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

DE-FE0026919

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DE-FE0026919 Continuation Application Status Meeting
NETL, Pittsburgh, PA, February 27, 2017

Outline

- **Project Objective and Scope**
- **Process and Membrane**
- **BP1 Accomplishments**
- **Membrane Performance**
- **Techno-Economic Analysis Results**
- **Proposed BP2 & BP3 Tasks & Budgets**
- **Closing Statement**

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**
  - Laboratory-scale membrane synthesis, characterization and transport performance studies
  - High-level preliminary techno-economic analysis
- **BP2: 03/01/2017 – 02/28/2018**
  - Laboratory-scale membrane synthesis, characterization and transport performance studies to continue
  - Fabrication of larger size membrane (14” wide instead of 6”)
  - Fabrication, evaluation and down-selection 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 small pilot membrane modules (14” long)
  - Module testing 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
- 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

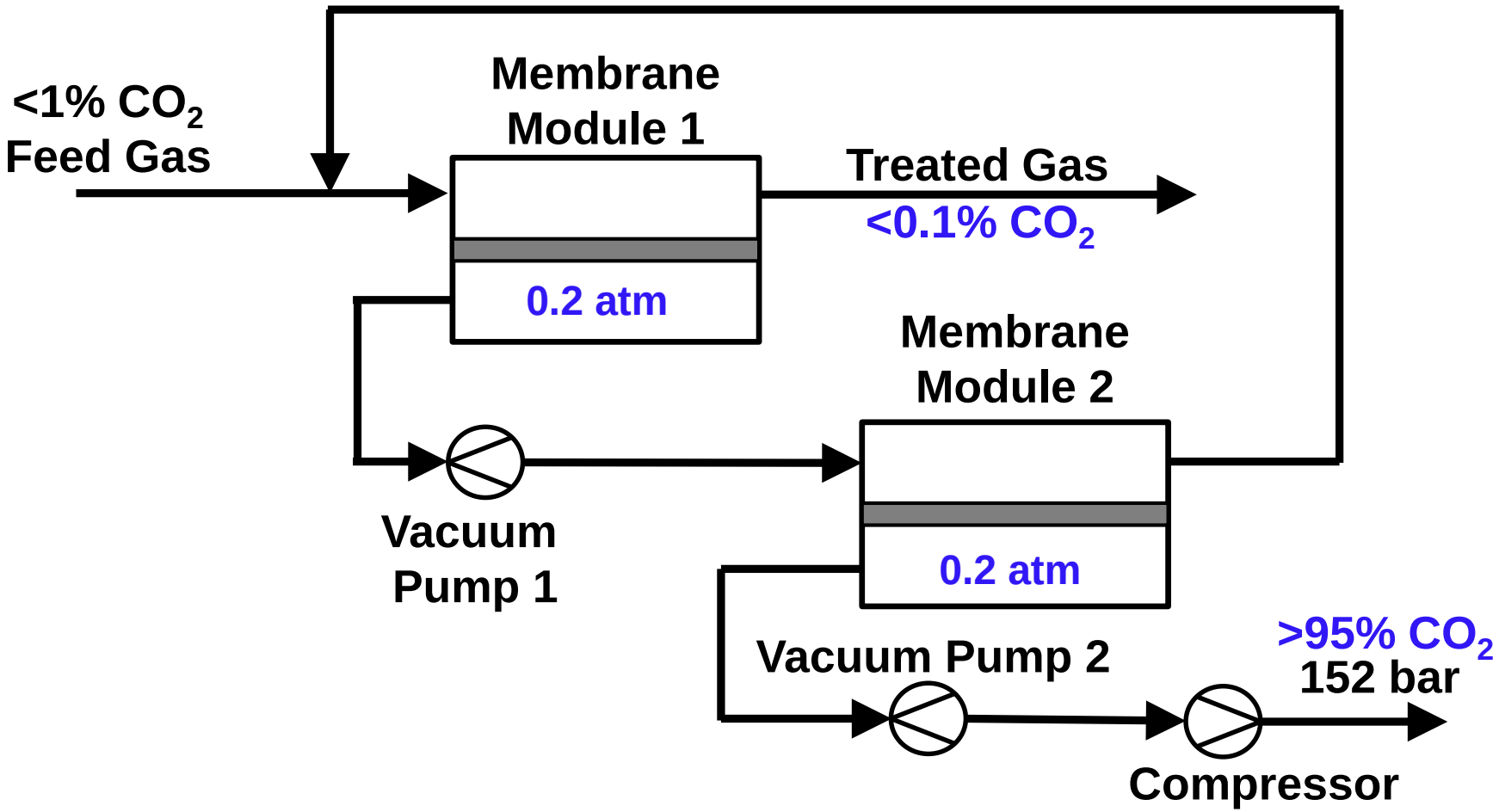
Steve Schmit

AEP

- Consult on plant integration and demonstration considerations

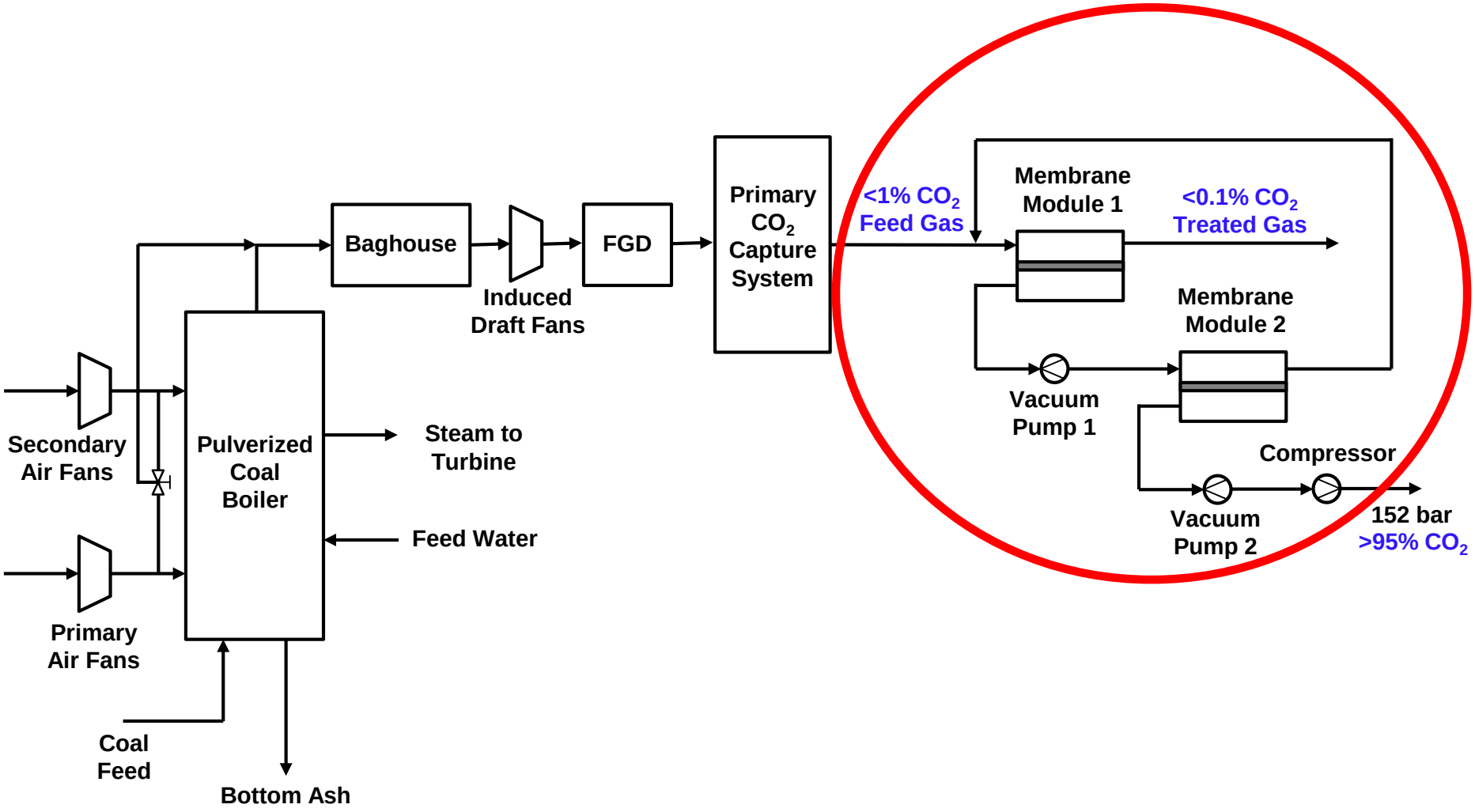
Matt Usher

Process Proposed for CO_2 Capture from <1% CO_2 Sources



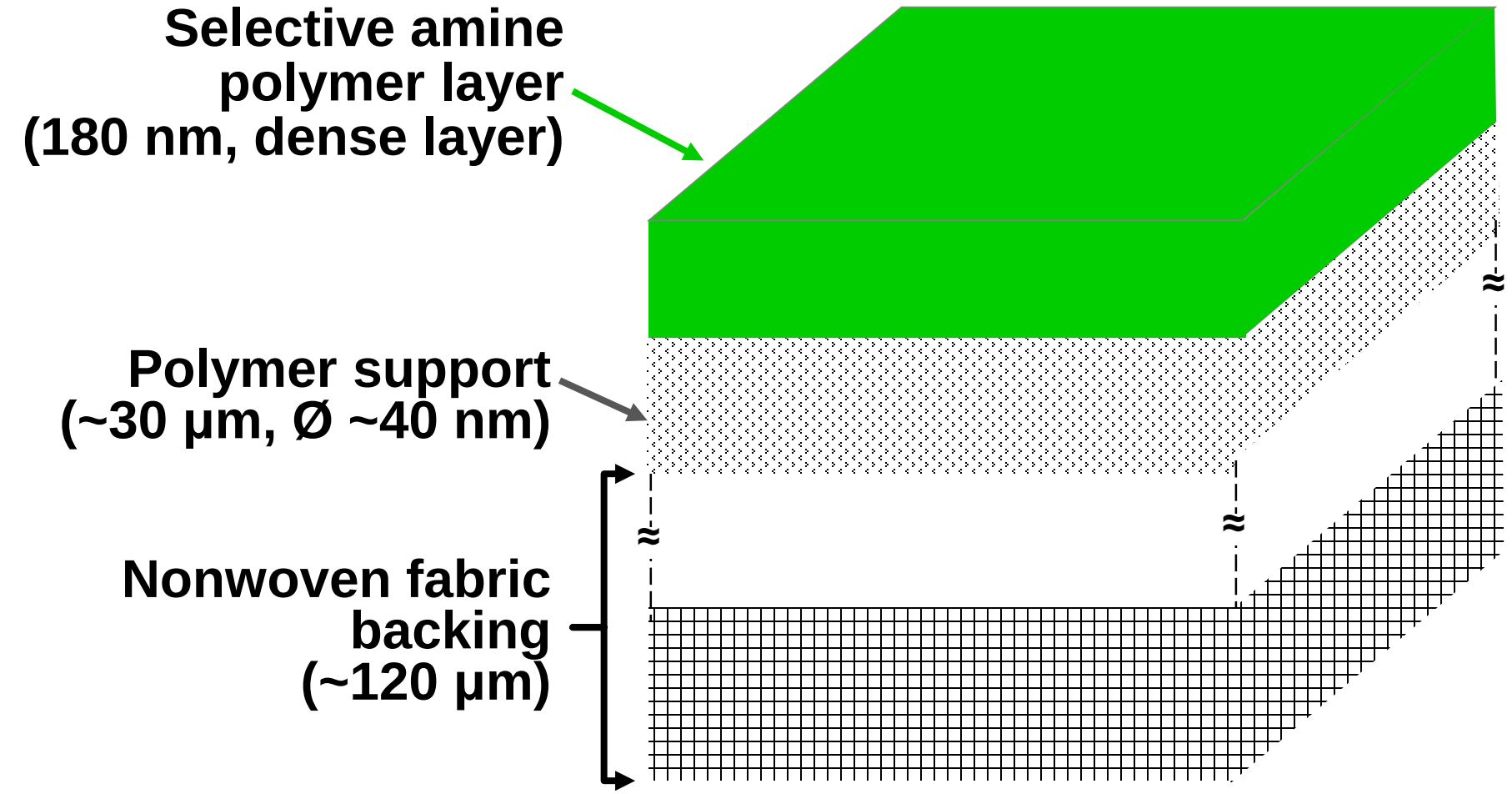
- Proposed membrane process does not require cryogenic distillation (compared to competition)

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**

