Novel Inorganic/Polymer Composite Membranes for CO_2 Capture

DE-FE0007632

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The Ohio State University

Steve Schmit, Director of R&D

Gradient Technology

FE0007632 Continuation Application Status Meeting
NETL, Pittsburgh, PA, August 7, 2014

Outline

- Project Objective and Scope
- Membrane Approaches
- BP1 Accomplishments
- BP2 Accomplishments
- Membrane and Process Performance
- Techno-Economic Analysis Results
- Proposed BP3 SOPO
- Closing Statement

Project Objective

- Develop a cost-effective design and manufacturing process for new membrane modules that capture CO_2 from flue gas
  - **BP1**
    - Bench scale membrane synthesis, characterization, downselection, and gas separation performance
    - Preliminary techno-economic analysis
  - **BP2**
    - Bench scale membrane synthesis, characterization and gas separation performance to continue
    - Continuous membrane fabrication
    - Membrane module testing in lab (CO_2, N_2, MOISTURE)
    - Update techno-economic analysis
  - **BP3**
    - 3 prototype modules for testing with simulated flue gas
    - Update techno-economic analysis
    - EH&S evaluation report will be developed

- Comprehensive program with fundamental studies, applied research, synthesis, characterization and transport studies, scale-up, techno-economic analysis, and EH&S

Project Organization and Roles

Ohio State University

- Technical lead
- Concept development and execution
- Novel membrane synthesis/characterization
- Membrane scale-up/continuous fabrication
- Process demonstration
- Cost calculations

