Novel CO_2-Selective Membranes for CO_2 Capture from <1% CO_2 Sources

DE-FE0026919

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2018 NETL CO_2 Capture Technology Project Review Meeting

Pittsburgh, PA, August 13 – 17, 2018

Project Objective

- **Develop a novel cost-effective membrane and design of membrane modules that capture CO_2 from <1% CO_2 sources**
  - **90% CO_2 Capture**
  - **95% CO_2 Purity**

3-Budget Period Project

- **BP1: 03/01/2016 – 02/28/2017**
  - **Conduct laboratory-scale membrane synthesis, characterization and transport performance studies**
  - **Carry out high-level preliminary techno-economic analysis**
- **BP2: 03/01/2017 – 02/28/2018**
  - **Continue laboratory-scale membrane synthesis, characterization and transport performance studies**
  - **Fabricate larger size membrane (~ 14” by > 20’)**
  - **Fabricate, evaluate and down-select from plate-and-frame and spiral-wound membrane modules**
  - **Update techno-economic analysis performed in BP 1**
- **BP3: 03/01/2018 – 02/28/2019**
  - **Fabricate 3 pilot membrane modules**
  - **Test modules with <1% CO_2 simulated gas mixture**
  - **Update techno-economic analysis**

- **Integrated program with fundamental studies, applied research, synthesis, characterization and transport studies, and high-level techno-economic analysis**

Funding and Performance Dates

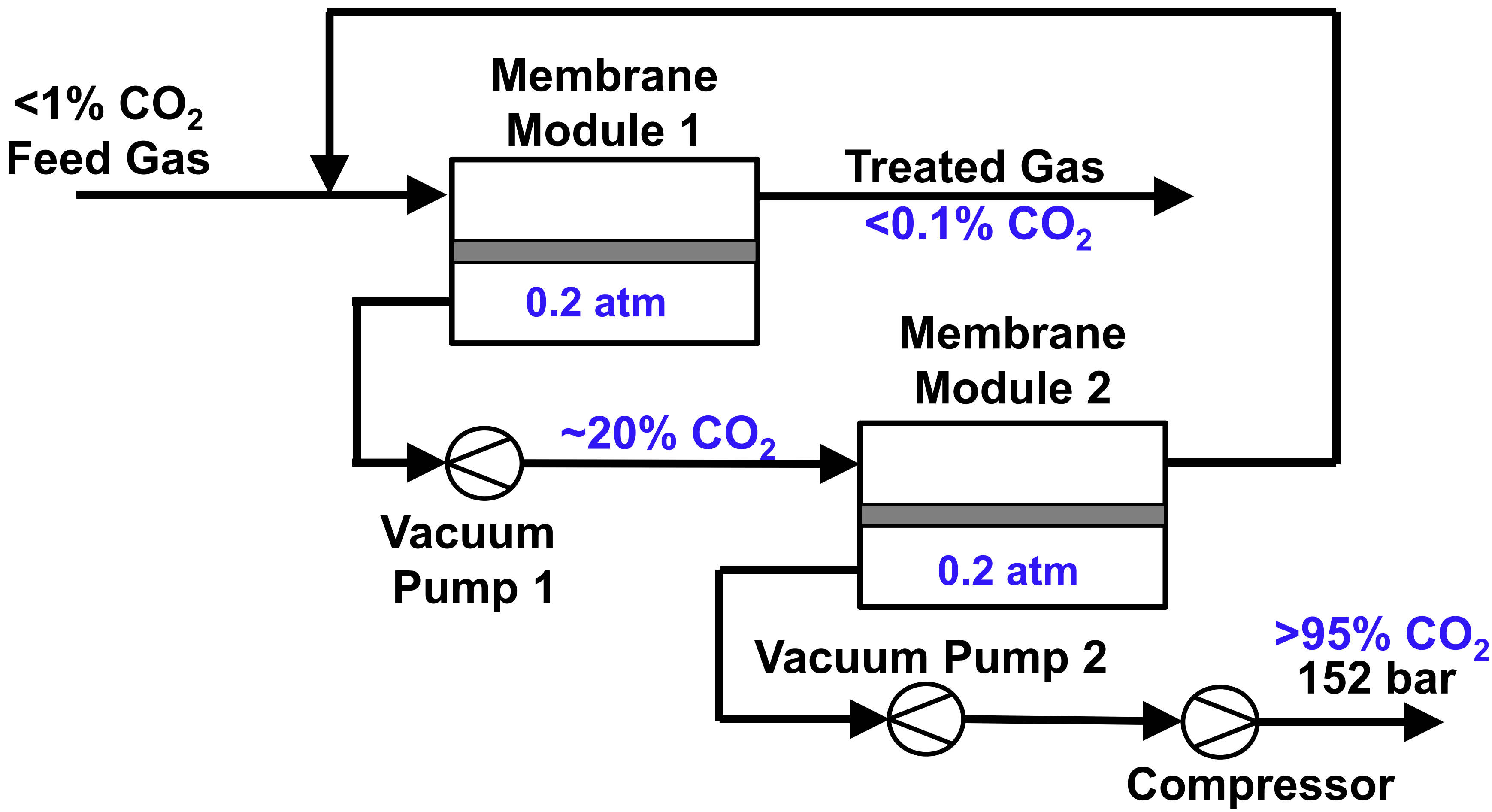
- **Total Budget: 03/01/2016 – 02/28/2019**
  DOE: $1,248,278; OSU: $372,864 (23% cost share)