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

  - **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**
  - **Economical substrate for lab membrane synthesis**
  - **Hydrophilic polymer incorporated for improving porosity, permeance and adhesion**
  - **Resulting in improved membrane performance**
- **Composite Membranes Synthesized in Lab**
  - **High molecular weight polyamine synthesized**
  - **Significant membrane performance improvement achieved**
  - **Carrier saturation phenomenon elucidated**
  - **982 GPU with 211 CO_2/N_2 selectivity obtained at 57°C from lab test using 1% CO_2 concentration feed gas**
    + Met BP1 target (700 – 850 GPU & CO_2/N_2 selectivity 100 – 140)
    + 806 GPU with 173 CO_2/N_2 selectivity obtained using 20% CO_2 concentration feed gas due to carrier saturation phenomenon

BP1 Accomplishments (cont'd)

- **High-Level Techno-economic Analysis Conducted**
  - **Capture cost of ~$302/tonne CO_2 (in 2011 $)**
  - **21.8% increase in COE**

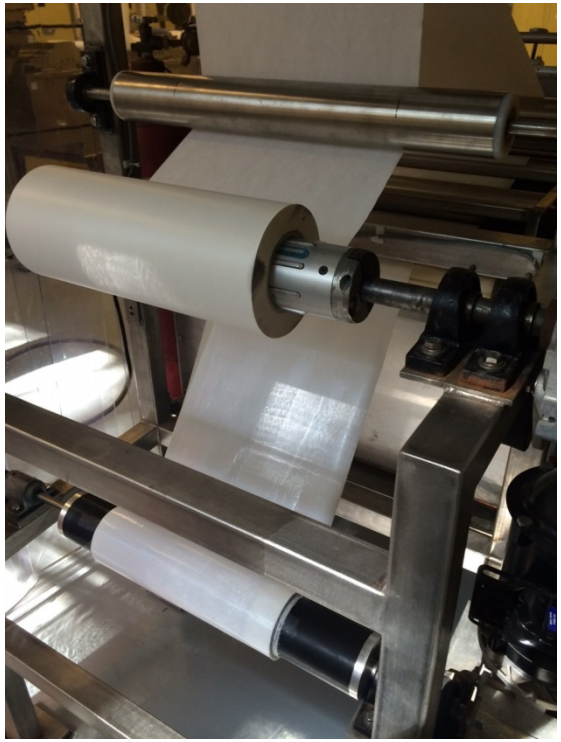
- **5 Patent Applications Filed**
  - **3 for new membrane compositions**
    + 2 U.S. patent applications
    + 1 PCT (Patent Cooperation Treaty) application
  - **2 for new membrane processes**
    + 1 U.S. provisional patent application
    + 1 PCT application

Scale-up for PES Support

Continuous Membrane Fabrication Machine at OSU

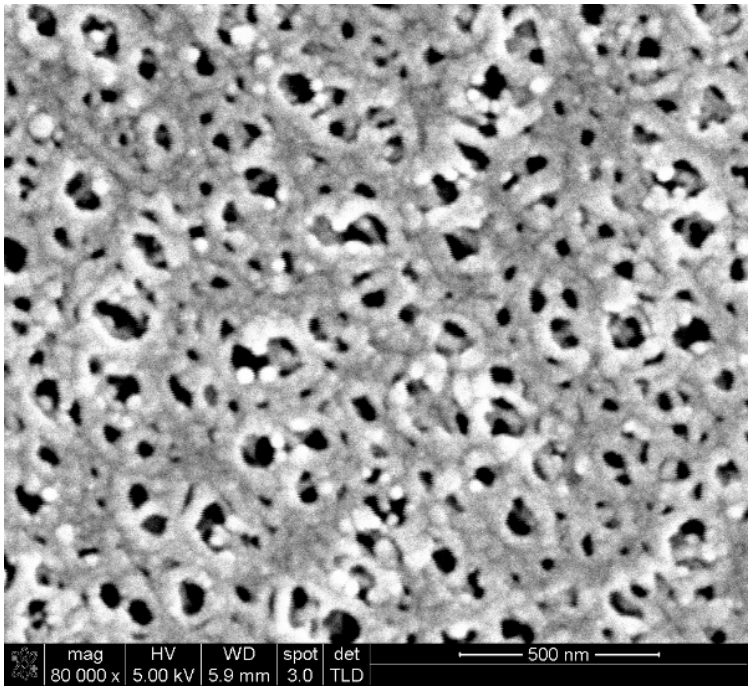
Successful Continuous Fabrication of Affordable PES Support Demonstrated

