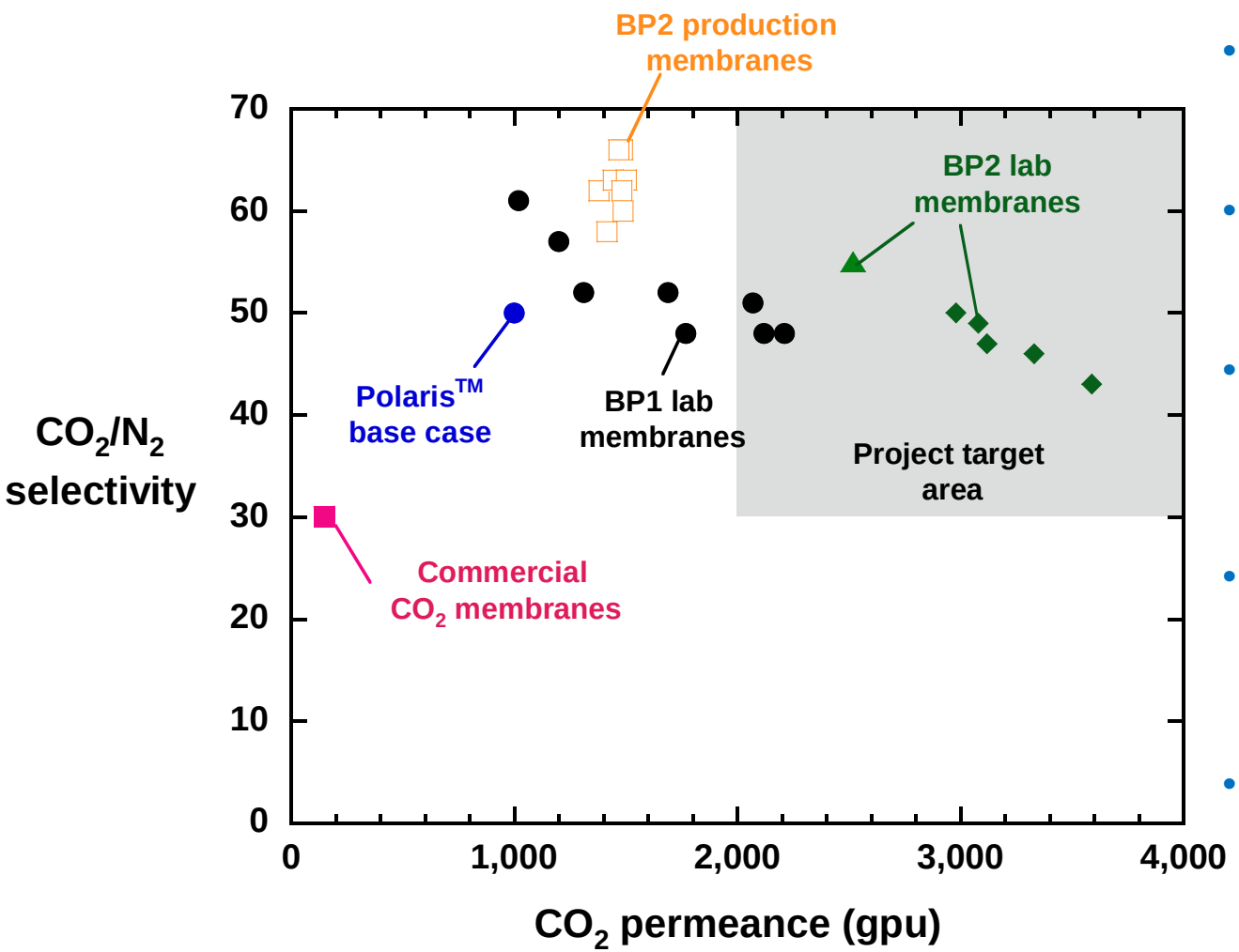
Membrane Development Strategy



- Polaris is a multi layer composite membrane.
- As the selective layer becomes thinner (and more permeable), resistance to flow in the support layers starts to impact performance.

- To overcome this issue, the standard approach is to make the support more “open” so that it offers less resistance.
- However, a more open support can be more difficult to coat with thin layers and may lose mechanical stability.
- These practical fabrication issues make it a lot harder to produce a high flux membrane than simple math would suggest (i.e., Permeance = Permeability divided by thickness, so 1,000 Barrer / 0.1 microns = 10,000 GPU).

Membrane Performance Improvements



- Recent lab membranes show CO_2 permeance up to 3,500 gpu and CO_2/N_2 > 40.
- These results illustrate the potential to make advanced high flux membranes.
- However, the current support is unstable and requires further development.
- For this project, 2nd gen membranes of 1,500 gpu are available at production scale.
- For nth plant, advanced membranes with >2,500 gpu will be available at scale.

Pure-gas data at 25°C and 50 psig feed pressure; 1 gpu = 10^{-6} cm^3(STP)/(cm^2 s cmHg)

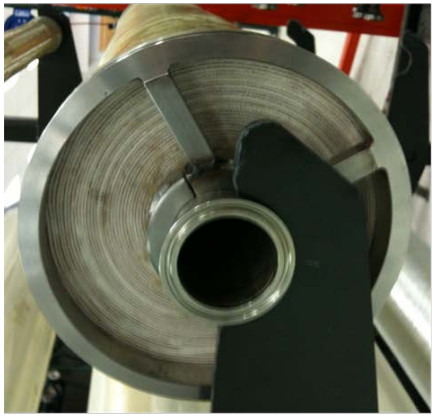
Cost Reduction Progress

- Permeance-normalized cost target
  - At start of project: Installed module cost ($500/m^2) / CO_2 permeance (1000 gpu) = $0.5/(m^2 gpu)
  - Project target: $0.1/(m^2 gpu)
- Achieved 60% reduction in the installed module cost (to $200/m^2)
  - Use of low-cost plastic components (20%)
  - Membrane casting/coating machine improvements (15%)
  - Automated module trimming (5%)
  - Use of multi-insert module vessels *(20%)*
- Combined with higher permeance membranes reaches project target
  - 1,500 gpu on a mass production scale → 200/1500 = $0.13/(m^2 gpu)
  - 2,500 gpu on a lab scale → 200/2500 = $0.08/(m^2 gpu)
- Ultimate goal is advanced membranes at low cost
  - 2,500 gpu with mass production costs → 50/2500 = $0.02/(m^2 gpu)