  - **BP1: 03/01/2016 – 02/28/2017**
    DOE: $407,616; OSU: $121,756

  - **BP2: 03/01/2017 – 02/28/2018**
    DOE: $419,628; OSU: $125,344

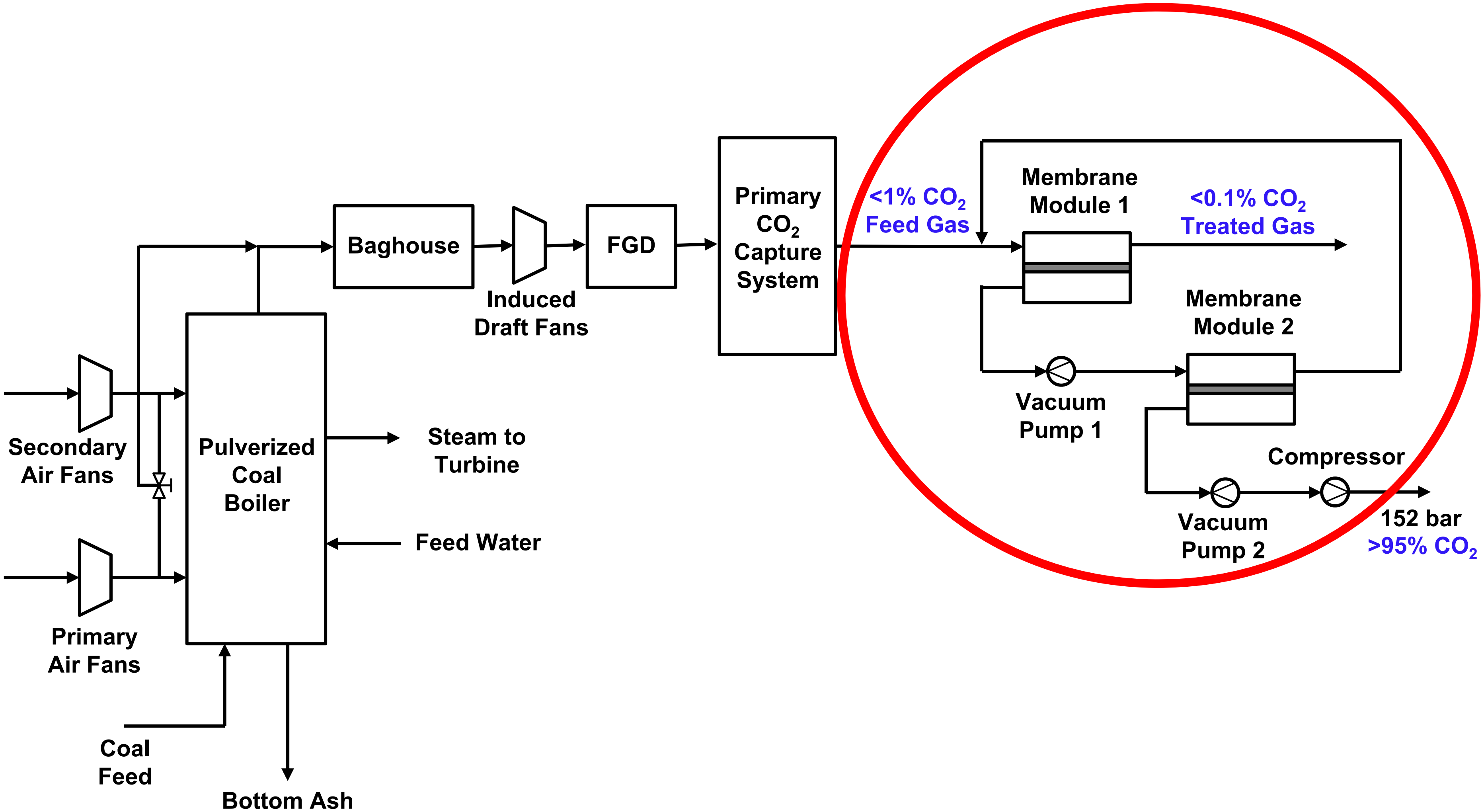
  - **BP3: 03/01/2018 – 02/28/2019**
    DOE: $421,034; OSU: $125,764