Casting Machine



14-inch PES Support

SEM – Top View

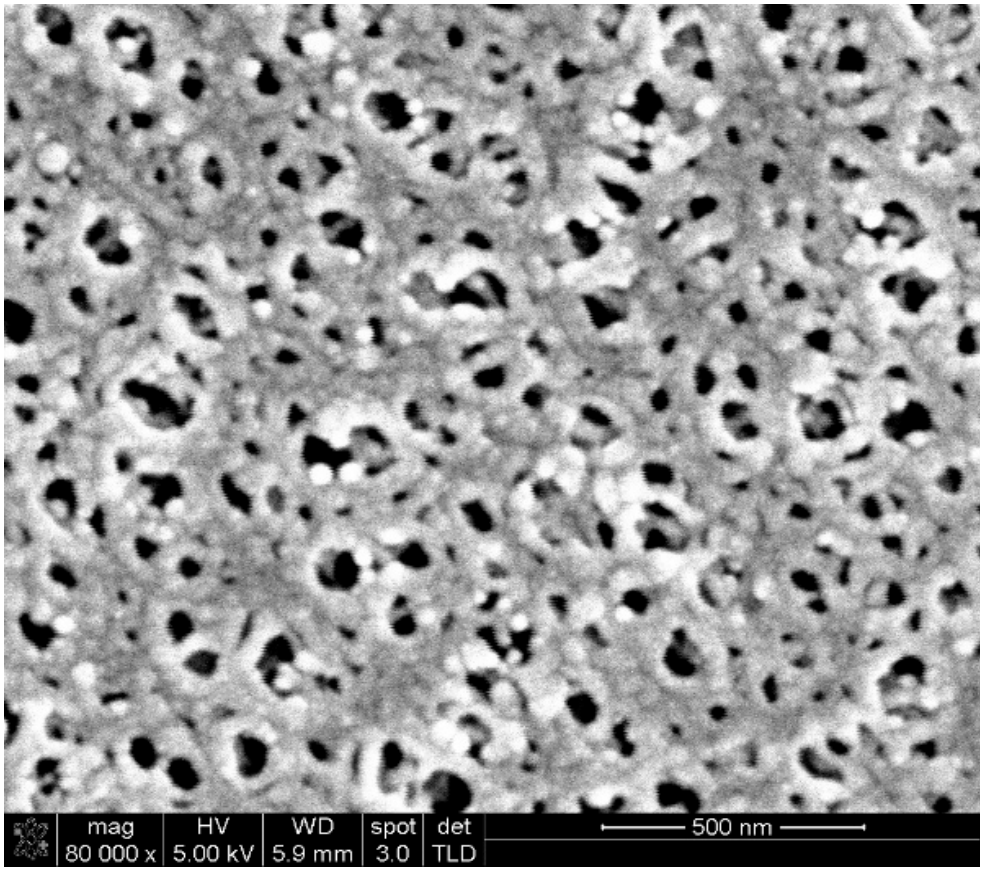


600 feet fabricated in BP1

- **Manufacturer could not supply PES for DE-FE0007632**
- **PES synthesized/developed at OSU to resolve supply issue**
- **PES technology being transferred to a membrane company**

