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

DE-FE0026919

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2016 NETL CO_2 Capture Technology Project Review Meeting

Pittsburgh, PA, August 8 – 12, 2016

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 lab size membrane (~ 6” by 6”)
  - 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 laboratory 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**

Project Organization and Roles

Ohio State University

- Technical lead
- Concept development and execution
- Novel membrane synthesis/characterization
- Laboratory-size membrane scale-up
- Process design considerations
- Cost calculations

Winston Ho

DOE NETL

Project Manager

José Figueroa

TriSep Corporation

- Consult on membrane scale-up/module fabrication

Peter Knappe

Gradient Technology

- Consult on system and cost analyses

Steve Schmit

AEP

- Consult on plant integration and demonstration considerations

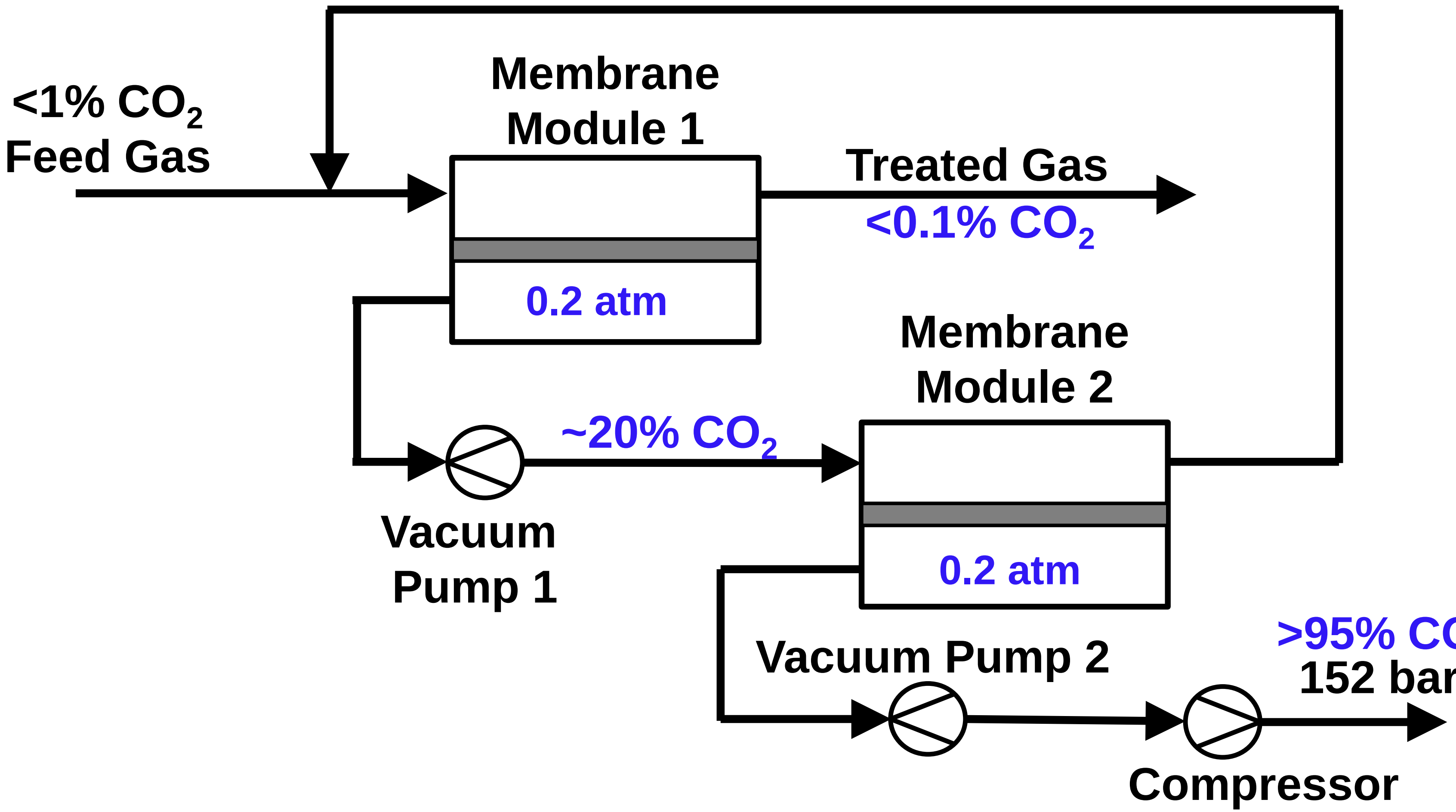
Matt Usher

Funding and Performance Dates

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

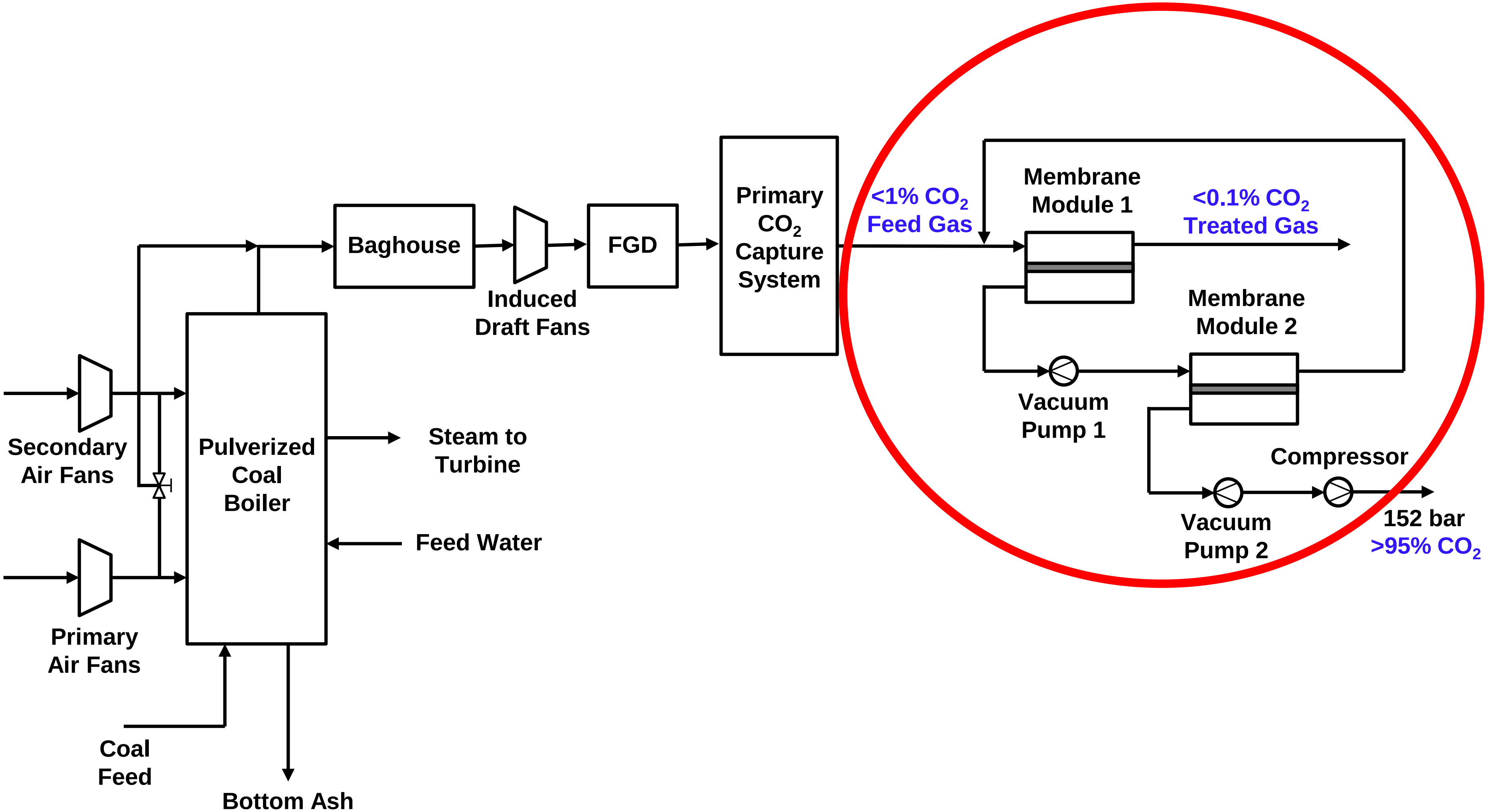
  - **BP1: 03/01/2016 – 02/28/2017**
    DOE: $407,616; OSU: $121,756
  - **BP2: 03/01/2017 – 02/28/2018**
    DOE: $419,628; OSU: $125,344
  - **BP3: 03/01/2018 – 02/28/2019**
    DOE: $421,034; OSU: $125,764