Process Proposed for CO_2 Capture from <1% CO_2 Sources



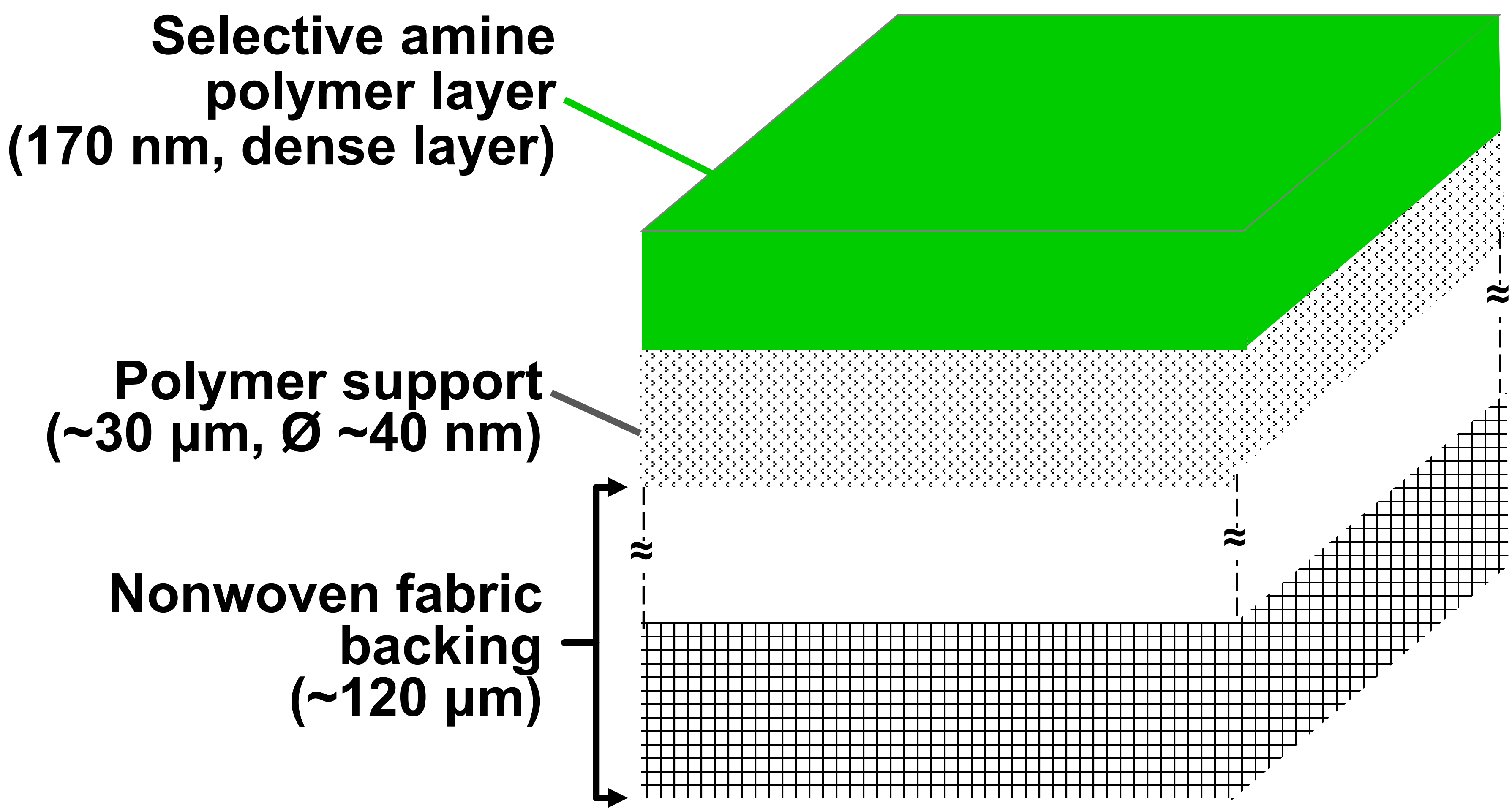
- Proposed membrane process does not require cryogenic distillation (compared to competition)

Location of Proposed Technology in Coal-fired Power Plant



Selective Amine Polymer Layer on Polymer Support

Simplicity of Membrane for Low Cost



Selective Amine Polymer Layer on Polymer Support

- **Selective Amine Polymer Layer**
  - Facilitated transport of CO_2 via reaction with amine

$$CO_2 + R\text{-}NH_2 + H_2O \rightleftharpoons R\text{-}NH_3^+ + HCO_3^-$$

  - Facilitated transport = flux augmentation via reaction
  - High CO_2 permeance and CO_2/N_2 selectivity

BP1 Accomplishments

- **Improved 14"-wide PES Polymer Support Fabricated with Continuous Machine**
  - 13900 GPU CO_2 permeance obtained
- **Composite Membrane Synthesized in Lab**
  - Elucidated carrier saturation phenomenon
  - 980 GPU with 170 CO_2/N_2 selectivity obtained at 57^oC from lab test using 1% CO_2 concentration feed gas
    - + 780 GPU with 150 CO_2/N_2 selectivity obtained using 20% CO_2 feed
- **High-Level Techno-economic Analysis Showed Capture Cost of ~$305/tonne CO_2 (in 2011 $)**
  - ~22% increase in COE
- **2 PCT (Patent Cooperation Treaty) Applications Filed for New Membrane Composition and Process**