Winston Ho and Prabir Dutta

DOE NETL

Project Manager

José Figueroa

Gradient Technology

- System, cost analysis
- EH&S analysis

Steve Schmit

TriSep Corporation

- Consult on continuous membrane fabrication

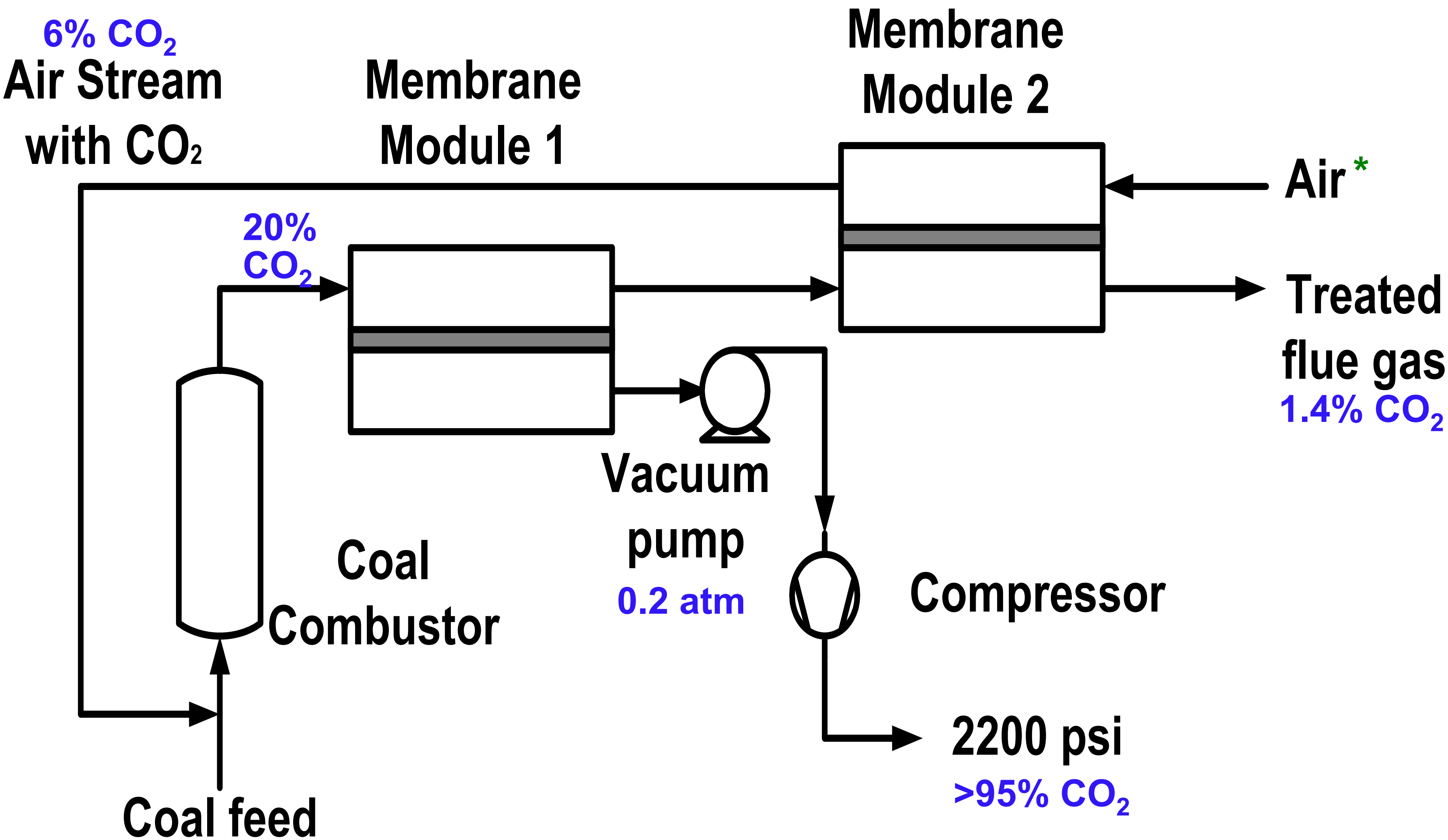
Peter Knappe

AEP

- Consult on plant integration, demonstration and EH&S

Dan Duellman

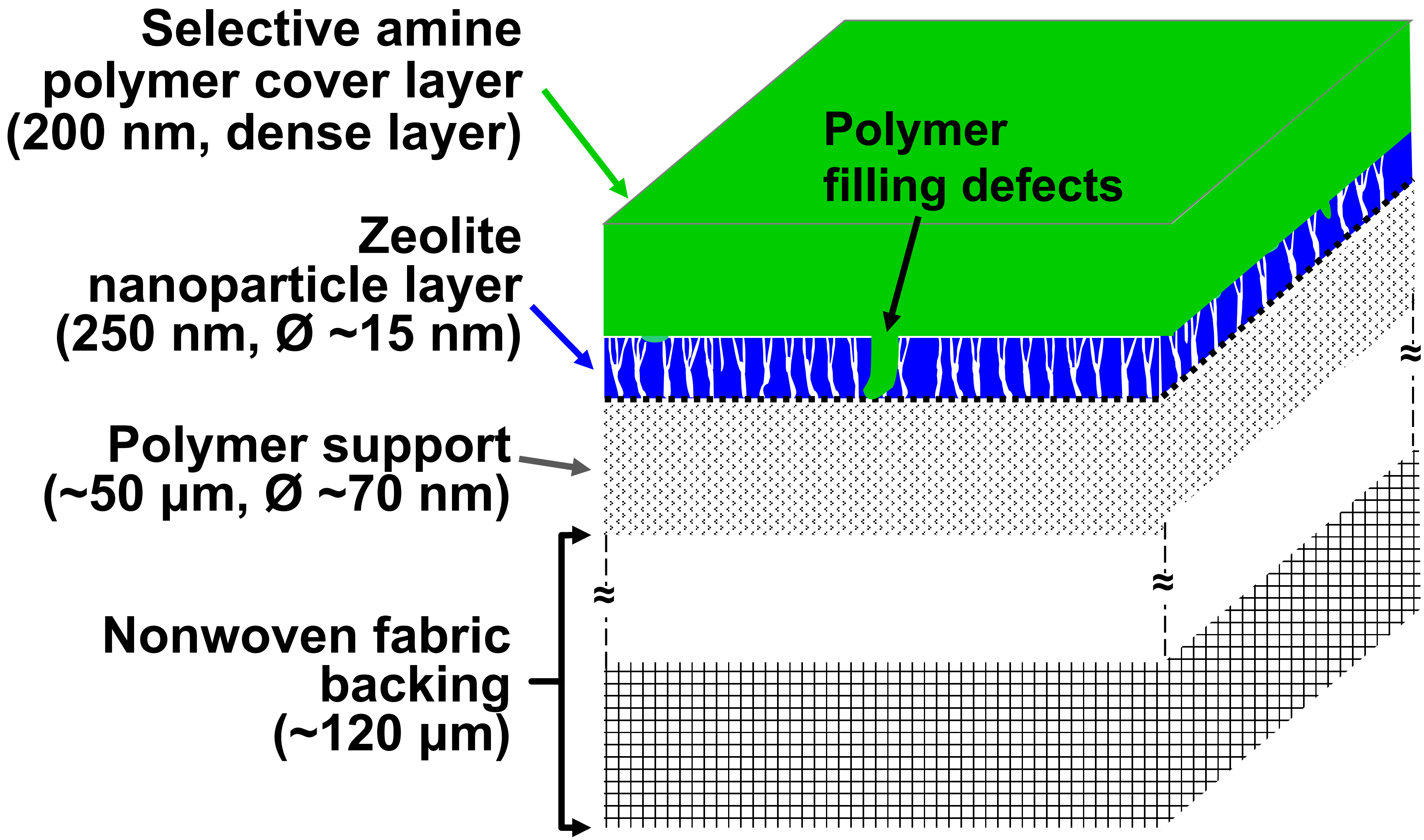
Process Proposed for CO_2 Capture from Flue Gas in Coal-Fired Power Plants