Process Proposed for CO_2 Capture from <1% CO_2 Sources



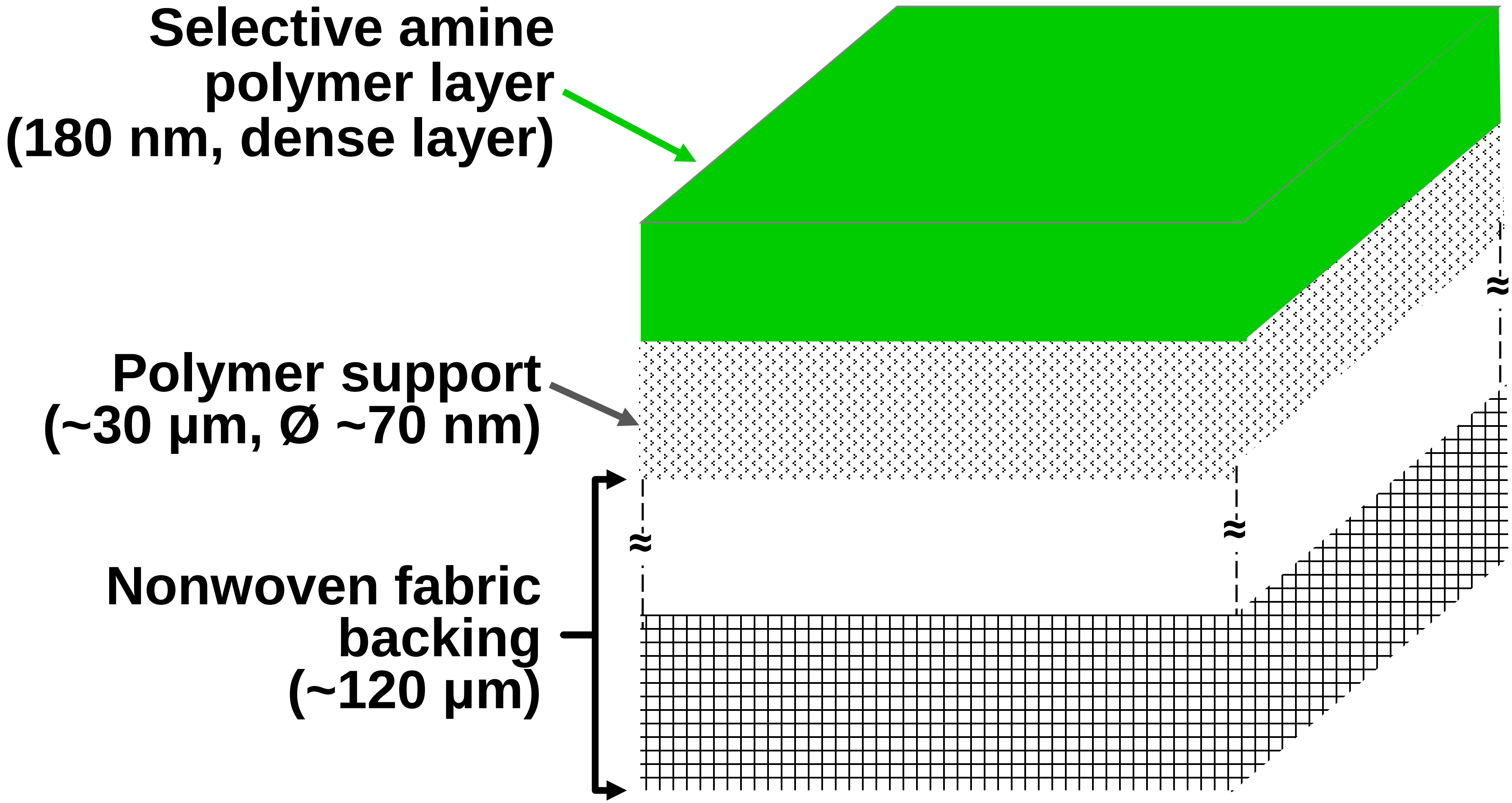
- **Proposed membrane process does not require cryogenic distillation (compared to competition)**

Location of Proposed Technology in Coal-fired Power Plant



Selective Amine Polymer Layer / Polymer Support

Simplicity of Membrane for Low Cost



Selective Amine Polymer Layer / Polymer Support

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

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

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

BP1 – 5-Month Accomplishments

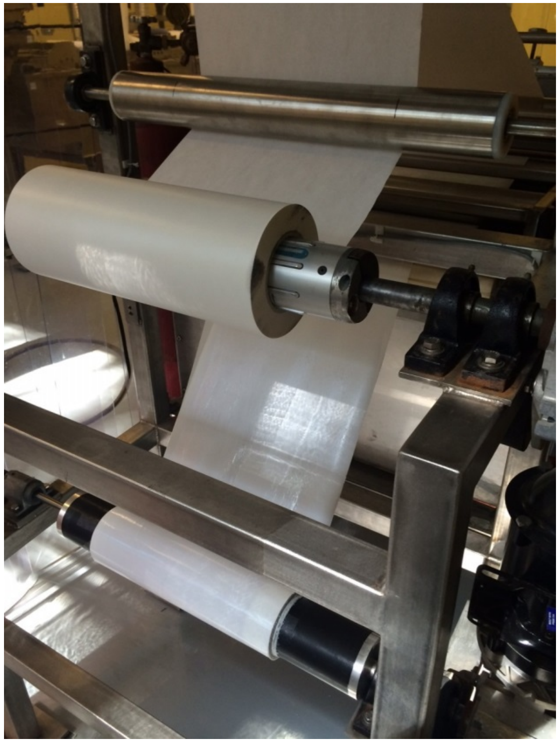
- **Improved 14"-wide PES Polymer Support Fabricated with Continuous Machine**
  - **Economical substrate for lab membrane synthesis**
- **Composite Membrane Synthesized in Lab**
  - **Elucidated carrier saturation phenomenon**
  - **940 GPU with 150 CO_2/N_2 selectivity obtained at 57°C from lab test using 1% CO_2 concentration feed gas**
    - **+ 770 GPU with 140 CO_2/N_2 selectivity obtained using 20% CO_2 concentration feed gas due to carrier saturation phenomenon**
- **High-Level Techno-economic Analysis Showed Capture Cost of ~$310/tonne CO_2 (in 2011 $)**
  - **~22% increase in COE**
- **2 PCT (Patent Cooperation Treaty) Applications Filed for New Membrane Composition and Process**