BP2 Accomplishments

- **Improved 14”-wide PES Support Fabricated with Continuous Machine (22500 GPU)**
- **Pilot Composite Membranes Synthesized**
  - **Membrane scaled up to 14” by roll-to-roll successfully**
- **Plate-and-Frame and Spiral-Wound (SW) Modules Fabricated**
  - **Both showed ~1500 GPU with ~220 selectivity at 57^{o}C**
    - + Similar results to scale-up flat-sheet membrane
  - **Both gave similar and acceptable pressure drop results**
  - **Down-selected to SW module for ease of manufacture**
- **Good Module Stability (3 ppm SO_2 & 7% O_2) – 1700 h**
- **High-Level Techno-economic Analysis Showed Capture Cost of $268/tonne CO_2 (in 2011 $)**
  - **~19% increase in COE**
- **8 Patent Applications Filed (New compositions & processes)**

BP3 – 6-Month Accomplishments

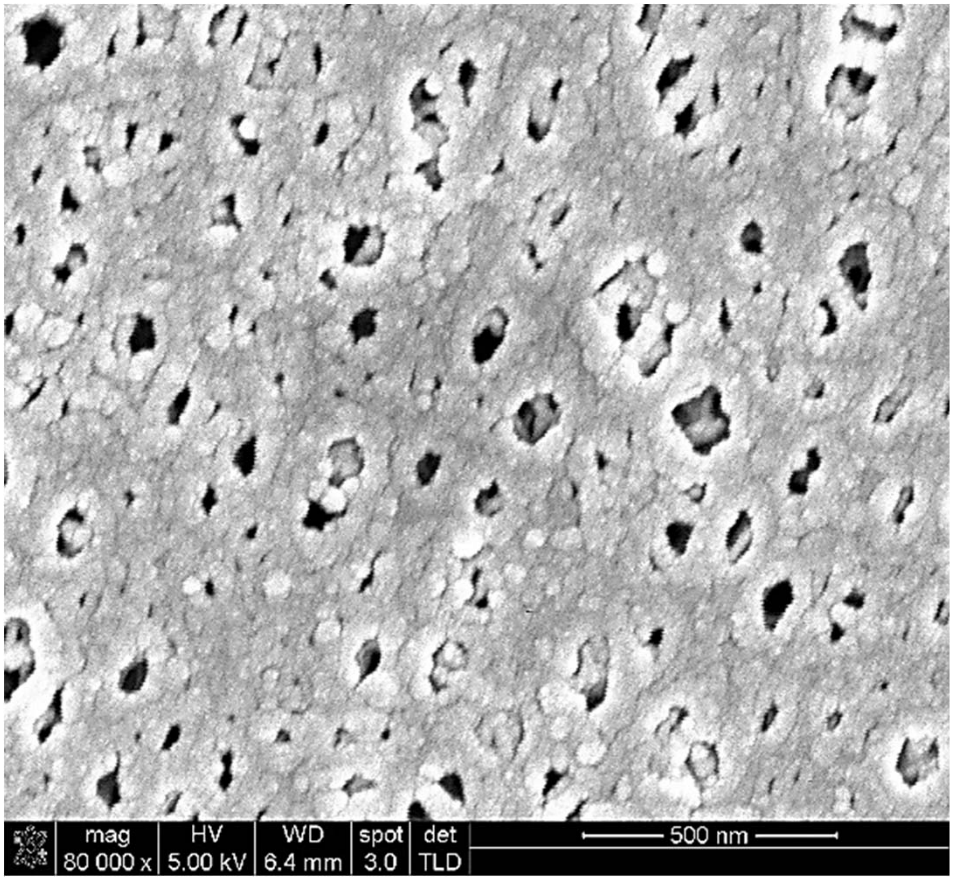
- **Optimized Composite Membranes Synthesized**
  - **Membrane scaled up to 14” by roll-to-roll successfully**
  - **~1930 GPU with 220 CO_2/N_2 selectivity obtained at 67°C using 1% CO_2 conc. feed gas – similar to lab-scale results**
  - **~1450 GPU & 180 Selectivity for 20% CO_2 conc. feed gas**
- **8 Spiral-Wound (SW) Modules Fabricated**
  - **All showed ~1930 GPU with ~220 selectivity at 67°C using 1% CO_2 conc. simulated residual flue gas**
    - + ~1450 GPU & 180 Selectivity for 20% CO_2 conc. feed gas
    - + Similar results to scale-up flat-sheet membrane
    - + 1900-h good module stability obtained (3 ppm SO_2 & 7% O_2)
  - **All gave similar and acceptable pressure drop results**
- **SW Module Test at NCCC (Related effort conducted under a separate ODSA-funded project)**
  - **Module showed ~1450 GPU with ~180 selectivity at 67°C**
    - + Similar results to scale-up flat-sheet membrane and modules using simulated flue gas
  - **500-hour good module stability obtained**
  - **Similar and acceptable pressure drop results obtained**