*Air Sweep first used by MTR

Approach 1: Selective Amine Polymer Layer / Zeolite Nanoparticle Layer / Polymer Support

High Inorganic Performance and Low-Cost Polymer Processing Benefits



Approach 1: Selective Amine Polymer Layer / Zeolite Nanoparticle Layer / Polymer Support

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

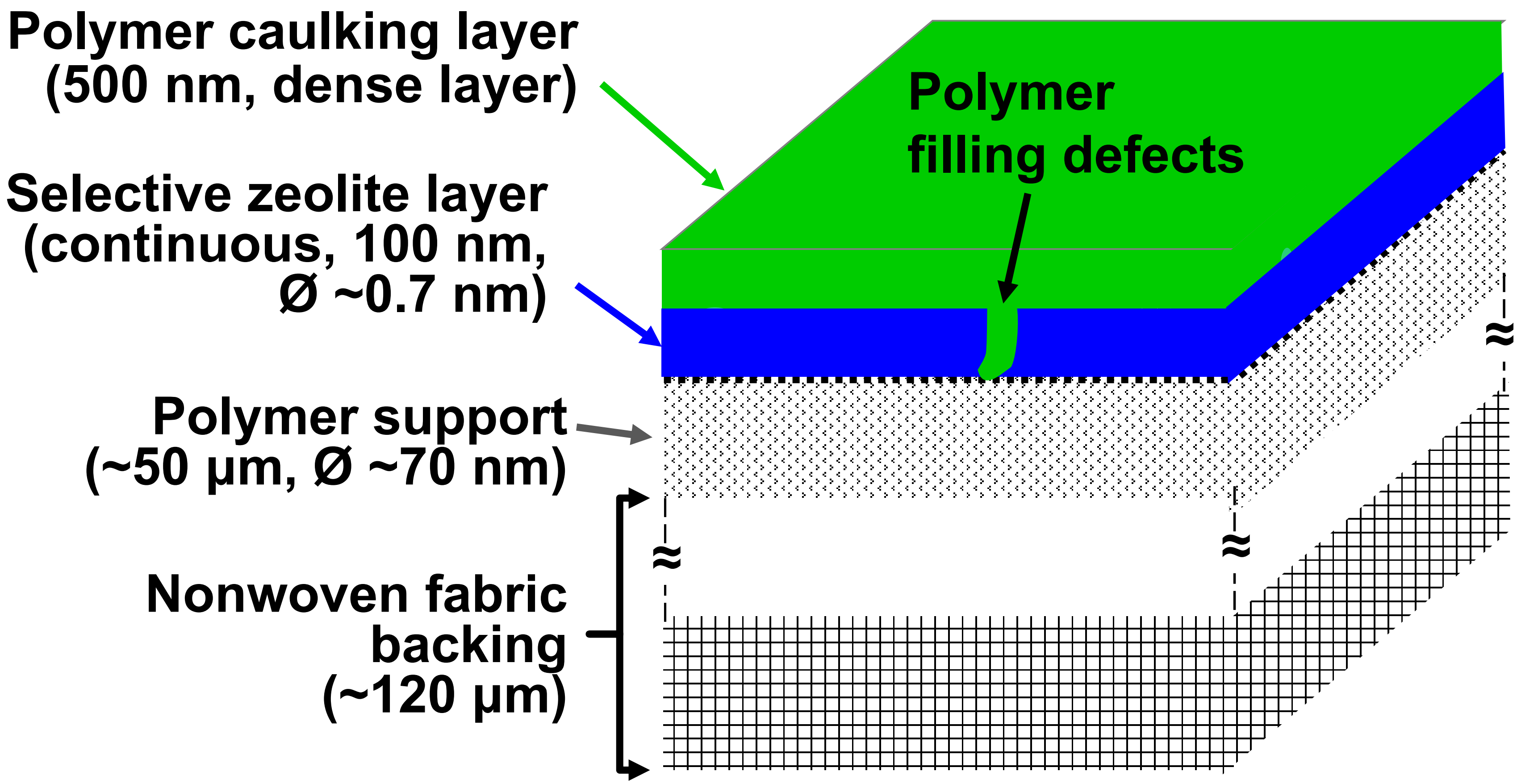
$$CO_2 + R\text{-}NH_2 + H_2O \rightleftharpoons R\text{-}NH_3^+ + HCO_3^-$$