Cost Reduction Examples

Low cost components

(a) Stainless steel seal carrier



(b) Plastic seal carrier

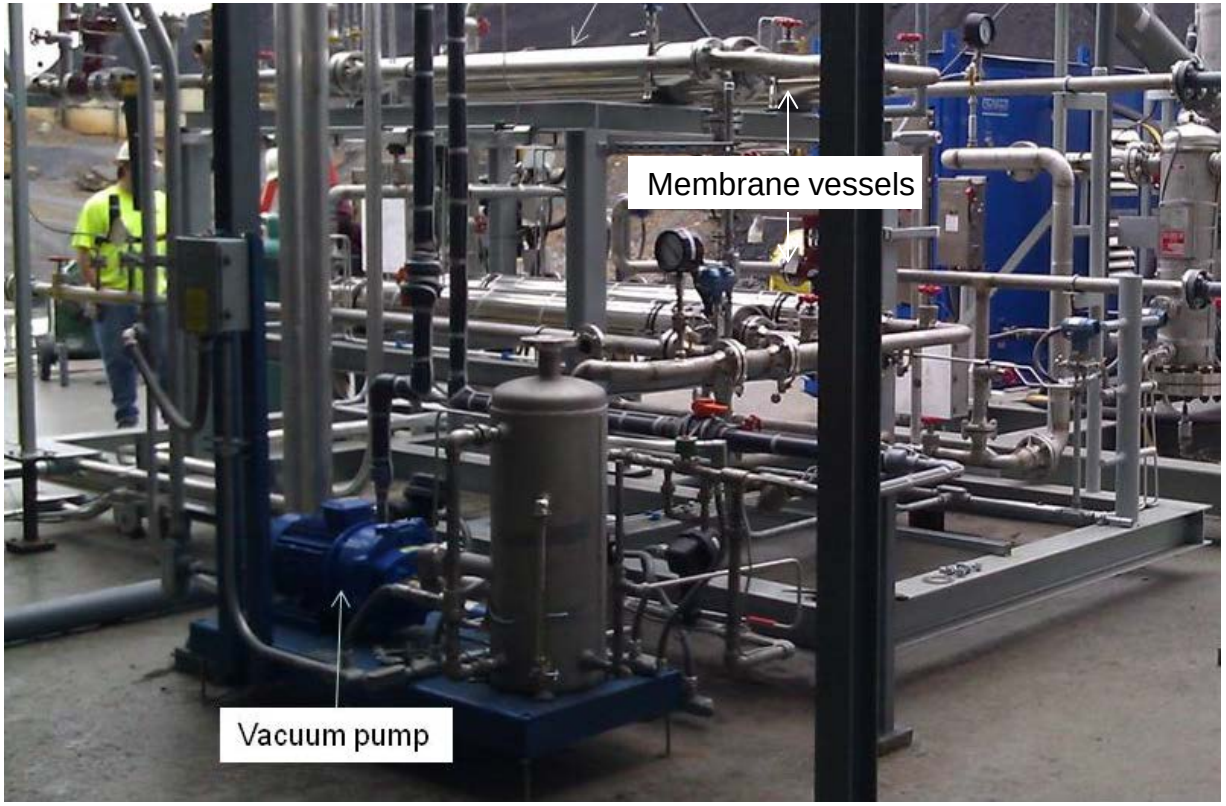
Multi-tube modules

Membrane casting/coating improvements

Automated module trimming

Validation Testing at NCCC

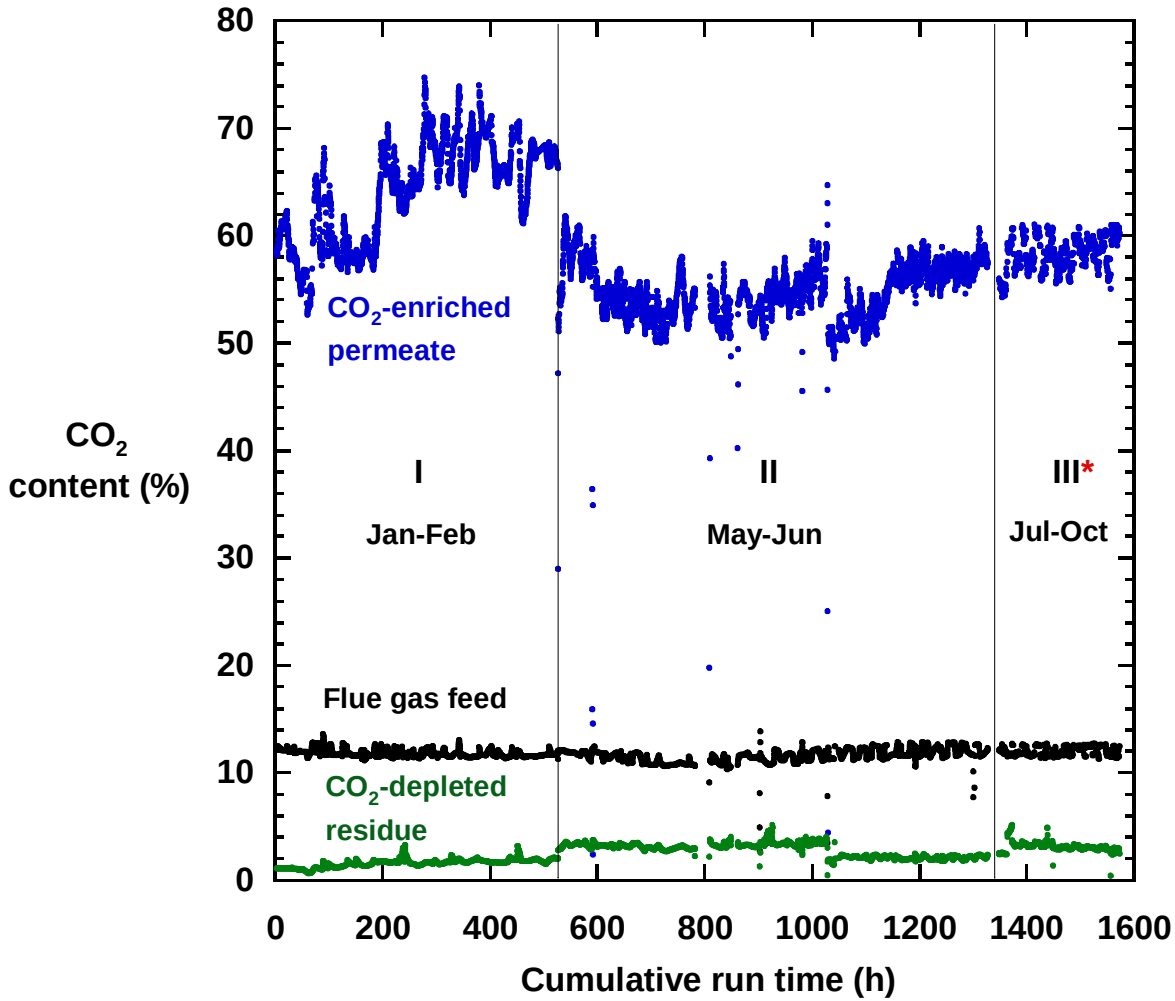
1 TPD System at NCCC



- System is testing vacuum and air sweep membrane steps
- Sized to capture 1 ton CO_2/day
- Individual modules have 3000 hours of operation w/o performance decline
- Now validation testing 2nd generation Polaris modules and monitoring lifetime of base modules

System reliability improved dramatically in 2013 after installation of liquid ring compressor in Dec 2012