Scale-up of PES Support and Composite Membrane

Continuous Membrane Fabrication Machine at OSU

Successful Continuous Fabrication of Affordable PES Support

SEM Analysis of 14-inch PES Support

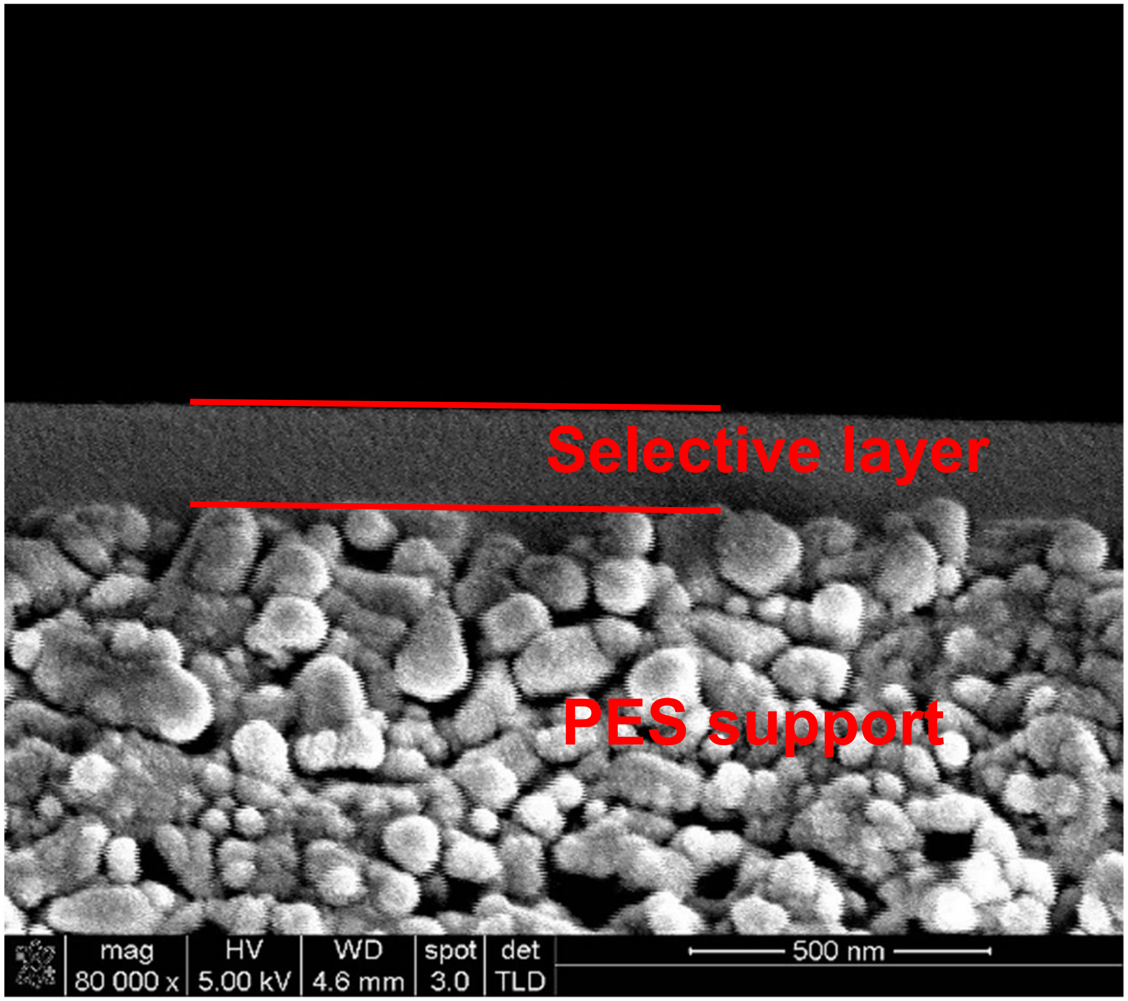


Ave. pore size = 32.5 nm, Porosity = 12.5%

- **Optimal pore size identified to reduce penetration during coating**
- **Hydrophilic additives improved adhesion & open porous morphology**