Affordable Fabrication of PES Support

Continuous Membrane Fabrication Machine at OSU

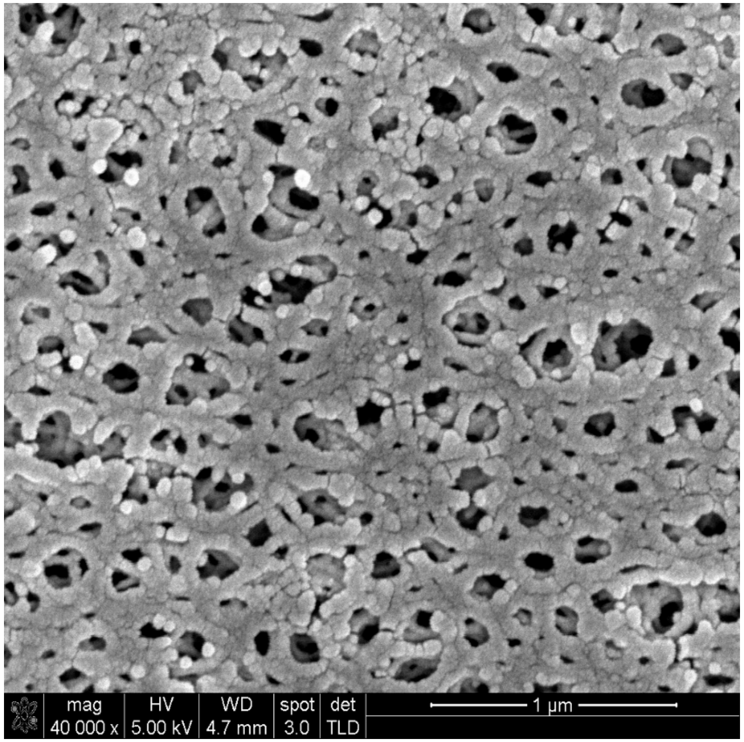
Successful Continuous Fabrication of Affordable PES Support Demonstrated in DE-FE0007632

Casting Machine



14-inch PES Support

SEM – Top View

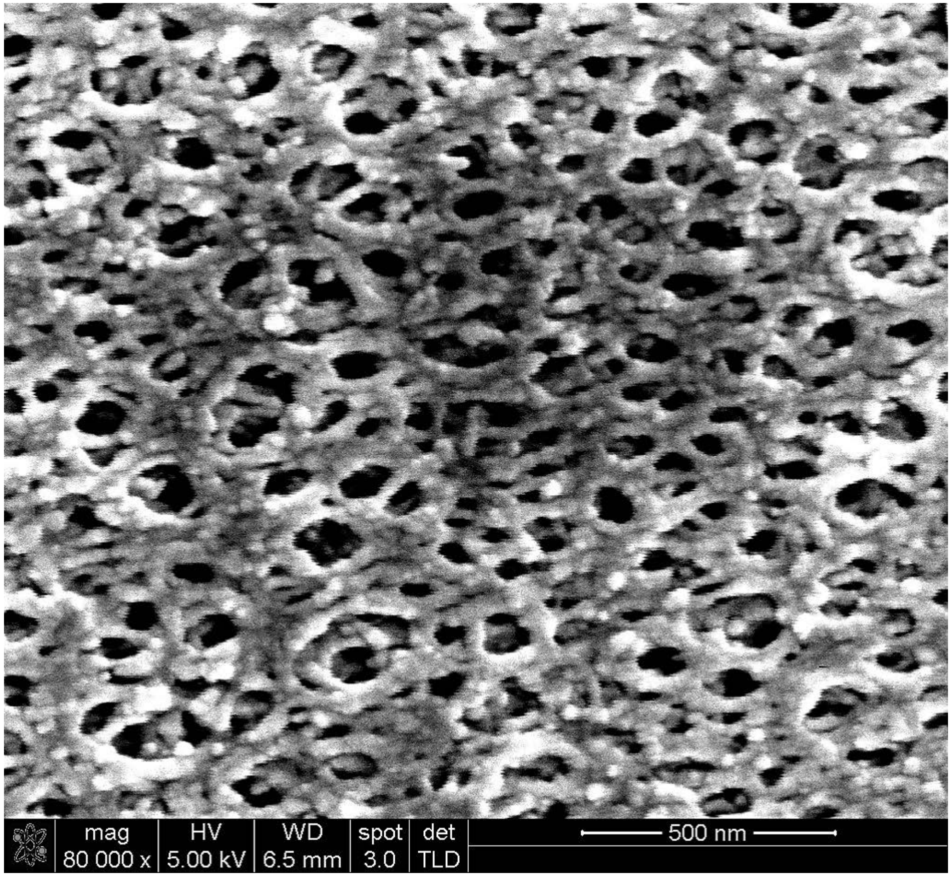


2500 feet fabricated

- **Manufacturer could not supply PES needed for scale-up**
- **PES synthesized/developed at OSU to resolve supply issue**
- **PES technology being transferred to a membrane company**