2013 Test Results at NCCC with Coal Flue Gas

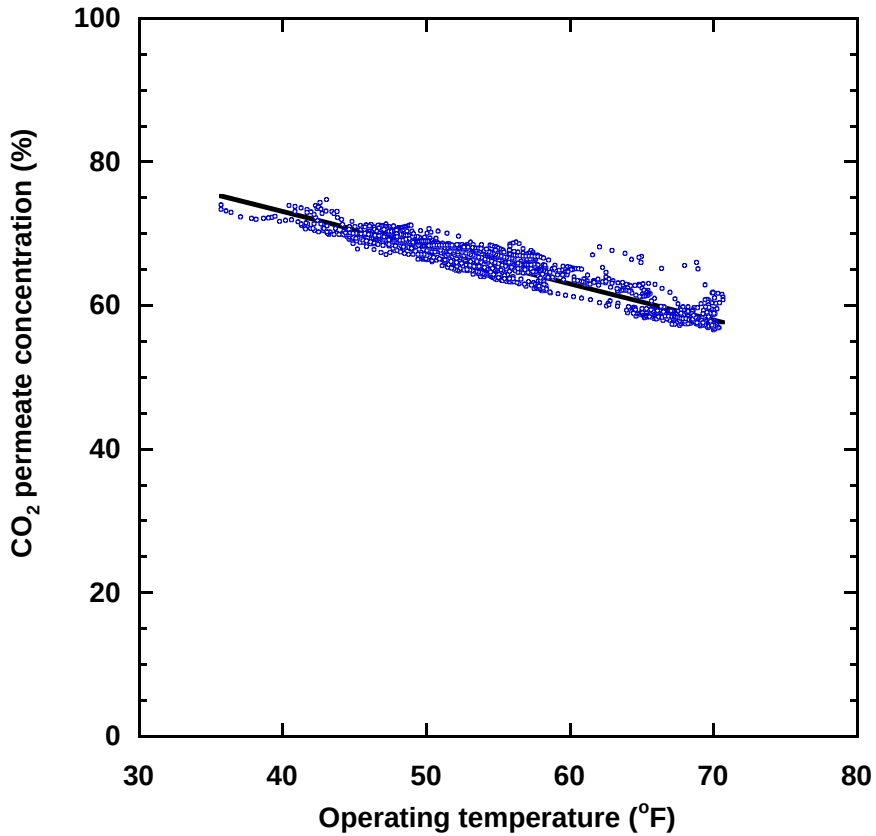


- Two types of membrane modules were tested on the system
  - Base case ($500/m^2) from Jan to Jun)
  - Low-cost ($200/m^2) from Jul to Oct
- Most concentration fluctuations due to changes in feed gas temperature
- Including time during which data were not recorded due to analyzer issues, the cumulative run time in 2013 is over 2,000 hours with coal plus 900 hours with simulated NGCC flue gas (see following slide)

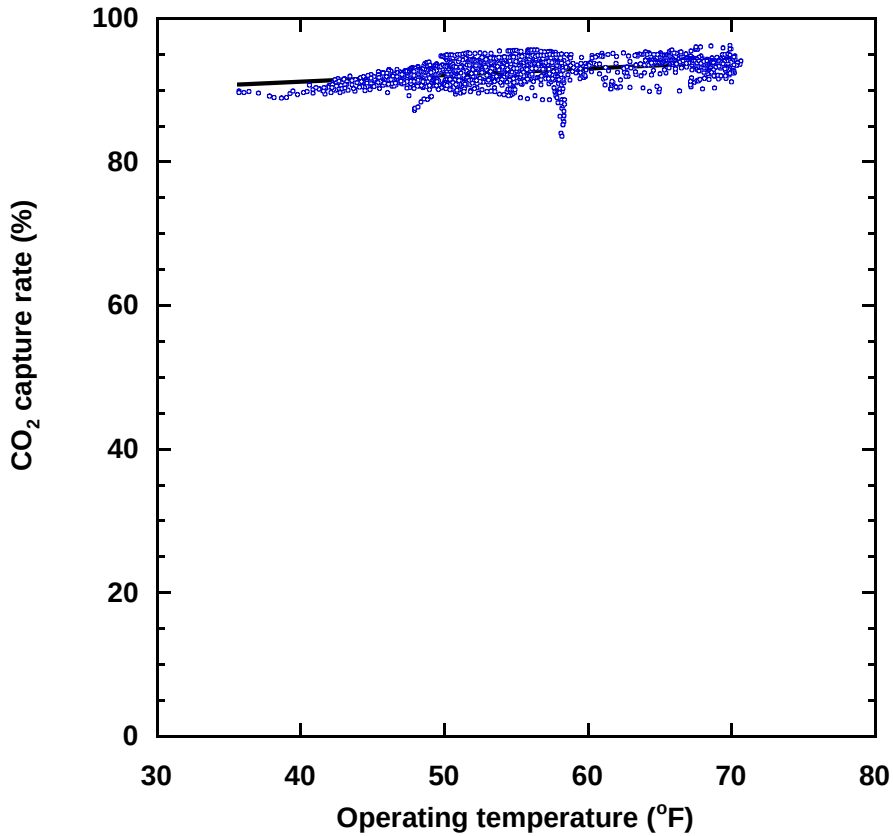
**System ran with NGCC flue gas mostly during this period*