  - High CO_2 permeance and CO_2/N_2 selectivity

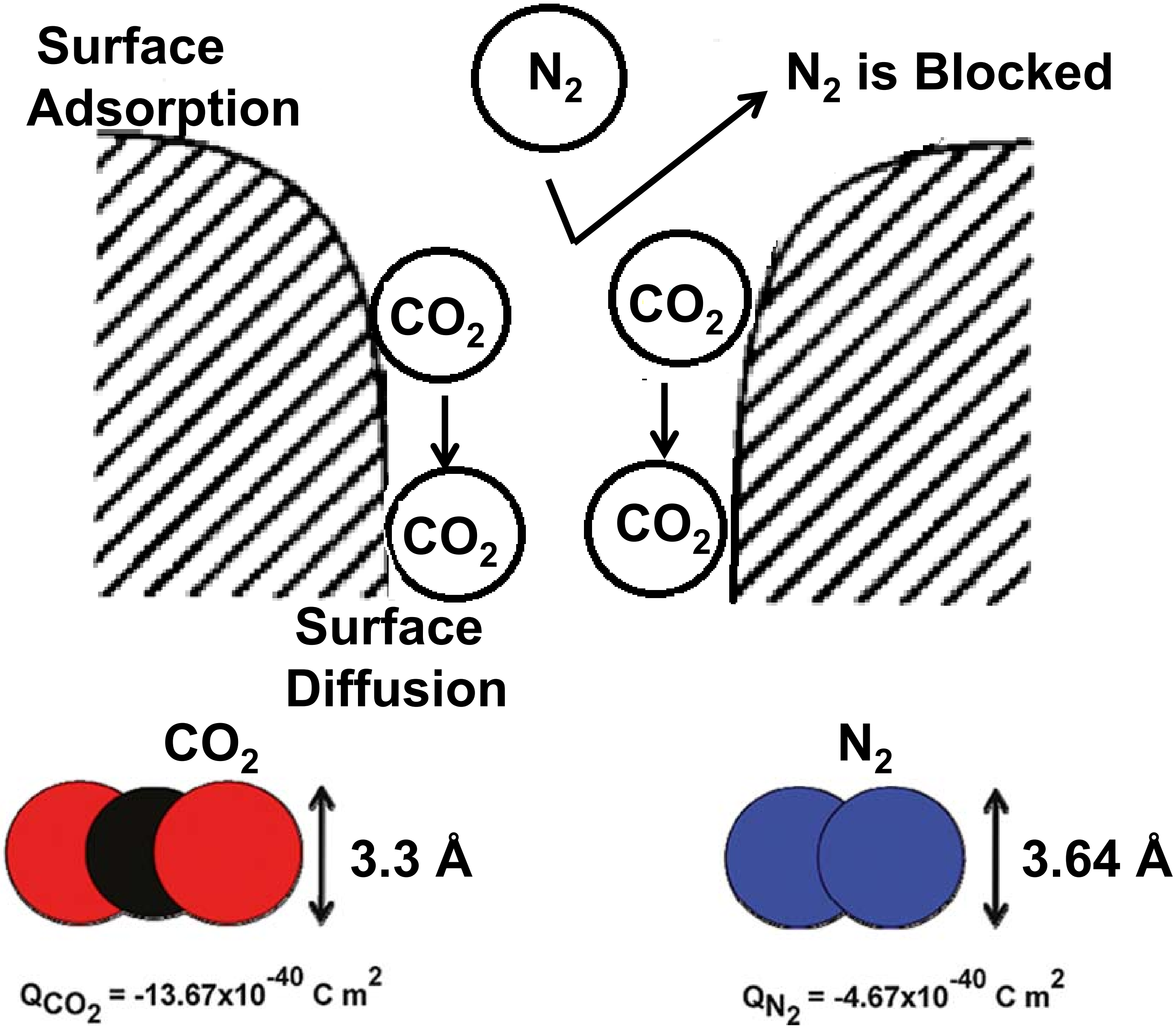
- **Zeolite Nanoparticle Layer**
  - Increased porosity
  - Reduced pore size → Thinner selective amine layer
  - Higher CO_2 permeance

Approach 2: Polymer Caulking Layer / Selective Zeolite Membrane / Polymer Support

High Inorganic Performance and Low-Cost Polymer Processing Benefits



Approach 2: Transport Mechanism through Zeolite



BP1 Accomplishments

- **Approach 1: Zeolite/Amine Polymer Composite Membranes Synthesized and Showed:**
  - 1100 GPU with ~800 CO_2/N_2 selectivity at 102^{o}C
  - 690 GPU with 123 CO_2/N_2 selectivity at 57^{o}C
  - Zeolite/polymer element hand rolled successfully (6” x 6” membrane leaf)
- **Approach 2: Significant Membrane Synthesis Improvements**
  - Discovery of rapid zeolite particle synthesis (< 1 hr vs. 8 hrs)
- **Preliminary Techno-economic Calculations**
  - Techno-economic model developed
  - 690 GPU with ~123 selectivity at 57^{o}C (based on 2007$)
    - ~$43/tonne CO_2