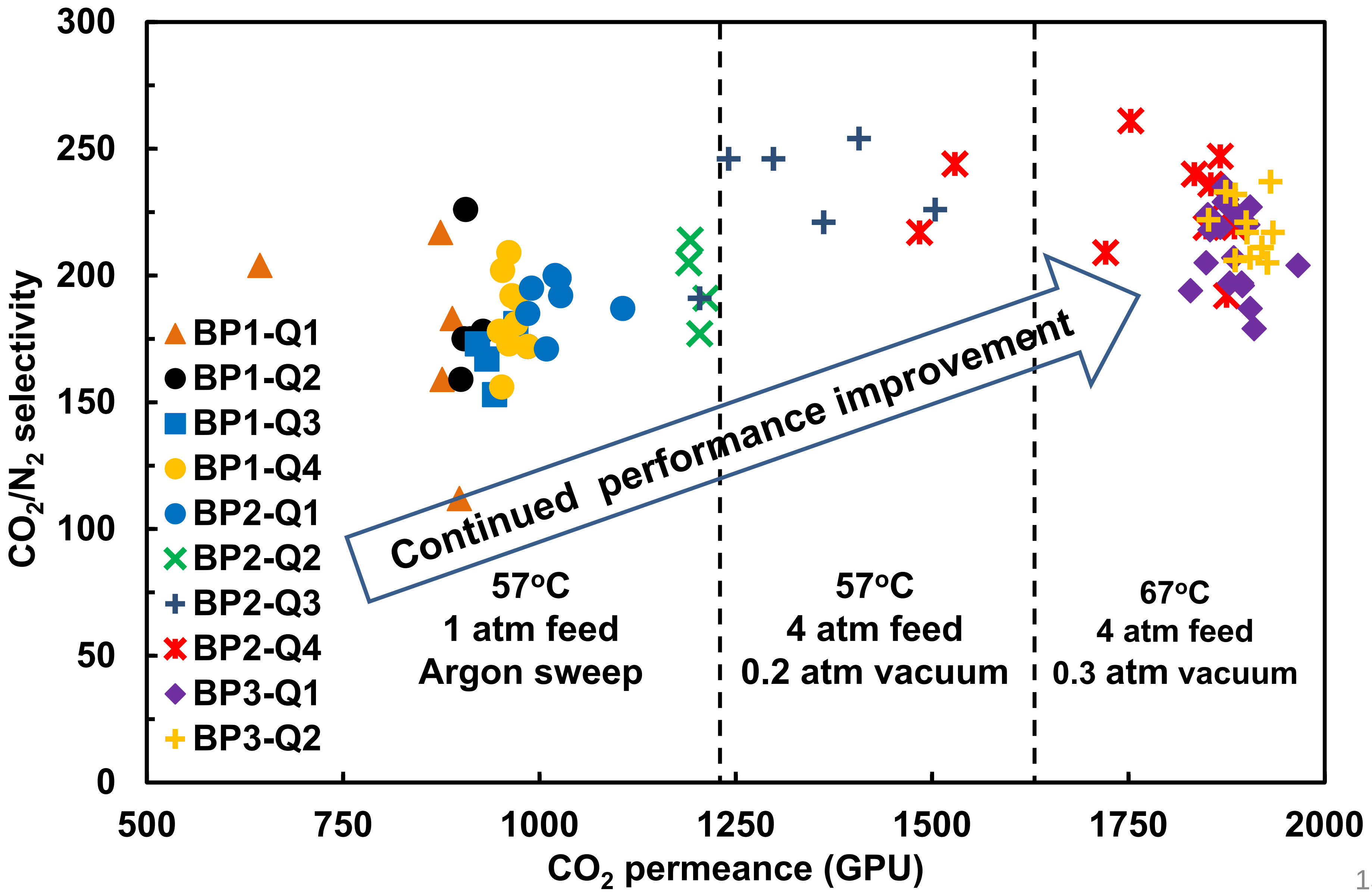
Composite Membrane Synthesized

Selective Amine Polymer Layer on PES Support



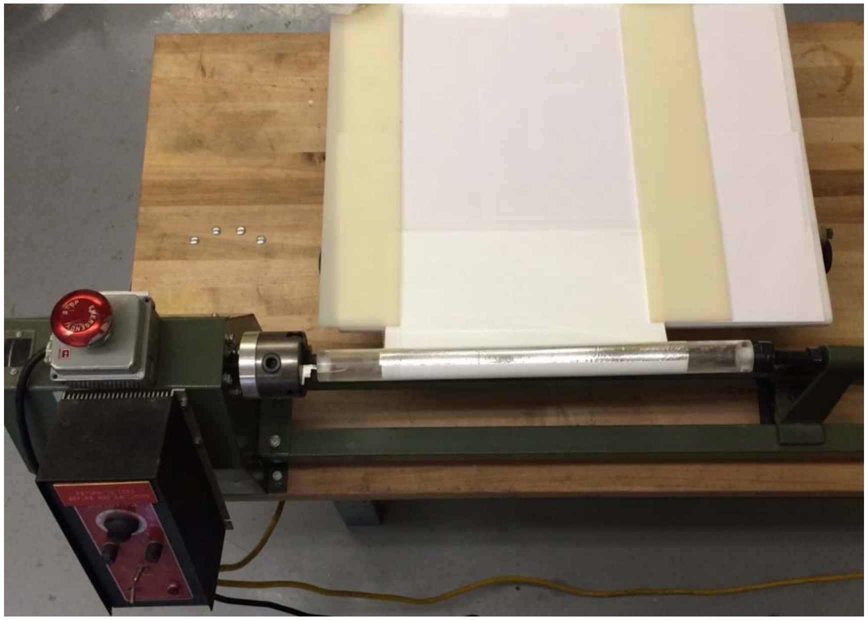
Selective layer = 165 nm

Significant Membrane Performance Improvement Achieved

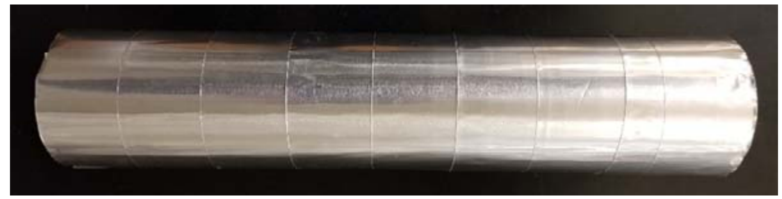


Spiral-Wound Membrane Module Fabricated

Element Rolling Machine



Spiral-Wound Membrane Element



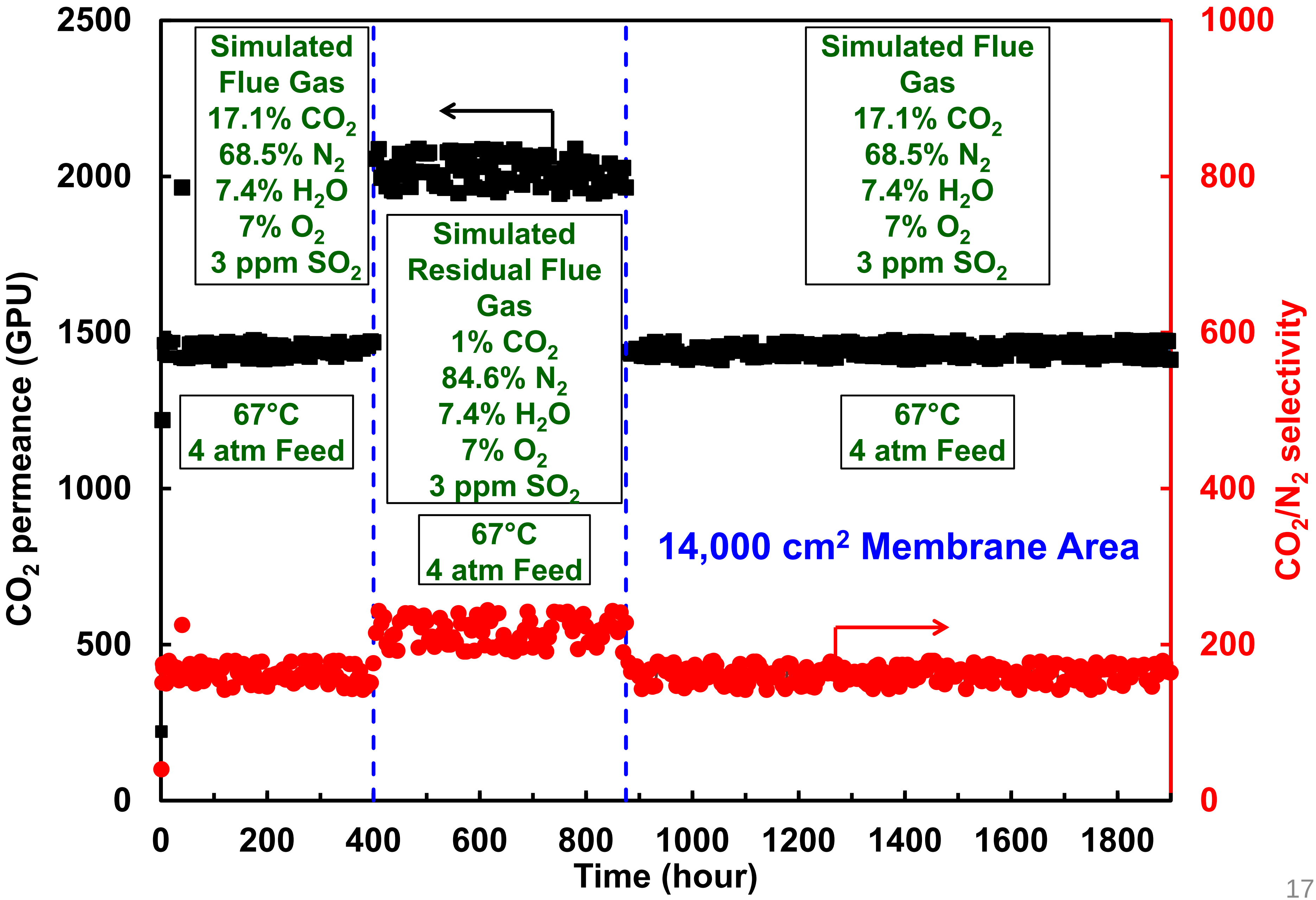
Membrane Module

Feed Outlet

Vacuum Permeate

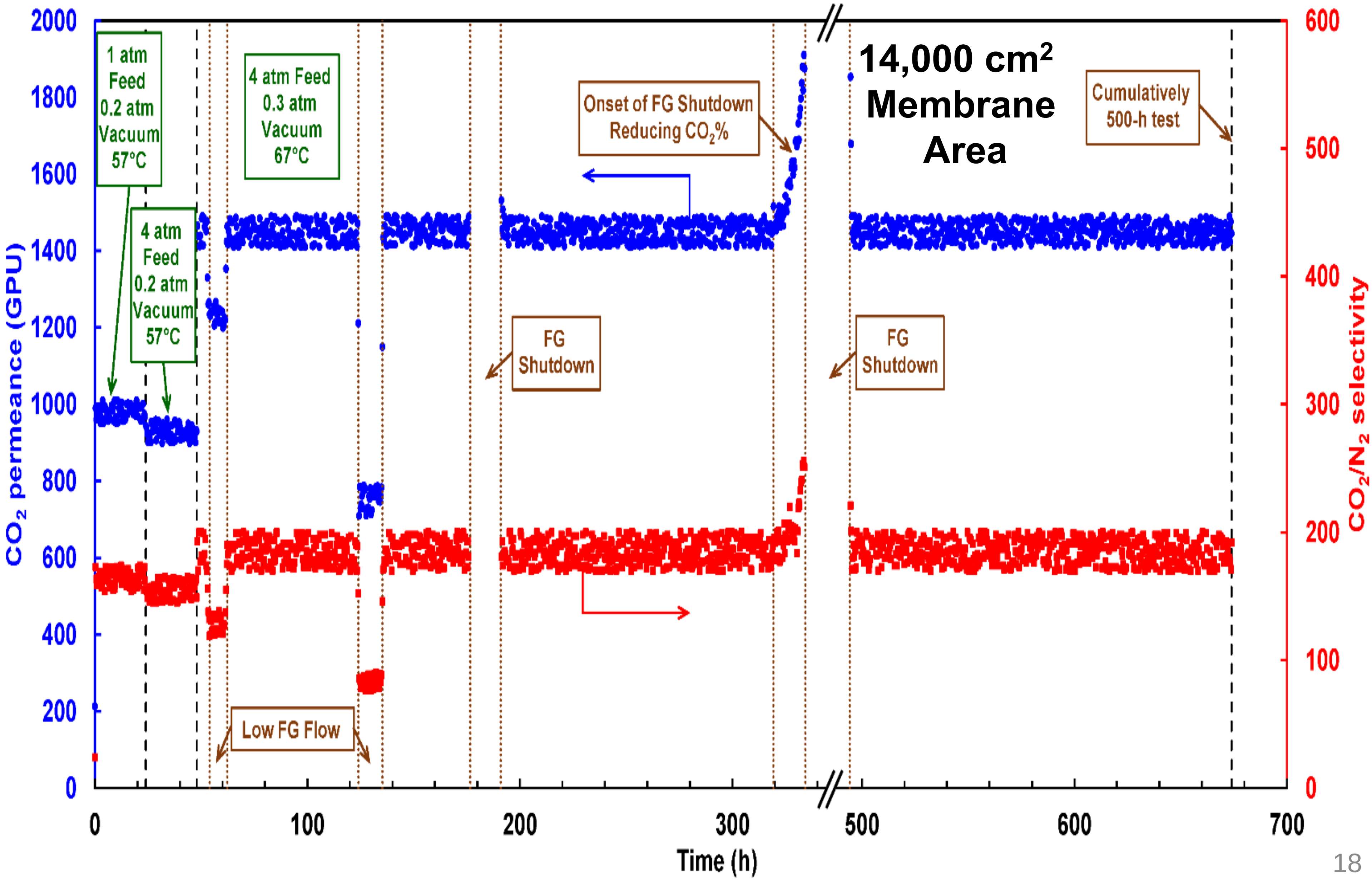
Feed Inlet

Good SW Module Stability Obtained



Good SW Module Stability at NCCC

Related effort conducted under a separate ODSA-funded project



High-Level Techno-Economic Calculations

- **Basis: Membrane Results at 67°C**