Successful Continuous Fabrication of Affordable PES Support

SEM Analysis of 14-inch PES Support

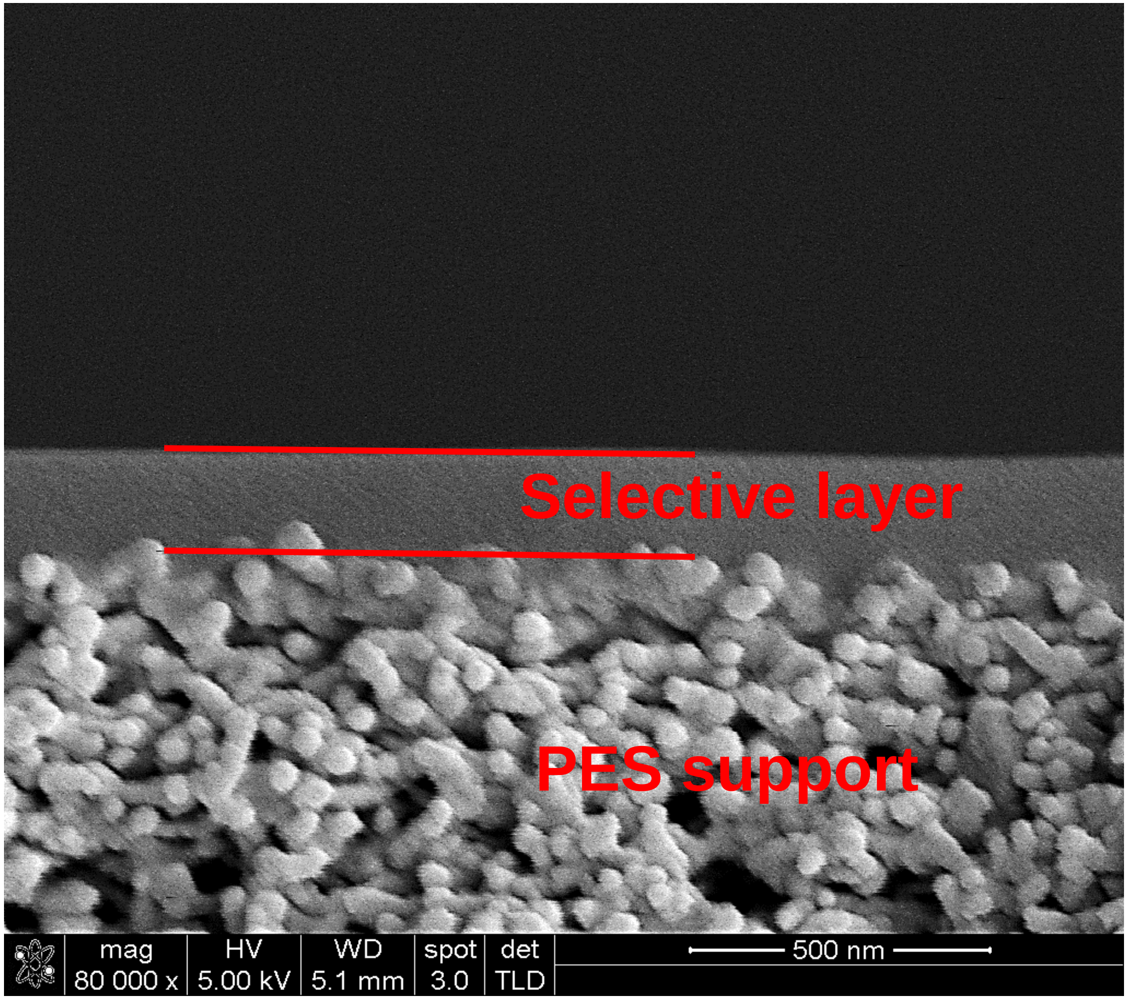


Ave. pore size = 43.7 nm,   Porosity = 13.1%

- **Optimal pore size identified to reduce penetration for improving membrane performance**