Correlation of CO_2 Purity and Capture Rate With Temperature

CO_2 Concentration

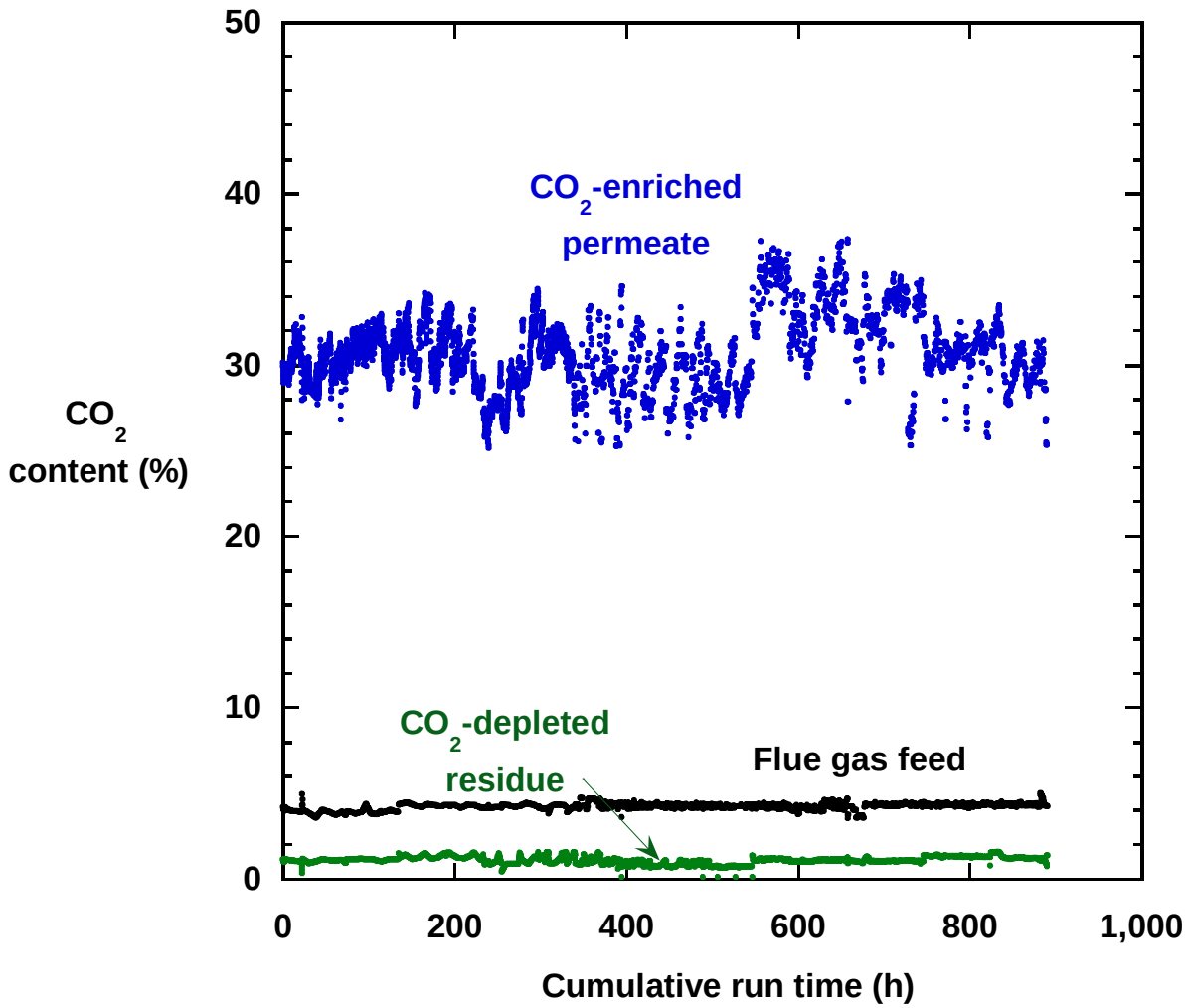


Capture Rate



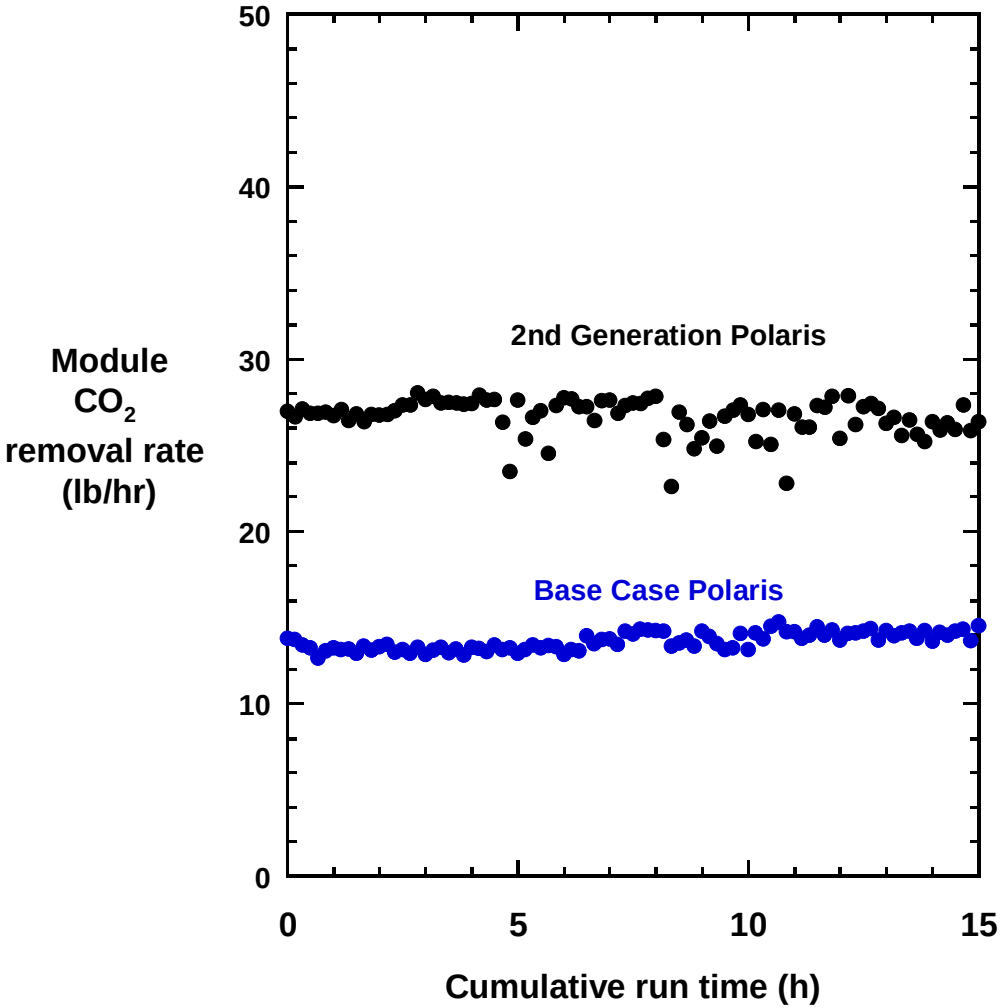
- Higher temperatures yield higher gas permeances, leading to greater CO_2 capture, but at lower purity; could be controlled by switching modules on and offline depending on temperature.

2013 Test Results at NCCC with Simulated NGCC Flue Gas



- CO_2 enriched about 8 times in the permeate compared to the feed gas
- With sweep recycle to increase the feed CO_2 content to 10+%, this enrichment would yield 80+% CO_2 ready for liquefaction

Recent NCCC Tests with Second Generation Polaris Modules



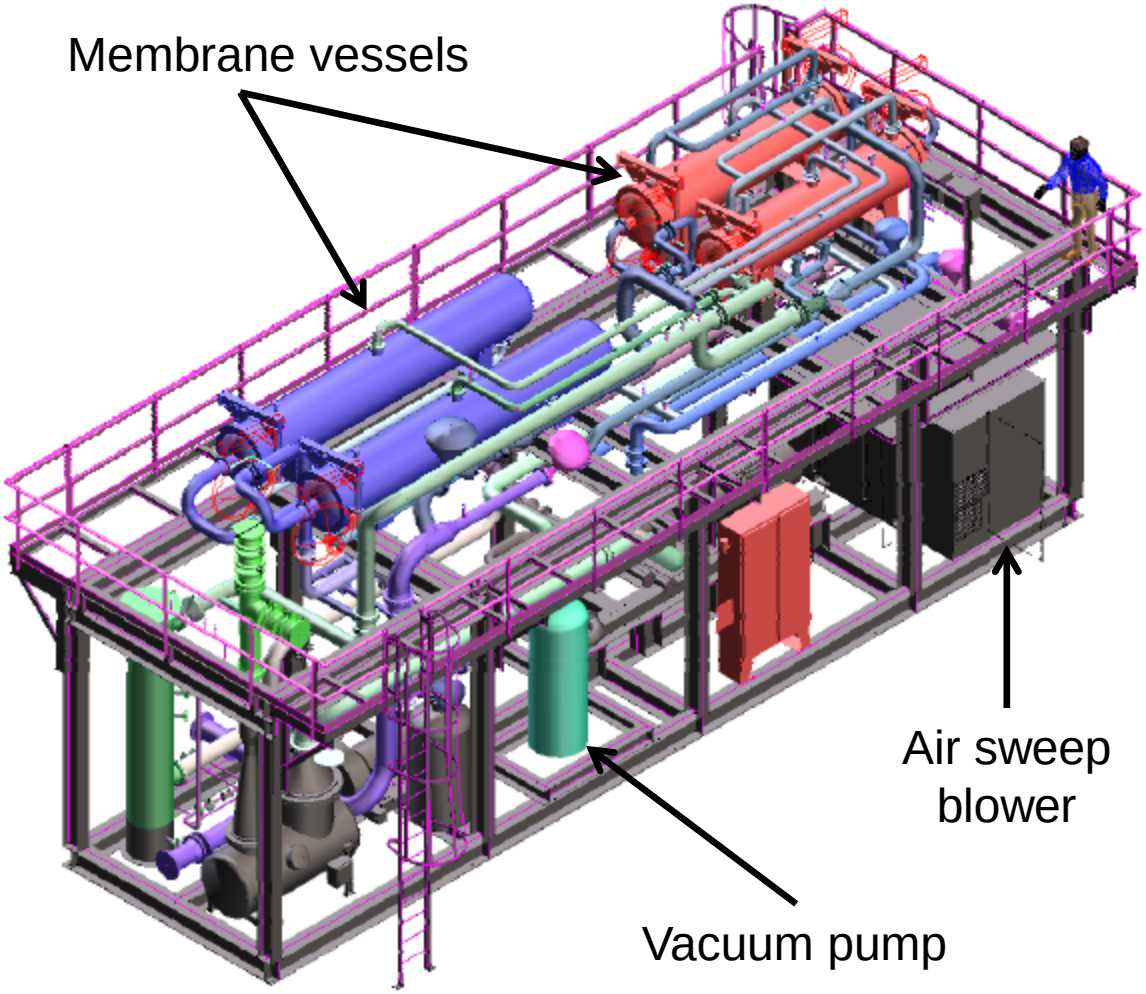
- Both 1st and 2nd generation Polaris modules show stable performance
- The 2nd generation Polaris module shows 60%-70% more CO_2 removal capacity than that of the base case module

Test Plans for 1 TPD System in BP3

- Continued module testing through 2QFY2015 to validate laboratory performance improvements and to collect membrane/module lifetime data
- Demonstration of CO_2 purification (membrane-assisted liquefaction)