  - **1930 GPU & 220 Selectivity for 1% CO_2 concentration feed gas**
  - **1450 GPU & 180 Selectivity for 20% CO_2 conc. feed gas**
  - **Include Membrane Module Installation Cost and 20% Process Contingency**
  - **In 2011 dollar: NETL Case 12 of *Updated Costs (June 2011 Basis) for Selected Bituminous Baseline Cases***

- **Calculated Cost Results**
  - **32.0 tonne/h of CO_2 captured from 1% CO_2 source**
  - **$91 million bare equipment cost**
    - Membrane 22%, blowers and vacuum pumps 73%, others 5%
  - **1.56 ¢/kWh (1.12 ¢/kWh capital cost, 0.21 ¢/kWh fixed cost, 0.20 ¢/kWh variable cost, and 0.03 ¢/kWh T&S cost)**
    - COE = 8.09 ¢/kWh for 550 MW supercritical pulverized coal power plant
  - **$266/tonne capture cost ($15.6/MWh × 550 MW/(32.0 tonne/h))**
  - **19.1% Increase in COE (1.56/8.09 = 19.1%)**

Plans for Future Testing/Development

- **Remaining BP3**
  - Test new modules with <1% CO_2 simulated gas mixture
  - Update techno-economic analysis
- **Will also complete testing of 3 pilot membrane modules at NCCC under related ODSA-funded project**
  - One module for 500-hour testing

Acknowledgments

José Figueroa & David Lang, **DOE/NETL**
Matt Usher & Dean Bell, **AEP Eng. Services**
Great efforts and strong inputs

Tony Wu & Bob Lambrecht, **NCCC Team**
Excellent analytical and mechanical supports

Financial Supports

DOE/NETL

DE-FE0026919

- **Also serving as cost share to ODSA project**

ODSA (Ohio Development Services Agency)

OER-CDO-D-15-09

- **AEP cost sharing**
- **NCCC membrane module testing**