Successful Continuous Fabrication of Affordable PES Support

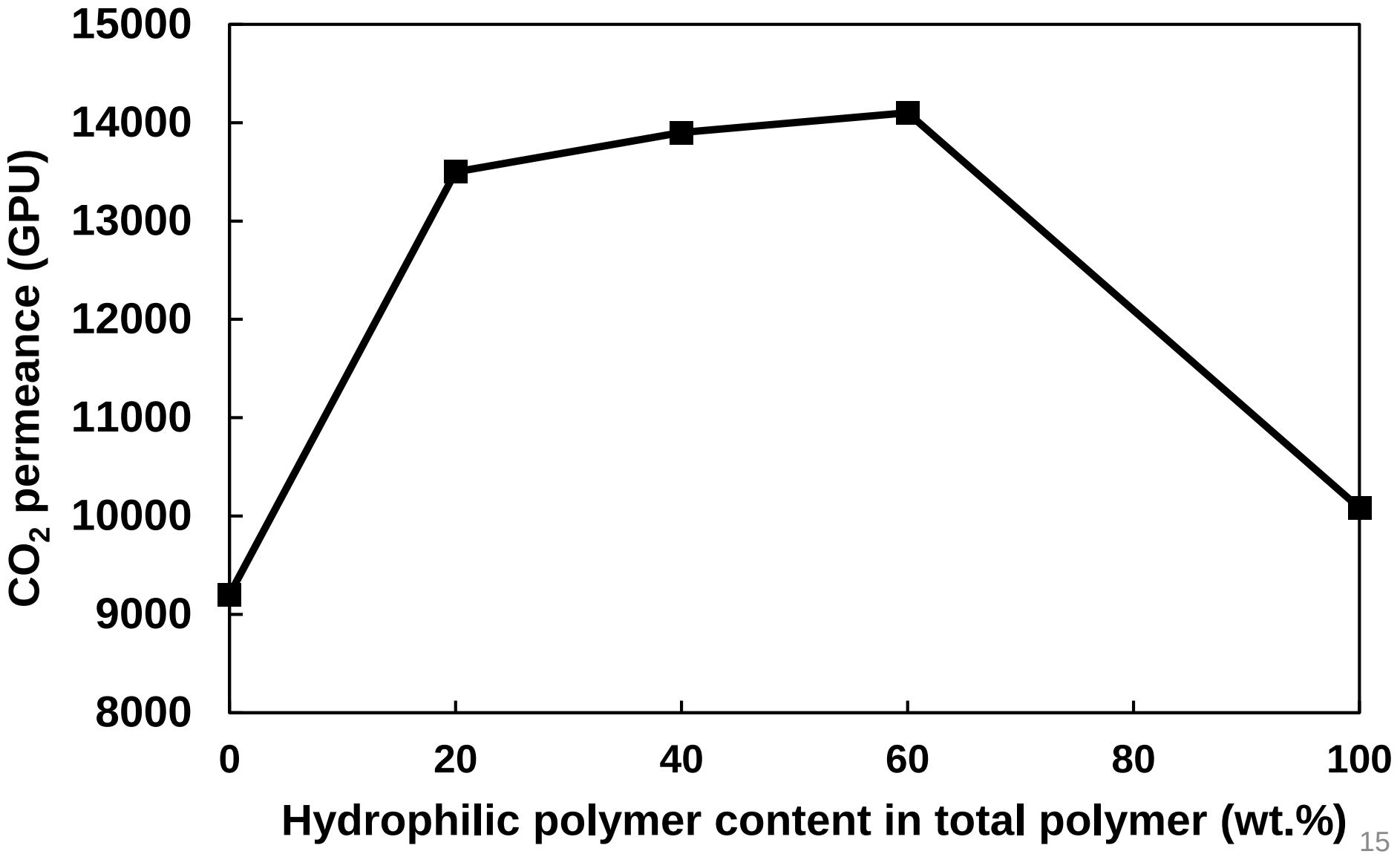
SEM Analysis of 14-inch PES Support



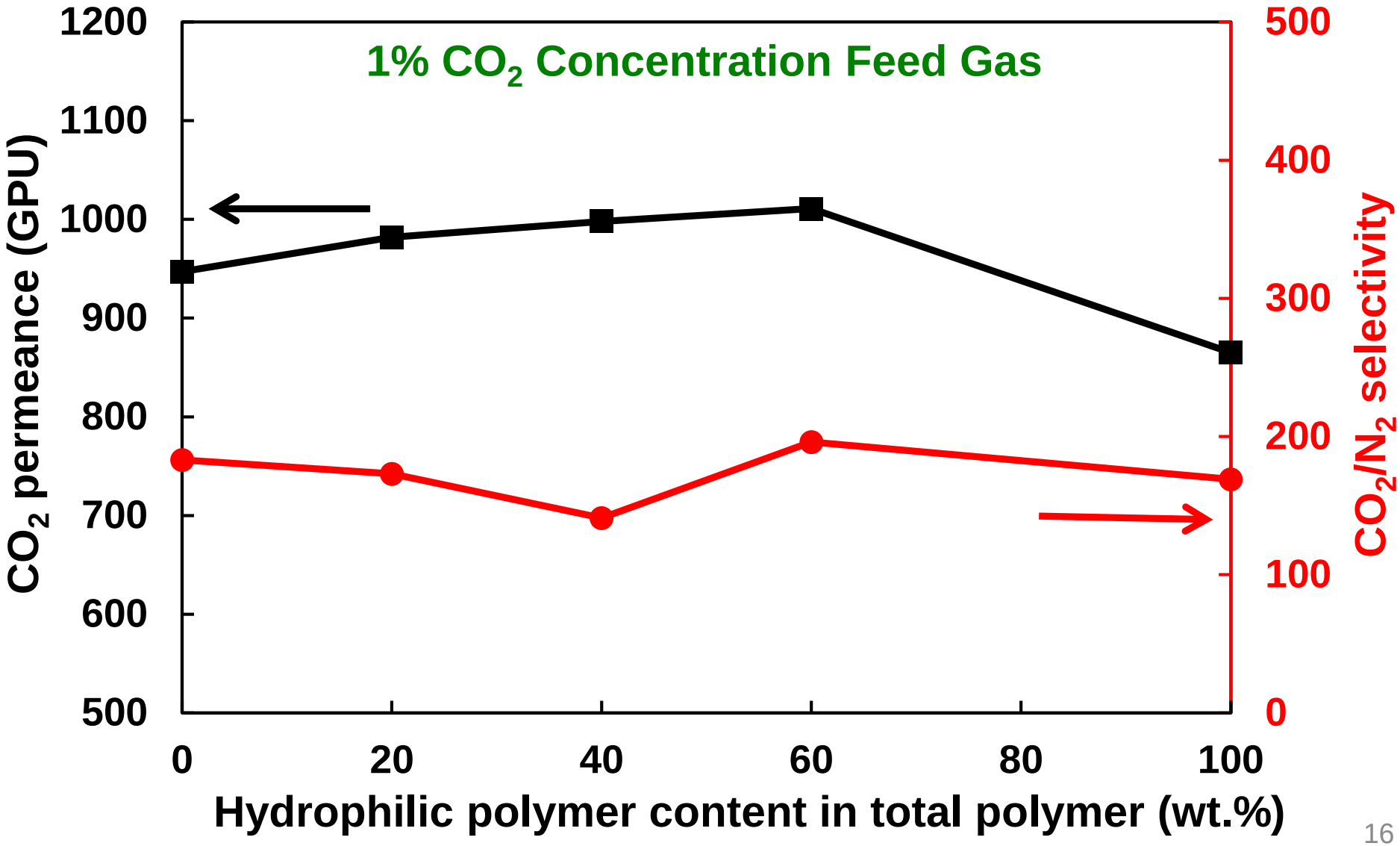
Ave. pore size = 41.1 nm, Porosity = 12.5%