20 TPD System Update

20 TPD System Status



- 20 TPD skid (1 MW_e) is now in commissioning at NCCC
- 6 month demonstration to start by June 1
- With planned plant Gaston outage in fall, testing will likely extend to 1QCY2015
- Objective is 3 months steady state operation at 90% capture, and validation of Plate & Frame modules designed for low pressure drop and small footprint

20 TPD System Under Construction

- Top floor of skid showing membrane module vessels

20 TPD System Arriving at NCCC

- System shipped from fab shop in Houston to NCCC April 2

Installation of System's 2nd Floor

- Crane lowering 2nd floor of system into place at NCCC

20 TPD System in Final Location

- View of system with Linde and PSTU in background

20 TPD System at NCCC

- View of opposite side of system showing module vessels

Drawing of 20 TPD System at NCCC

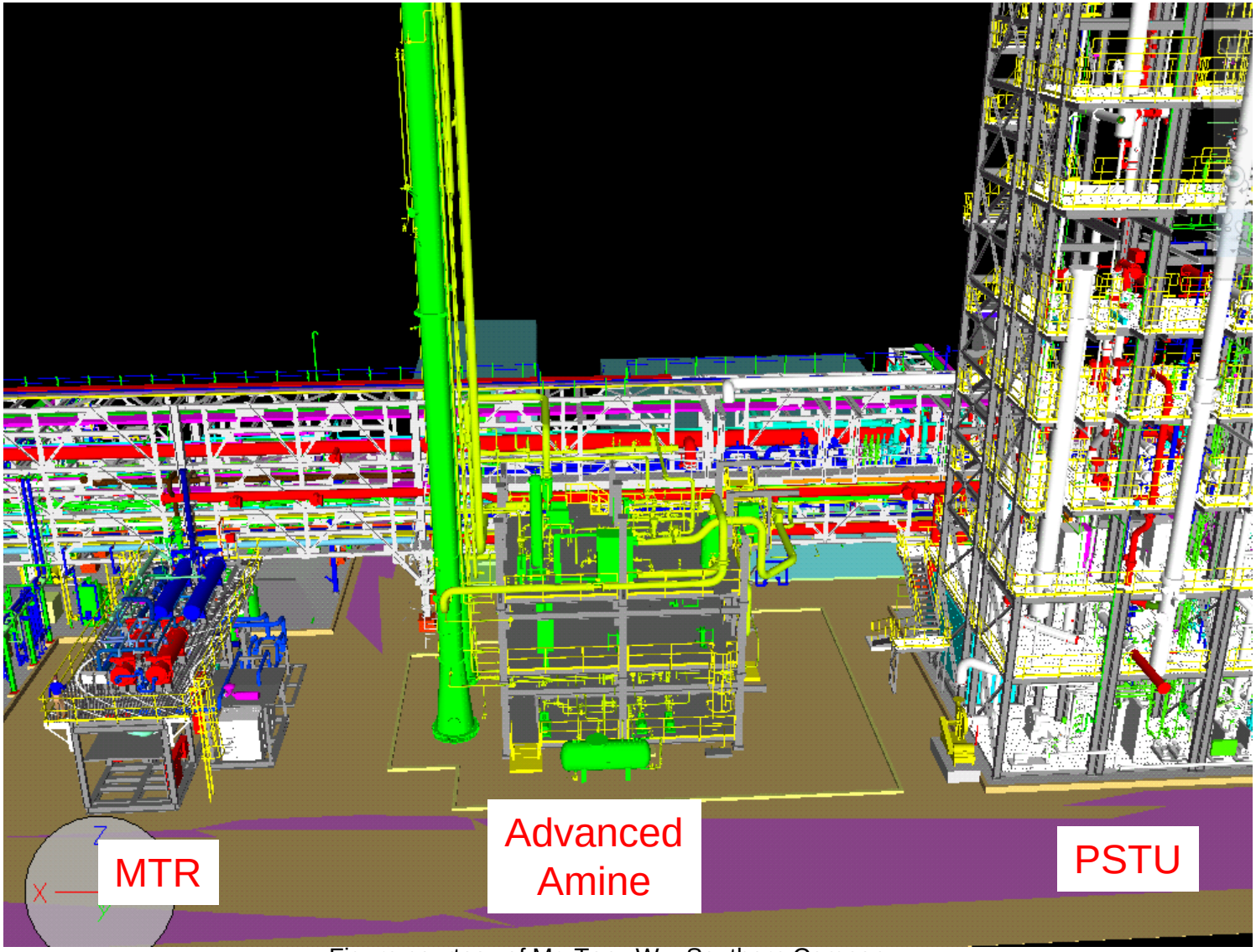
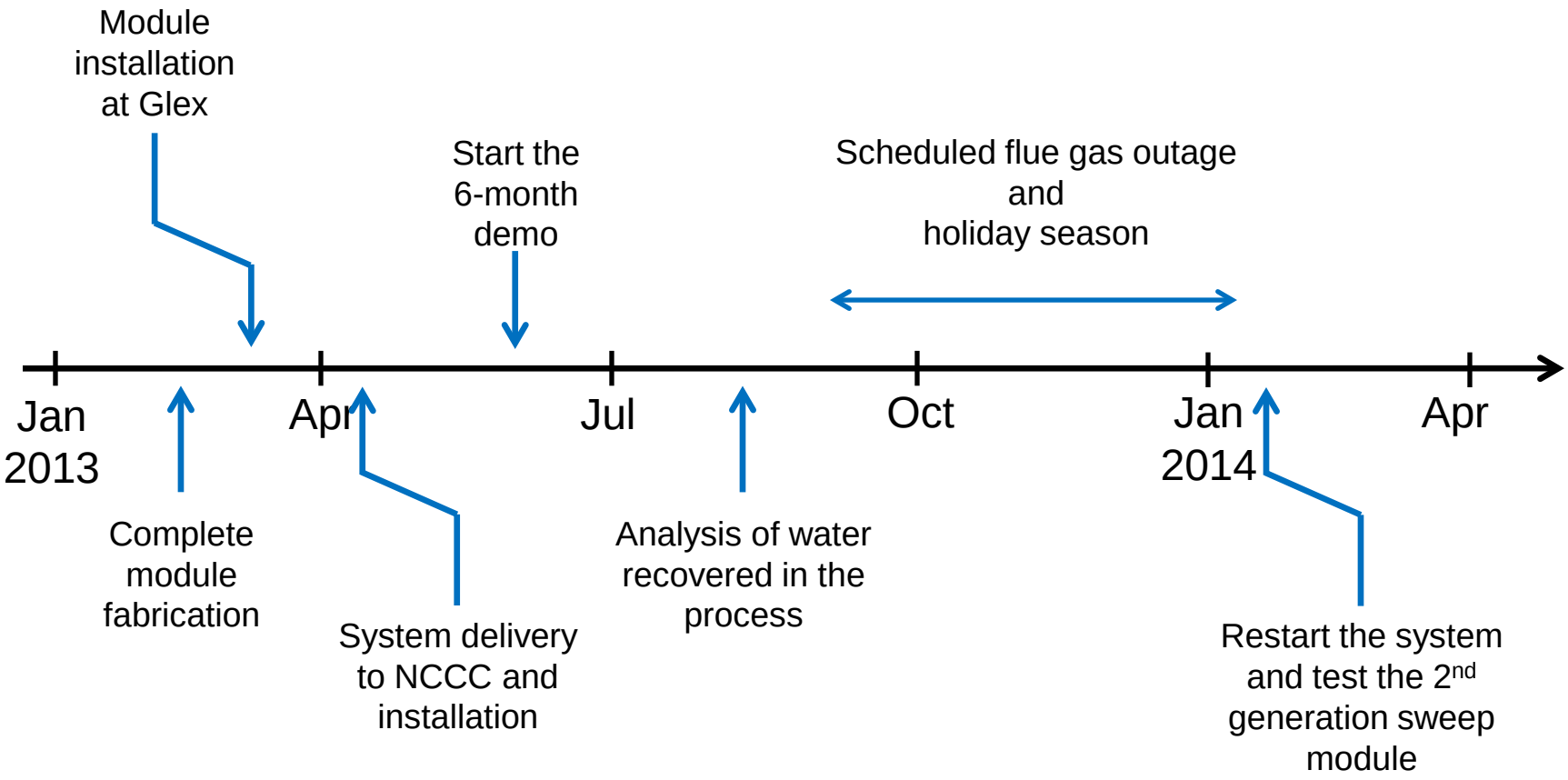