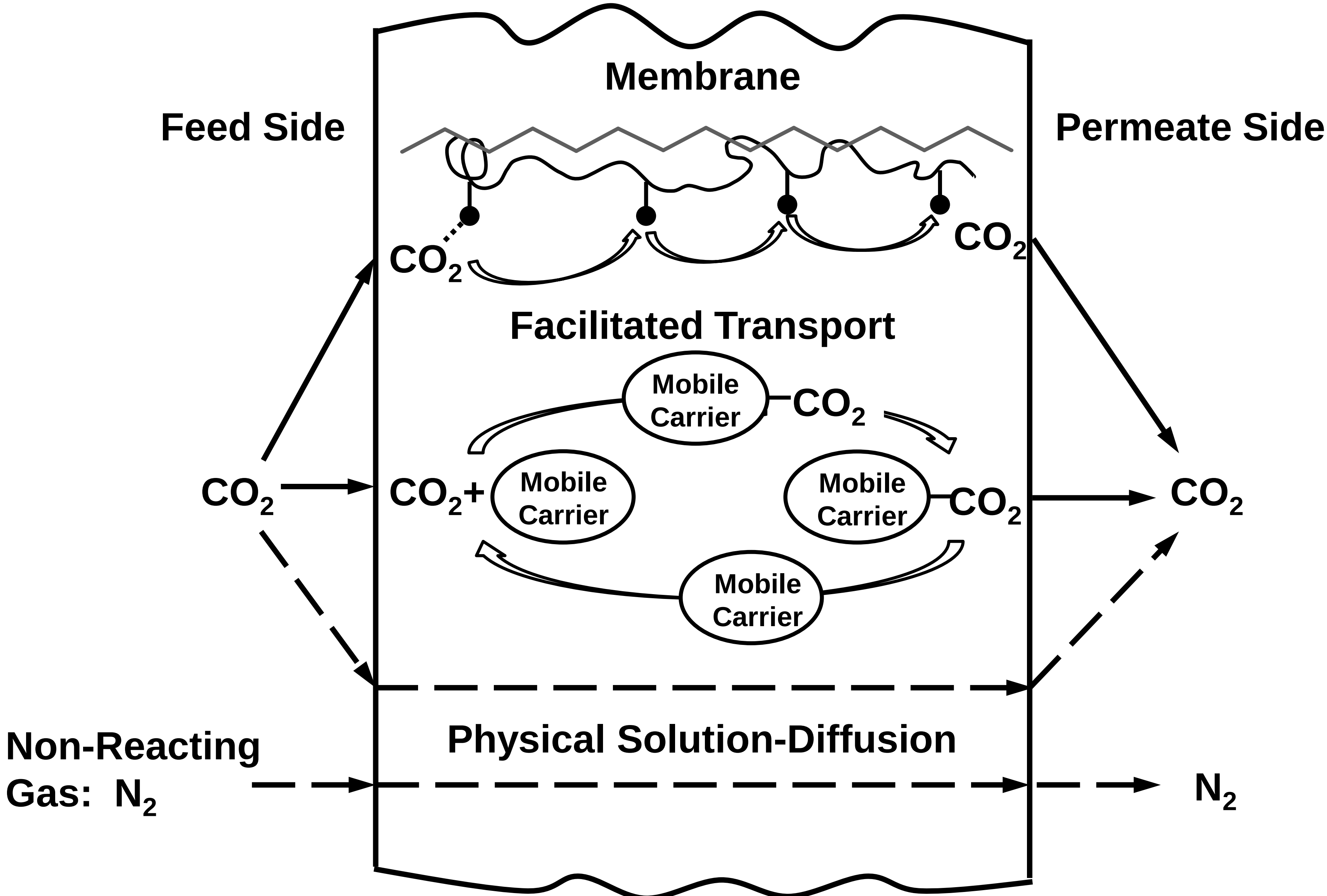
Composite Membrane Synthesized

Selective Amine Polymer Layer on PES Support



Selective layer = 165 nm

Amine Polymer Layer Contains Mobile and Fixed Carriers: Facilitated Transport



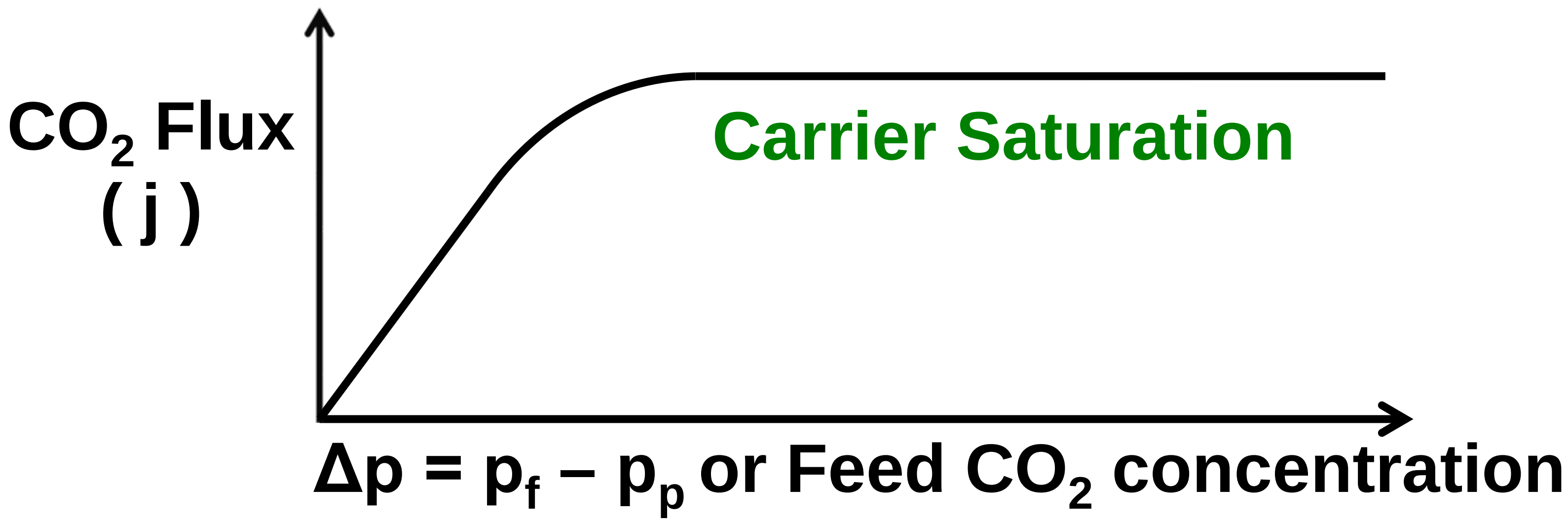
Facilitated Transport vs. Solution-Diffusion Mechanism