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

Hydrophilic Polymer Incorporated Improved Substrate Permeance

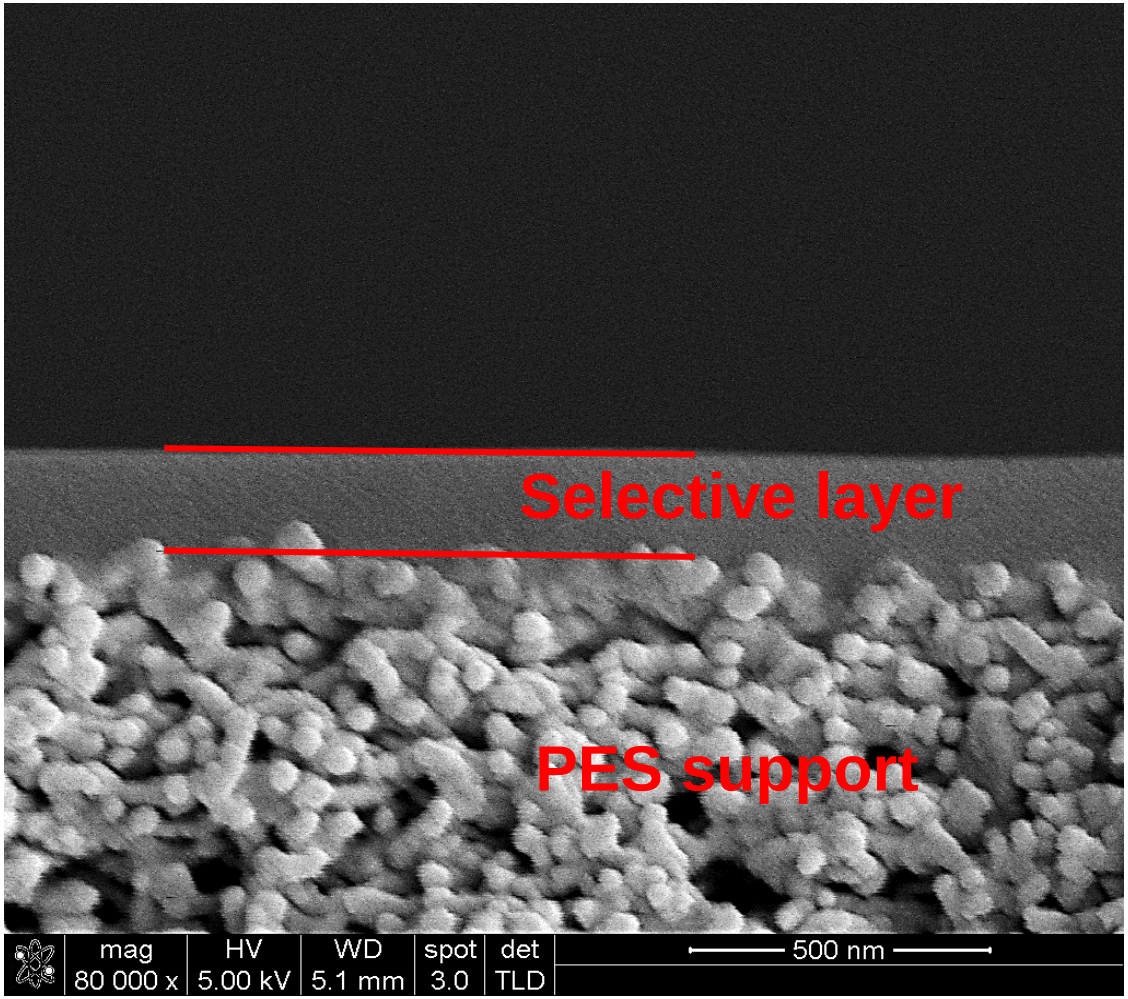


Hydrophilic Polymer Incorporated Improved Membrane Permeance



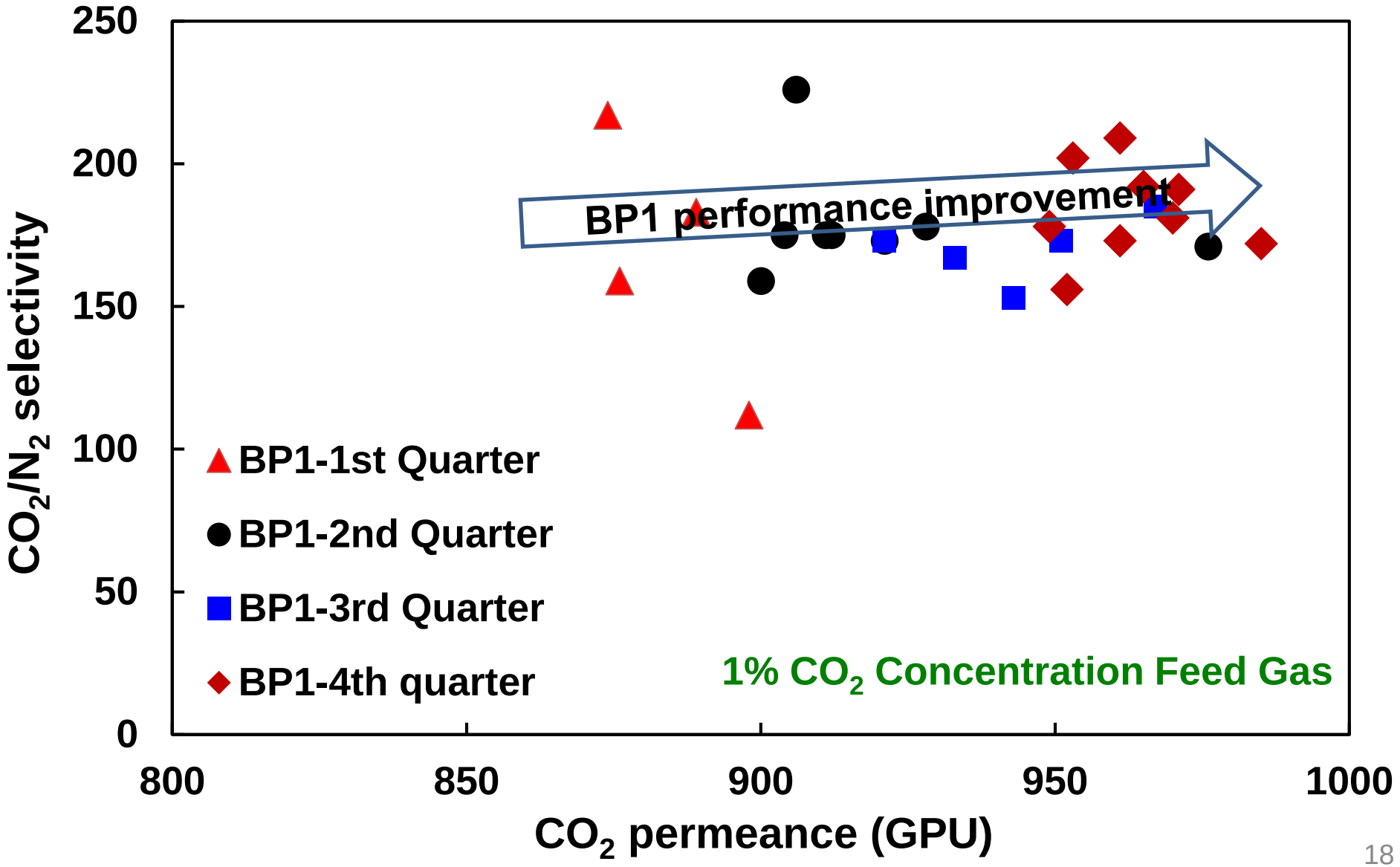
Composite Membrane Synthesized

Selective Amine Polymer Layer on PES Support

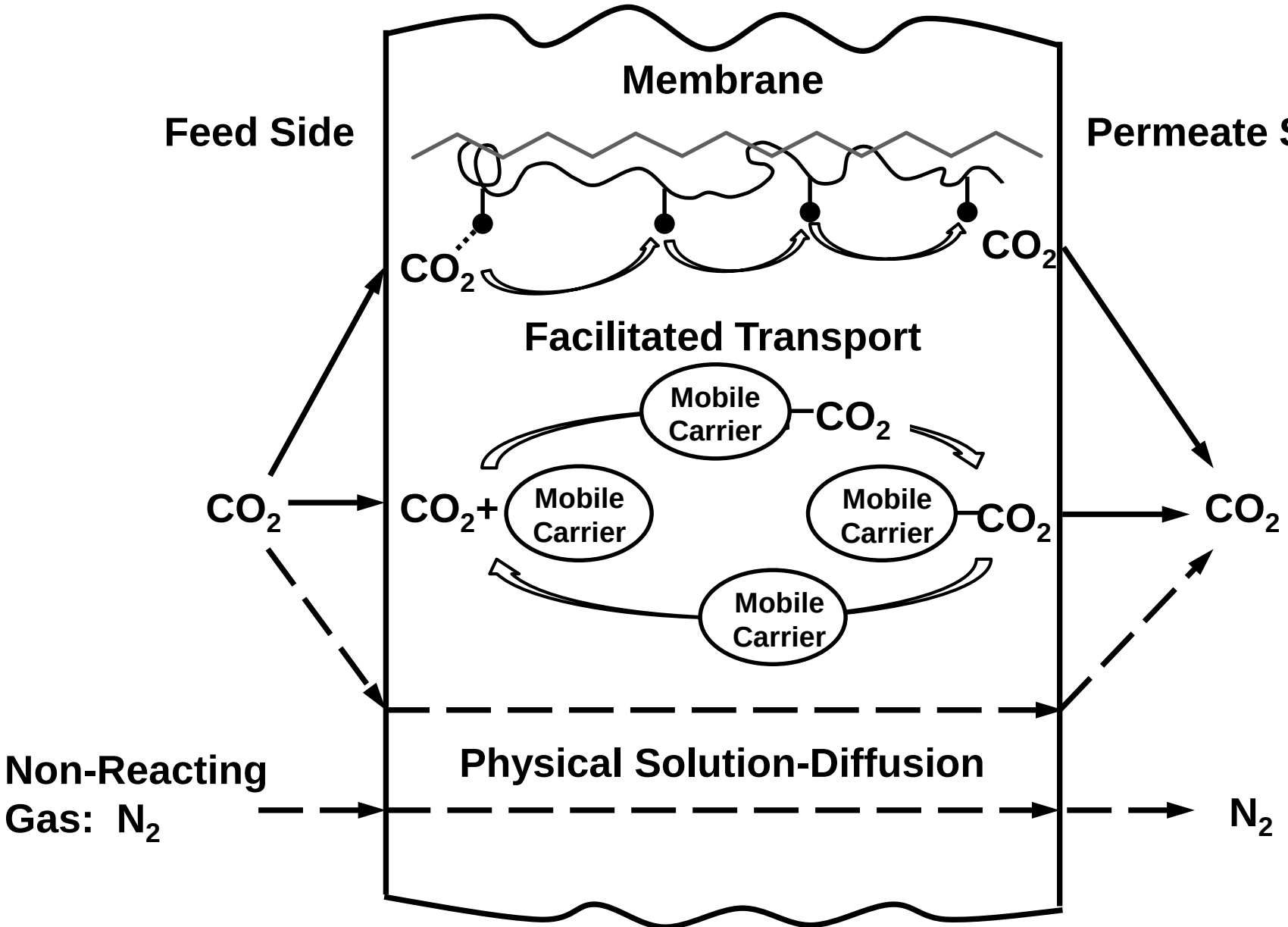


Selective layer = 165 nm

Significant Membrane Performance Improvement Achieved