Figure courtesy of Mr. Tony Wu, Southern Company

20 TPD System at NCCC

20 TPD Installation and Test Timeline



20 TPD Test Details

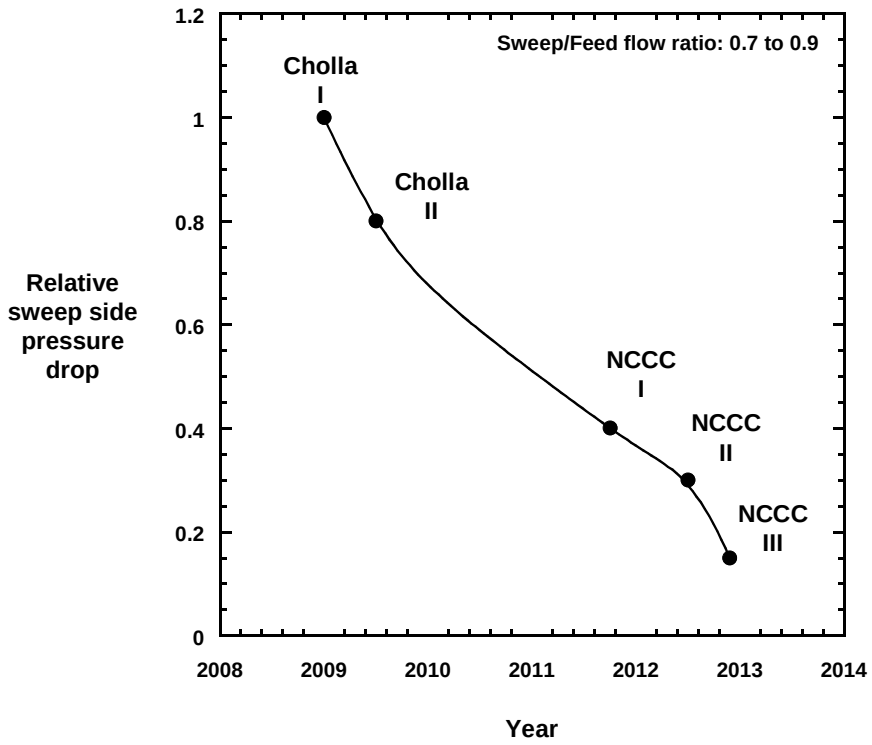
- Installation currently underway
- Shakedown operations to start in mid-May
- Once performance tuning is complete, we will aim for 3 months (June-August) of steady state operation
- During this period, MTR personnel at NCCC continuously and remote real-time data monitoring from MTR
- In July, EPRI will collect feed, and permeate water samples for quality analysis; also begin updated TEA
- After fall plant shutdown (Sept-Nov), two test objectives:
  - Comparison testing using the 2nd gen sweep modules
  - Parametric tests (50% capture, upset response, etc)

MTR

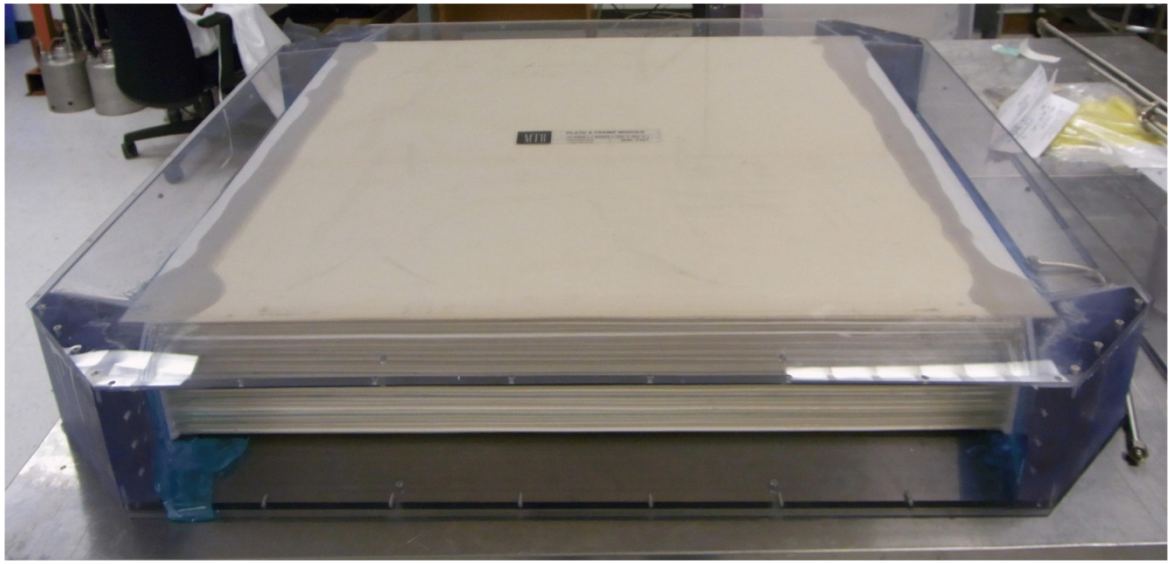
Sweep Module Update

Module Pressure Drop

- Pressure drop through modules is a key issue because each psi pressure drop corresponds to ~3 MW fan power for a 500 MW plant
- Feed side pressure drop through spiral modules is low (<1 psi) and already meets project target (<1.5 psi)
- Sweep side pressure drop is higher in spirals due to channel compression and longer, more tortuous flow path length
- Significant progress in reducing sweep pressure drop, but current value (4 psi) is still high and near a practical limit
- Module redesign for low pressure sweep operation is best solution



Low Pressure Drop, High Packing Density Sweep Modules



- Under project 7553, a new sweep module was designed using CFD analysis
- Prototype modules are compact and show good flow distribution (example contains 100 m^2 – equivalent to five 8-inch spirals)
- Show very low pressure drops (<0.5 psi, feed and sweep)
- Will be validation tested on the 1 MW system after steady state operation with Gen 1 spiral sweep modules is completed

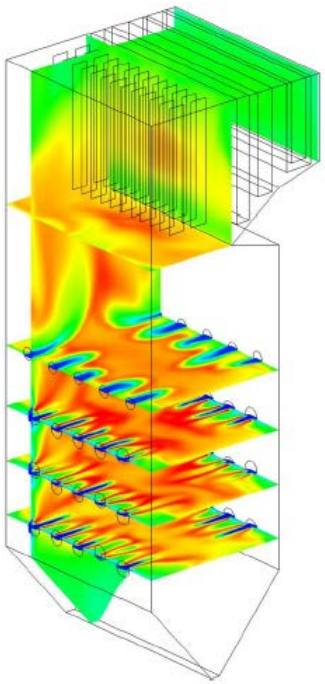
500 m^2 Sweep Module Skid

- Compact design
  - Skid footprint: 6’ x 7’
  - Vessel: 5’ diameter, ~5’ tall
- Vessel contains five 100 m^2 membrane modules
- Able to isolate individual modules for performance testing
- Cross-flow and partial countercurrent sweep modules will be tested
- Will be installed for testing at NCCC in 2014