- CO_2 Facilitated Transport Flux: Very High
  - CO_2-amine reaction enhances CO_2 flux

- N_2 Flux: Very Low
  - N_2 does not react with amine
  - N_2 transport follows conventional physical solution-diffusion mechanism, which is very slow

Carrier Saturation Phenomenon

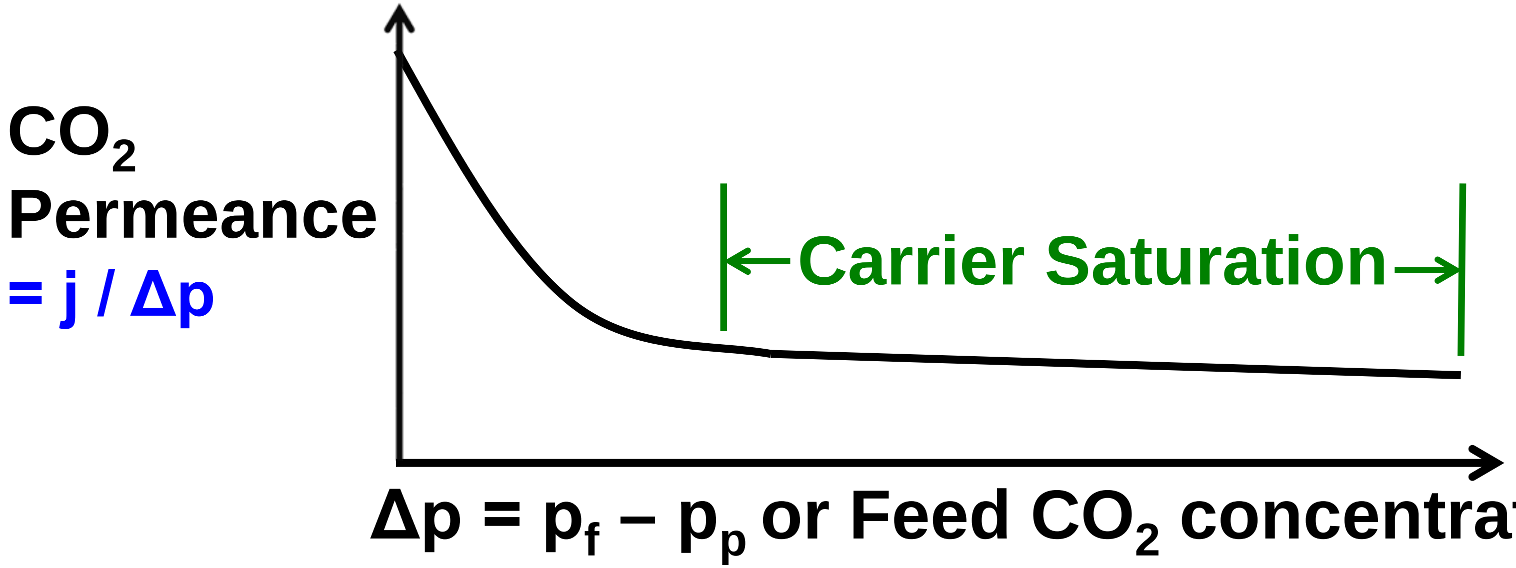
- **CO_2 Flux Increases as Pressure Increases until Carrier Saturation Occurs**



- **At Carrier Saturation, i.e., High CO_2 Pressure**
  - **CO_2 at high pressure reacts with all carriers incorporated in the membrane**
  - **CO_2 flux reaches maximum and does not increase with pressure any further**