Amine Polymer Layer Contains Mobile and Fixed Carriers: Facilitated Transport



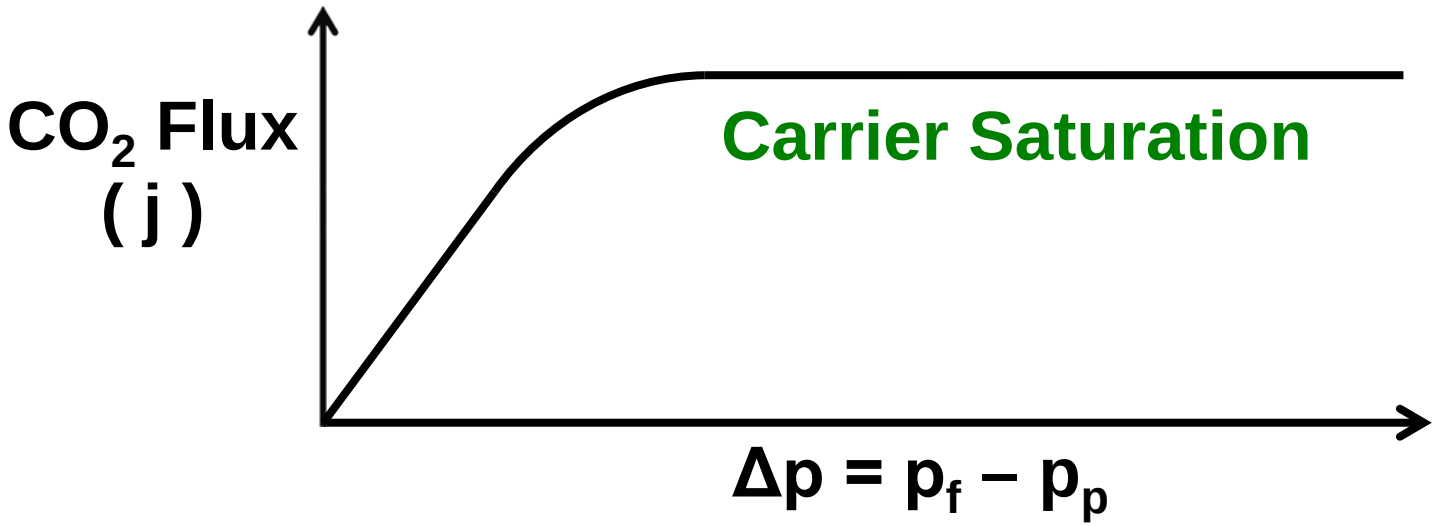
Facilitated Transport vs. Solution-Diffusion Mechanism

- **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

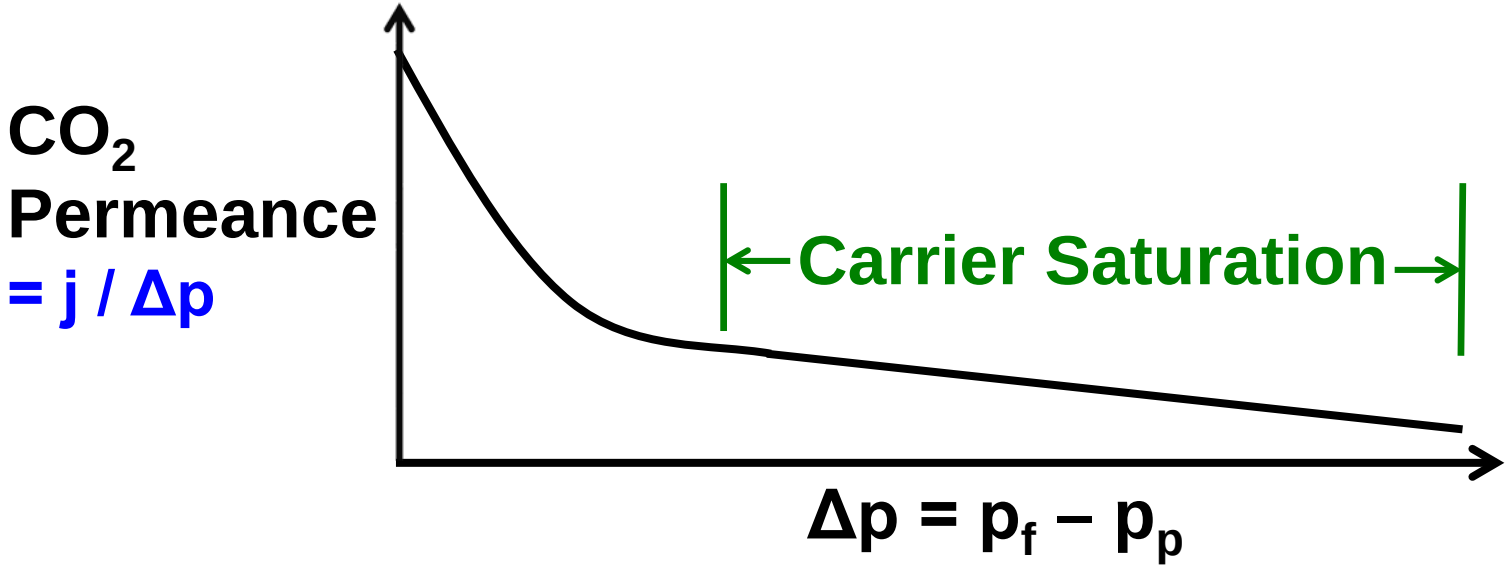
- **CO_2 Flux Increases as Pressure Increases until Carrier Saturation Occurs**



- **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**

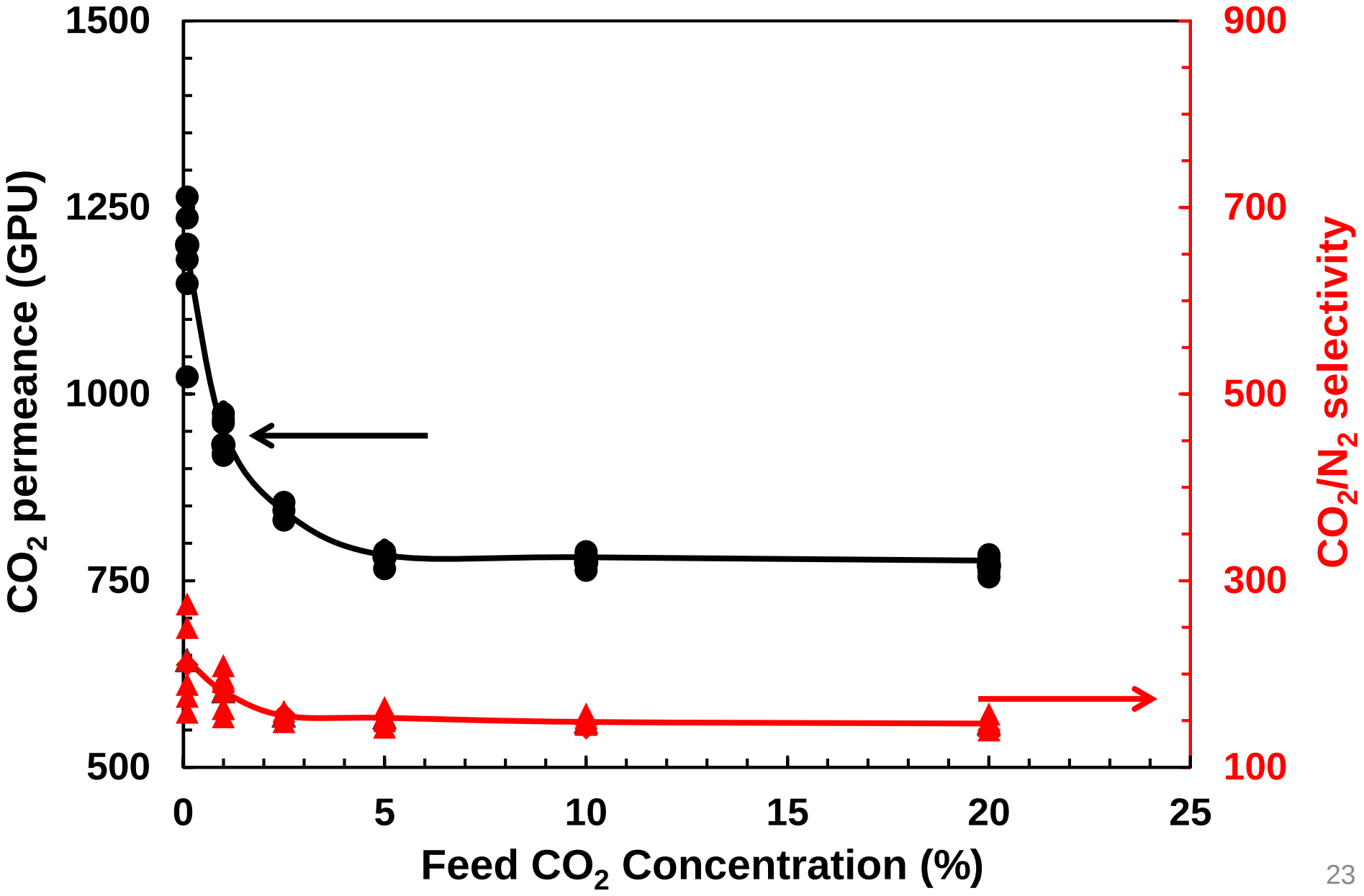
Carrier Saturation Phenomenon (cont'd)