Boiler Testing at B&W

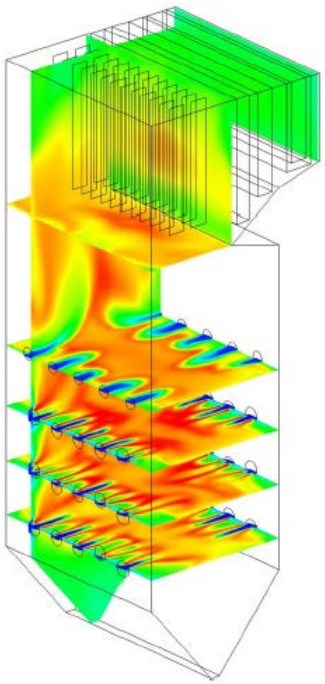
Boiler Testing at B&W

- One of the key questions about the MTR design is the impact of recycled CO_2 on boiler performance
- During BP1, B&W conducted a CFD modeling study of CO_2 recycle to two boiler configurations (radiant boiler firing bituminous coal and SWUP firing PRB coal)
- 2 cases were examined: fixed secondary air flow and fixed stoichiometry
- Fixed secondary air flow results in high unburned carbon and CO at furnace exit
- Fixed stoichiometry causes a small change in distribution of heat absorption, but from combustion standpoint appears feasible for retrofits
- Boiler testing in BP2 was recommended to validate modeling results

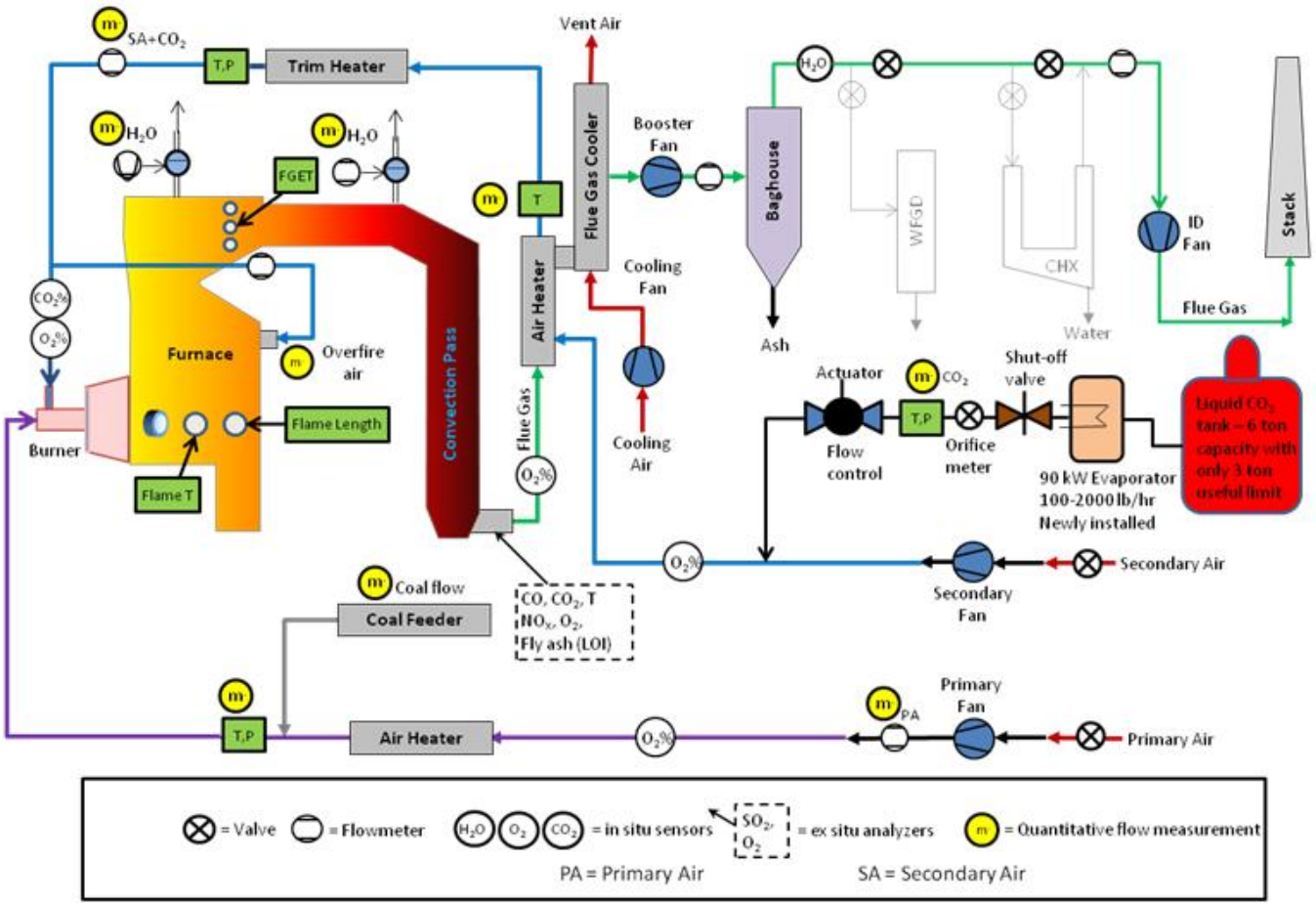


BP2 Pilot Testing

- 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 Testing at B&W

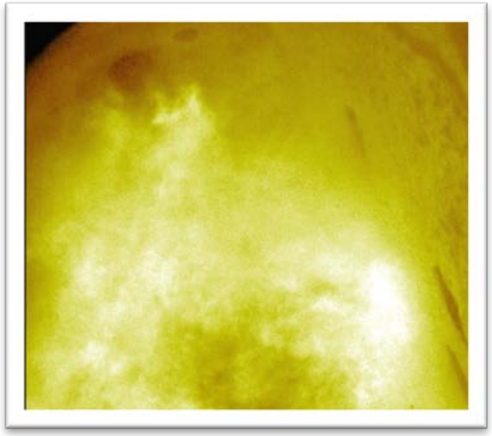


Boiler testing was conducted at B&W's SBS-II pilot facility in Barberton, OH to validate BP1 computer modeling results