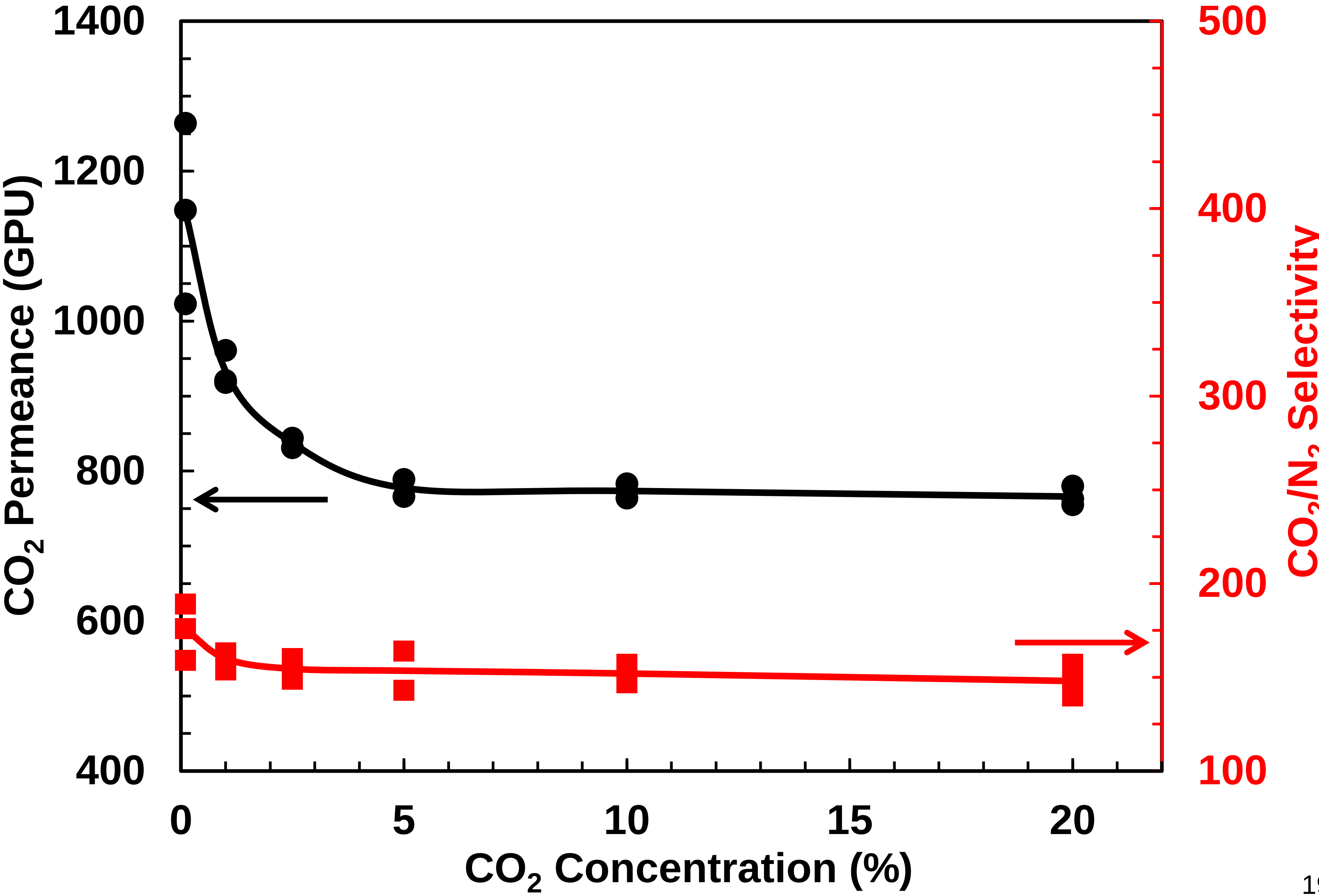
Carrier Saturation Phenomenon (cont'd)

- **At Carrier Saturation (High CO_2 Pressure), i.e., Maximum, But Constant CO_2 Flux (j)**
  - CO_2 permeance reduces as pressure increases
  - That is: CO_2 permeance increases as pressure reduces



- **At Low CO_2 Pressure, i.e., Less CO_2 Molecules**
  - More free carriers available for reaction with CO_2
    - + Greater CO_2 facilitation and then higher CO_2 permeance
  - CO_2 permeance increases as pressure reduces

Carrier Saturation Phenomenon Data



High-Level Techno-Economic Calculations

- **Basis: Membrane Results at 57ºC**
  - **940 GPU & 150 Selectivity for 1% CO_2 concentration feed gas**
  - **770 GPU & 140 Selectivity for 20% CO_2 concentration 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**
  - **32.1 tonne/h of CO_2 captured from 1% CO_2 source**
  - **$112 million bare equipment cost**
    - Membrane 25%, blowers and vacuum pumps 61%, others 14%
  - **1.82 ¢/kWh (1.29 ¢/kWh capital cost, 0.23 ¢/kWh fixed cost, 0.26 ¢/kWh variable cost, and 0.04 ¢/kWh T&S cost)**
    - COE = 8.09 ¢/kWh for 550 MW supercritical pulverized coal power plant
  - **$311/tonne capture cost ($18.2/MWh × 550 MW/(32.1 tonne/h))**
  - **22.4% Increase in COE (1.82/8.09 = 22.4%)**

Plans for Future Testing/Development

- **Remaining BP1**
  - **Continue laboratory-scale membrane synthesis, characterization & transport performance studies in BP1**
  - **Complete carrier saturation phenomenon study**
  - **Update high-level preliminary techno-economic analysis**
- **BP2**
  - **Continue laboratory-scale membrane synthesis and characterization for performance improvement**
  - **Fabricate larger lab-size membrane (~ 6” by 6”)**
  - **Fabricate, evaluate and down-select from plate-and-frame and spiral-wound membrane modules**
  - **Update techno-economic analysis performed in BP 1**
- **BP3**
  - **Fabricate 3 laboratory membrane modules**
  - **Test modules with <1% CO_2 simulated gas mixture**
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Acknowledgments

José Figueroa

Great efforts and strong inputs

DOE/NETL

Financial support