- **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

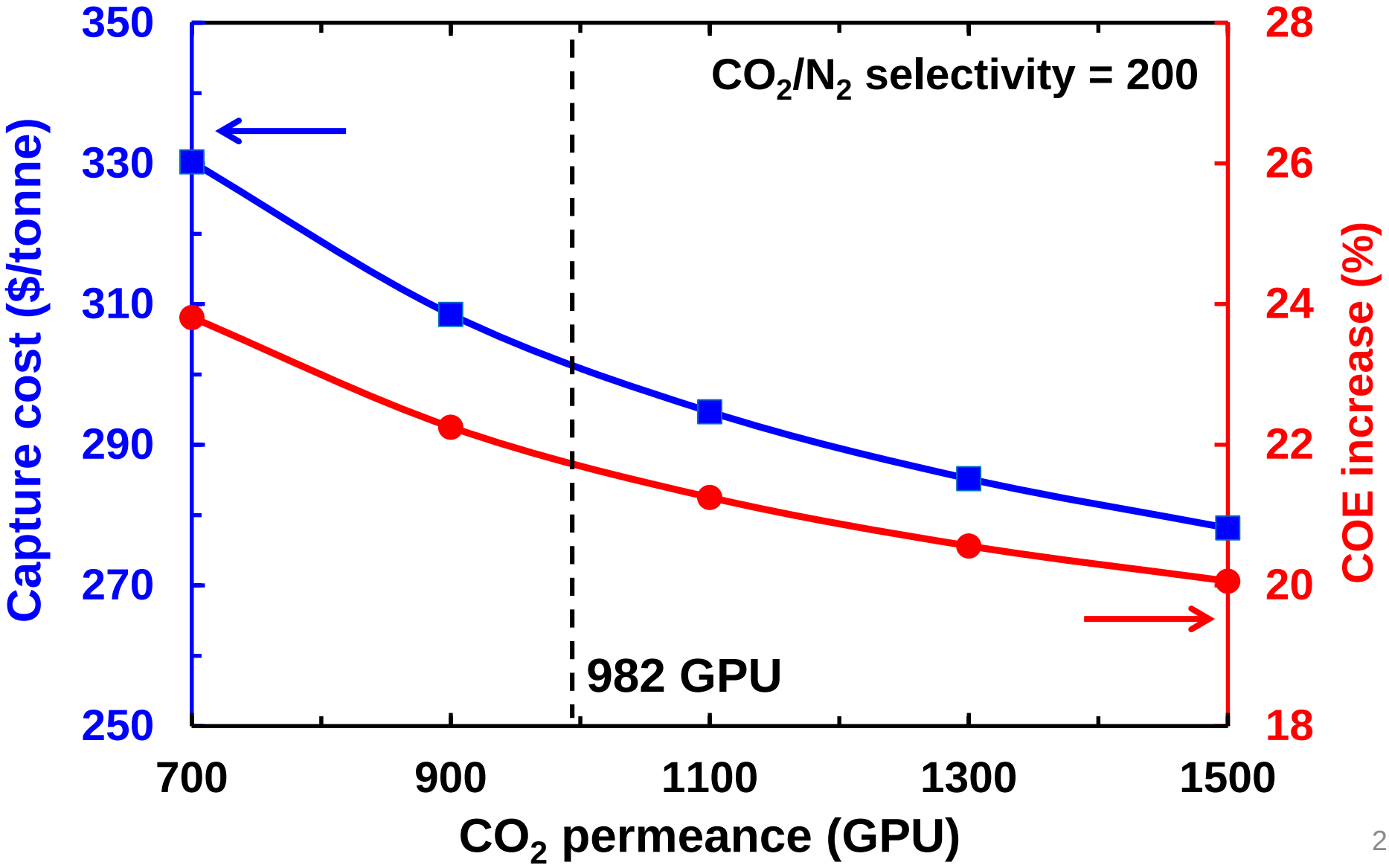


High-Level Techno-Economic Calculations

- **Basis: Membrane Results at 57ºC**
  - **982 GPU & 211 Selectivity for 1% CO_2 concentration feed gas**
  - **806 GPU & 173 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**
  - **$107.8 million bare equipment cost**
    - ➢ Membrane 34%, blowers and vacuum pumps 62%, others 4%
  - **1.76 ¢/kWh (1.24 ¢/kWh capital cost, 0.22 ¢/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
  - **$302/tonne capture cost ($17.6/MWh × 550 MW/(32.1 tonne/h))**
  - **21.8% Increase in COE (1.76/8.09 = 21.8%)**

Effect of CO_2 Permeance on Techno-economic Analysis Results



BP1 Milestone Status Report

Milestone Title Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Task 1. Project Management and Planning	02/28/2017			Good project progress made
Project Kickoff Meeting	04/04/2016	04/04/2016	Presentation file	
Task 2. Synthesis of Improved Polymer Support	02/28/2017			To complete on time
Polymer support >9000 GPU	02/28/2017	12/31/2016	Transport measurement	>9000 GPU achieved
Task 3. Synthesis of Novel Membranes	02/28/2017			To complete on time
High MW polyamine synthesized	02/28/2017	12/31/2016	Laboratory notebook	High MW polyamine synthesized
Task 4. Membrane Characteriz.	02/28/2017			To complete on time
CO_2 permeance > 700 GPU	02/28/2017	12/31/2016	Performance data	BP1 target met
CO_2/N_2 selectivity > 140	02/28/2017	12/31/2016	Performance data	BP1 target met
Task 5. Carrier Saturation Phenomenon Study	02/28/2017		Transport results	Carrier saturation phenomenon elucidated
Task 6. Techno-economic and System Analysis	02/28/2017			To complete on time
High-level techno-economic analysis	02/28/2017	12/31/2016	Capture cost results	Capture cost obtained
Quarterly reports submitted	4,7,10/30/ 2016 and 1,4/30/2017	Q1: 04/25/2016 Q2: 07/30/2016 Q3: 10/29/2016 Q4: 01/26/2017	Project Manager	On Schedule
Annual report submitted	04/30/2017		Project Manager	To submit on time

BP2 and BP3 Budgets

Budget Period	Federal Share	Non-Federal Share	Project Total
2	$419,628	$125,344	$544,972
3	$421,034	$125,764	$546,798

- **BP2 budget amounts same as those submitted to and approved by NETL**
- **BP3 budget amounts also same as those submitted to and approved by NETL**

BP2 Tasks – No Major Changes

Task 7 – Project Management and Planning

Task 8 – Improved Membrane Synthesis
- Incorporate high permeance PES substrate
- Synthesize improved CO_2 carriers (high MW polyamines)

Task 9 – Improved Membrane Characterization
- Improve membrane performance in CO_2 permeance & selectivity