B&W Boiler Study Highlights

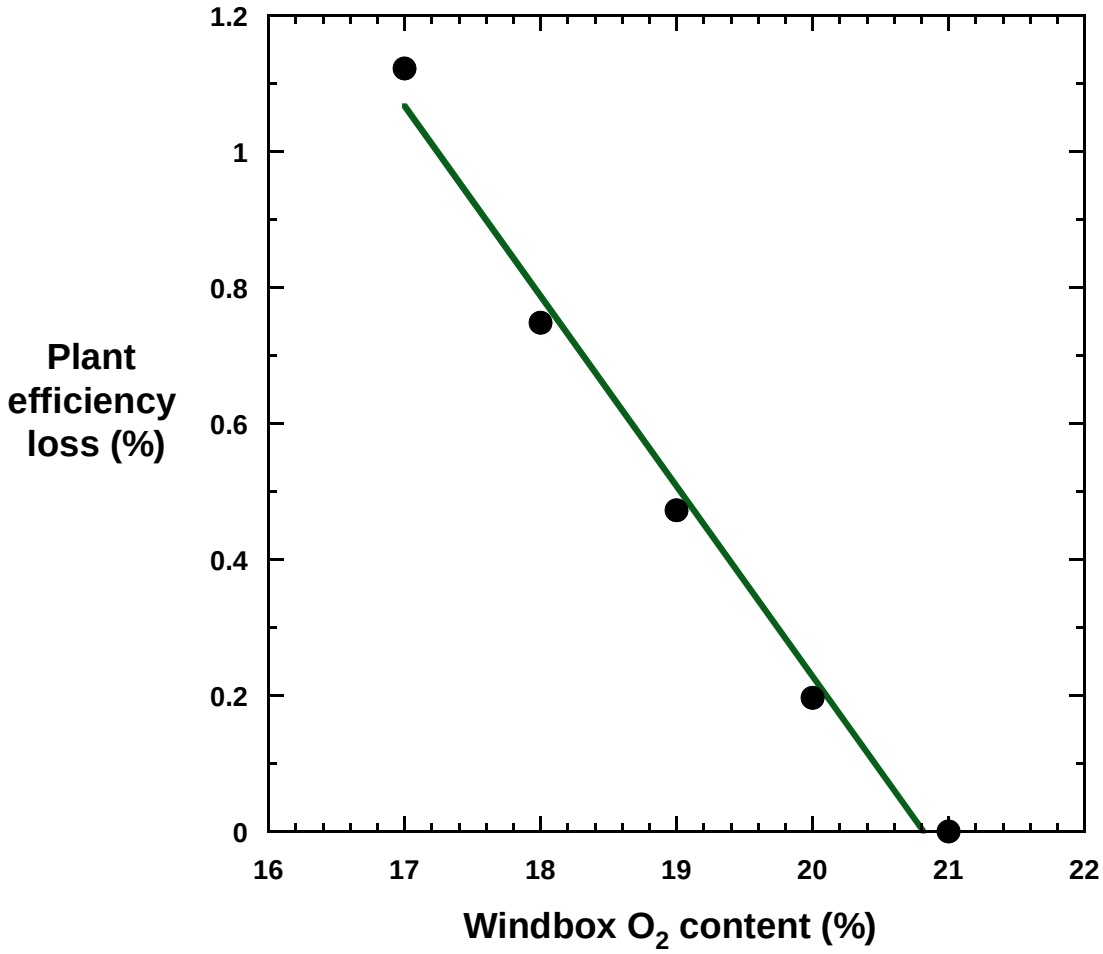
- Stable and attached flames with air (21% O_2) and CO_2-enriched air (16-18% O_2)
- CO_2-enriched flame was less luminous than air-fired case
- Lower furnace heat absorption but higher convection pass/air heater heat transfer for CO_2-enriched operation relative to air
- For bituminous coal, 30% lower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

Boiler Efficiency Versus Windbox O_2



- Increased CO_2 recycle reduces windbox O_2 content through dilution
- Decreased windbox O_2 reduces plant efficiency almost linearly
- However, increased CO_2 recycle ($O_2\downarrow$) reduces capture energy
- 18% O_2 appears to be optimum for retrofit because beyond this point tube erosion, abrasion, and slagging become important
- Because flame is stable to 16% O_2, this level of recycle should be further evaluated for new plants

Future Work Recommendations

- This boiler study and membrane testing at NCCC are showing that the individual components of the MTR capture design are feasible
- However, integration of the sweep recycle membrane unit with a boiler has not been demonstrated
- The impact of recycled impurities, O_2 loss, actual pressure drops, etc should be clarified
- To reduce risk before further scale-up, it is recommended that the 1 MW membrane skid be operated with the B&W pilot boiler
- This could be accomplished after the 1 MW system testing at NCCC; skid move, installation, and short demonstration could be achieved in FY2016; cost estimate in progress

MTR

Industrial CO_2 Update

Industrial CO_2 Background

- Refineries are large stationary sources of CO_2 (6% of world man-made emissions)
- Nevertheless, refinery streams are often smaller and have higher CO_2 partial pressure than power plant flue gas, making CO_2 capture easier
- Capture testing at industrial sources can be a stepping stone to large implementation at power plants
- During BP2, an industrial site was identified where MTR membranes could be tested for CO_2 removal from syngas
- An agreement was reached with Alberta Innovates and Enerkem to conduct testing at a research facility in Edmonton (AI funds Enerkem; DOE(80)/MTR(20) funds skid construction and MTR effort)

Testing at AERF

- Advanced Energy Research Facility (AERF) is a 10,000 sq ft lab for testing advanced gasification technologies and CO_2 capture
- Adjacent to Edmonton Waste Management Centre – which will convert municipal waste to 10 million gal/y methanol
- Owned by City of Edmonton and operated by Enerkem
- AERF gasifies 300 kg/h of biowaste to produce methanol
- Membrane skid will be used to separate CO_2 from syngas and recycle H_2 to methanol production

Current Progress and Future Plans

- Engineering drawings have been completed and Hazop meeting held this week
- Membrane skid installation to be completed by end of Sept 2014
- Testing during 1st and 2nd QFY2015
- After completion of testing in March 2015, a techno-economic report will be prepared
- Alberta Innovates, Enerkem and MTR will fund continued testing at AERF through 2QFY2016 to study CO_2 separation from ATR syngas

Summary

BP3 Objectives

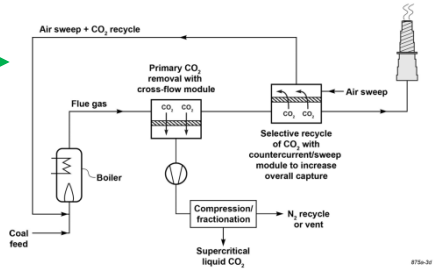
- Successful operation of the 20 TPD system including
  - 3 months of steady state operation at 90% capture
  - Validation testing of compact, low-pressure drop plate and frame sweep module
- Continued durability testing on the 1 TPD system
- Industrial CO_2 capture test with Enerkem
- Case study of a ~20 MW membrane capture system
- Validation of a CO_2 purification unit on the 1 TPD system

Key Project Accomplishments

- Successful production of higher performance, lower-cost Polaris membrane. This membrane is commercial and now being used in natural gas fuel gas conditioning systems
- Continuous operation of the 1 TPD system at ~90% capture with near 100% online time in 2014 when flue gas is available
- Stable 1st and 2nd gen Polaris module performance demonstrating up to 3000 hours operation with flue gas
- Demonstration of stable coal combustion with CO_2-laden air, and quantification of impact on performance
- Design and construction of a 1 MW membrane capture system
- >2-fold reduction in sweep module pressure drop, and preliminary design showing potential of plate-and-frame modules
- Identification of industrial CO_2 capture site and design
- Novel concept development including paper on NGCC CO_2 capture

CO_2 Capture Development Timeline

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

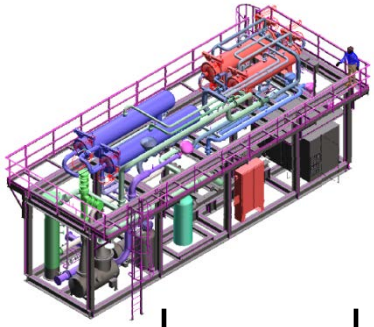


APS Red Hawk NGCC Demo
- First Polaris flue gas test
- 250 lb/d CO_2 used for algae farm

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-NT5795)
- 8,000 hours of 1 TPD system operation
- 1 MW_e (20 TPD) system to run 6 months

Hybrid Capture (DE-FE13118)
- Modeling of Series and Hybrid Design
- 0.1 MW_e pilot test at U. Texas, Austin



Integrated system will test:
- Boiler operation w/recycle
- Advanced membrane modules

Integrated Demo
- Validate full process on 1 MW_e boiler at B&W

25-50 MW_e Demo
- Demonstrate modular technology at full scale

TRL4 TRL5 TRL6 TRL7 TRL8

2006 2008 2010 2012 2014 2016 2018 2020

MTR

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