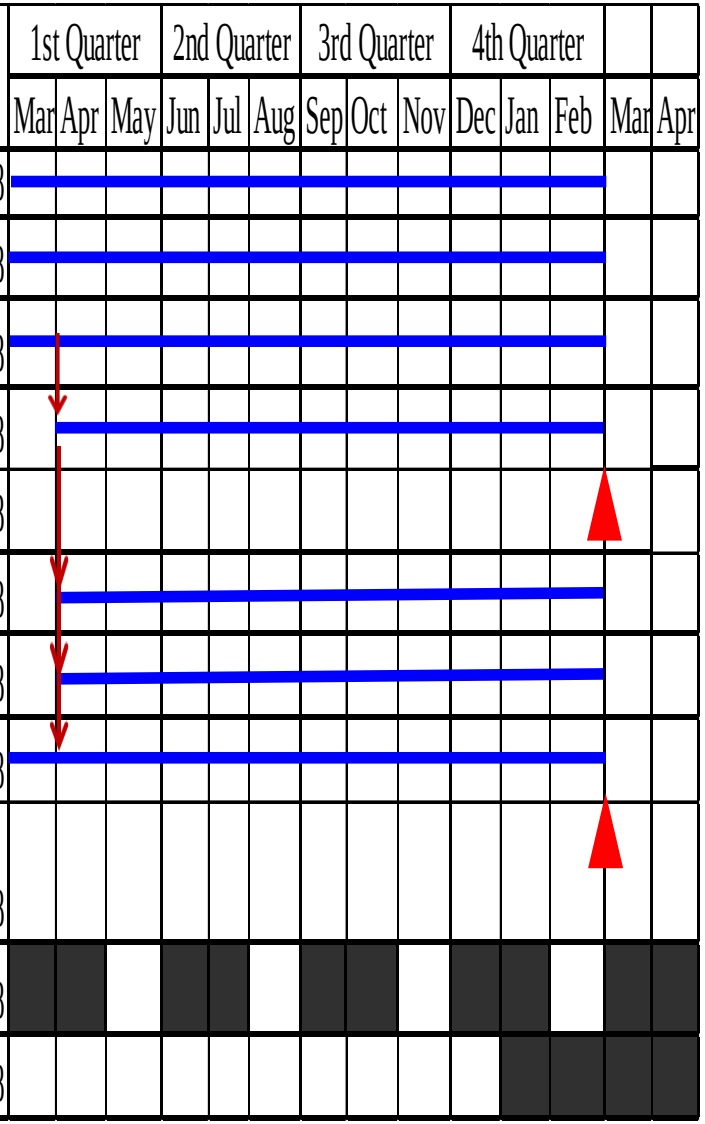
Task 10 – Comparative Membrane Configuration Evaluation
- Fabricate small pilot membrane modules with ~14 inches in length (instead of 6 inches in length to gain more progress)
- Evaluate both plate-and-frame and spiral-wound modules
- Down-select the better membrane module configuration

Task 11 – Contaminant Testing
- Use simulated gas mixture (<1% CO_2) containing 3% O_2 and 1 – 3 ppm SO_2
- Investigate effect of contaminants

Task 12 – Use and Refining of Techno-economic Analysis
- Predict economic feasibility of ≥90% CO_2 capture with ≥95% purity

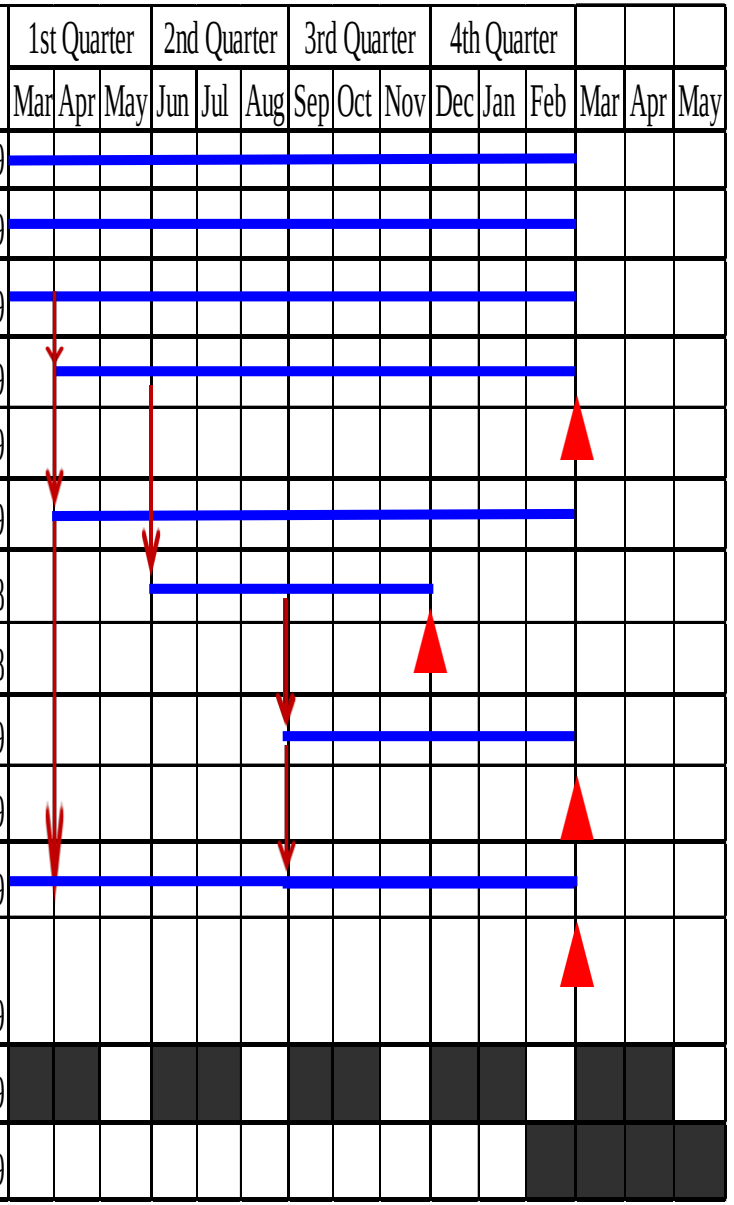
Budget Period 2

Task Name	Total Cost of Task ($)	Start	Finish
Budget Period 2	544,972	3/1/2017	2/28/2018
Task 7: Project Management and Planning	6,388	3/1/2017	2/28/2018
Task 8: Improved Membrane Synthesis	153,213	3/1/2017	2/28/2018
Task 9: Improved Membrane Characterization	140,467	4/1/2017	2/28/2018
Milestone 3: CO_2 permeance = 850-1000 GPU & CO_2/N_2 selectivity =100-140			2/28/2018
Task 10: Comparative Membrane Configuration Evaluation	153,213	4/1/2017	2/28/2018
Task 11: Contaminant Testing	70,234	4/1/2017	2/28/2018
Task 12: Use and Refining of Techno-economic Analysis	13,645	3/1/2017	2/28/2018
Milestone 4: Economic feasibility of ≥90% CO2 capture with ≥95% purity predicted			2/28/2018
Quarterly Progress Reports	4,322	3/1/2017	4/30/2018
Budget Period 2 Annual Report	3,490	1/1/2018	4/30/2018



Budget Period 3

Task Name	Total Cost of Task ($)	Start	Finish
Budget Period 3	546,798	3/1/2018	2/28/2019
Task 13: Project Management and Planning	6,388	3/1/2018	2/28/2019
Task 14: Optimized Membrane Synthesis	117,307	3/1/2018	2/28/2019
Task 15: Optimized Membrane Characterization	107,548	4/1/2018	2/28/2019
Milestone 5: CO_2 permeance = 1000-1800 GPU & CO_2/N_2 selectivity =140-200			2/28/2019
Task 16: Contaminant Testing and Analysis on Membrane Performance	58,653	4/1/2018	2/28/2019
Task 17: Membrane Module Fabrication	117,307	6/1/2018	11/30/2018
Milestone 6: 3 pilot membrane modules fabricated			11/30/2018
Task 18: Membrane Module Testing	117,306	9/1/2018	2/28/2019
Milestone 7: CO_2 permeance = 1000-1800 GPU & CO_2/N_2 selectivity =140-200			2/28/2019
Task 19: Update Techno-economic Model	13,645	3/1/2018	2/28/2019
Milestone 8: Economic feasibility of ≥90% CO_2 capture and ≥95% CO_2 purity targets predicted with final data and associated design guidelines			2/28/2019
Quarterly Progress Reports	4,322	3/1/2018	3/30/2019
Final Project Report	4,322	2/1/2019	5/30/2019



Summary

- **Achieved Milestones/Success Criteria for BP1**
  - **Composite membranes synthesized in lab**
    + 982 GPU with 211 CO_2/N_2 selectivity obtained at 57°C from lab test using 1% CO_2 concentration feed gas
    + 806 GPU with 173 selectivity obtained using 20% CO_2 concentration feed gas due to carrier saturation phenomenon
  - **Improved 14”-wide PES polymer support fabricated with continuous machine**
  - **Carrier saturation phenomenon elucidated**
  - **High-level techno-economic analysis conducted**
    + Capture cost of ~$302/tonne CO_2 (in 2011 $)
    + 21.8% increase in COE
- **Proposed BP2 Tasks in Place**
  - **Logical next step**
- **Asking NETL to Authorize Proposed BP2 Research, Budget, and Schedule**