BP2 Accomplishments

- **Approach 1: Zeolite/Amine Polymer Composite Membranes Prepared in Lab Showed:**
  - 1100 GPU with ~140 CO_2/N_2 selectivity at 57°C
  - 1460 GPU with >1000 CO_2/N_2 selectivity at 102°C
  - Patent application filed
- **Approach 1: Composite Membrane Scaled up to Prototype Size**
  - Membrane scaled up to 14" wide using continuous membrane rolling machine
  - 870 GPU with 218 CO_2/N_2 selectivity obtained at 57°C
  - 1800 GPU with 160 CO_2/N_2 selectivity obtained at 102°C
  - Developed affordable nanoporous polymer support (PES)
  - 1.8" (1.5" OD central tube) by 14" long spiral-wound membrane elements fabricated using rolling machine

BP2 Accomplishments (continued)

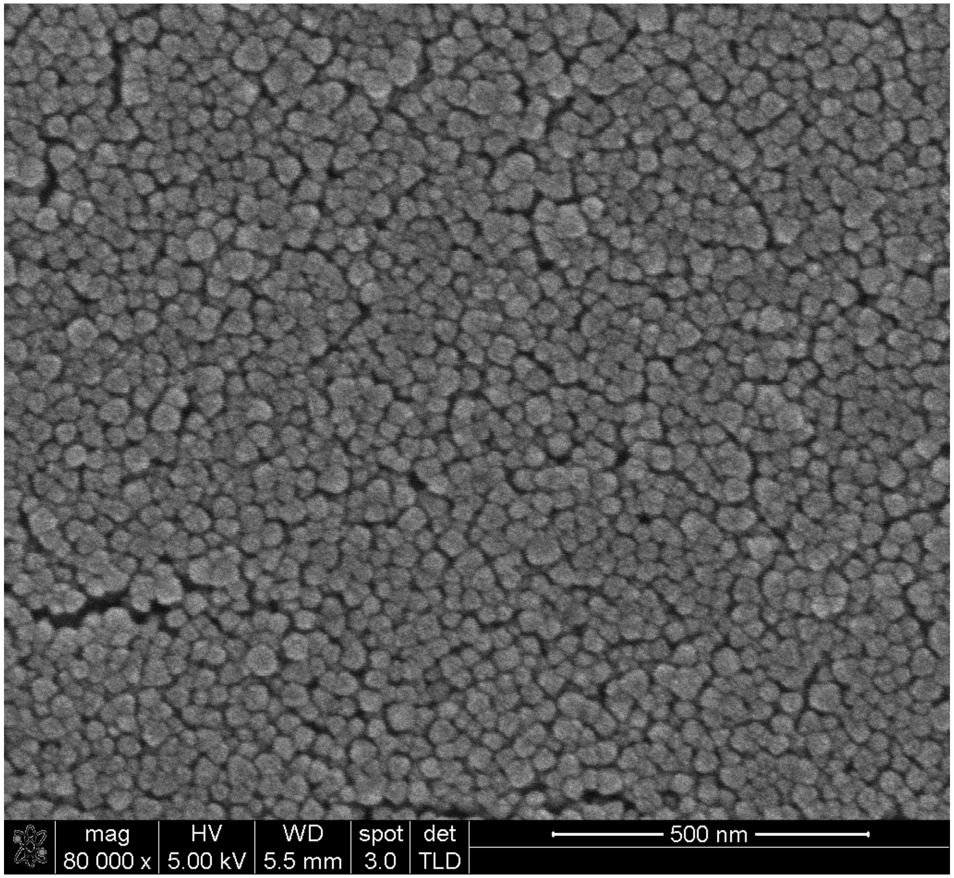
- **Preliminary Techno-economic Calculations showed**
  - **1100 GPU with ~140 selectivity at 57°C (based on 2007$)**
    - **\$37.5/tonne CO_2 – Exceed DOE target of \$40/tonne CO_2**
    - **52.2% COE increase**

- **Approach 2: Rapid Zeolite Membrane Growth (1 hour)**
  - **Patent application filed**
  - **Published in *Langmuir*, 2014, *30,* 6929-6937**

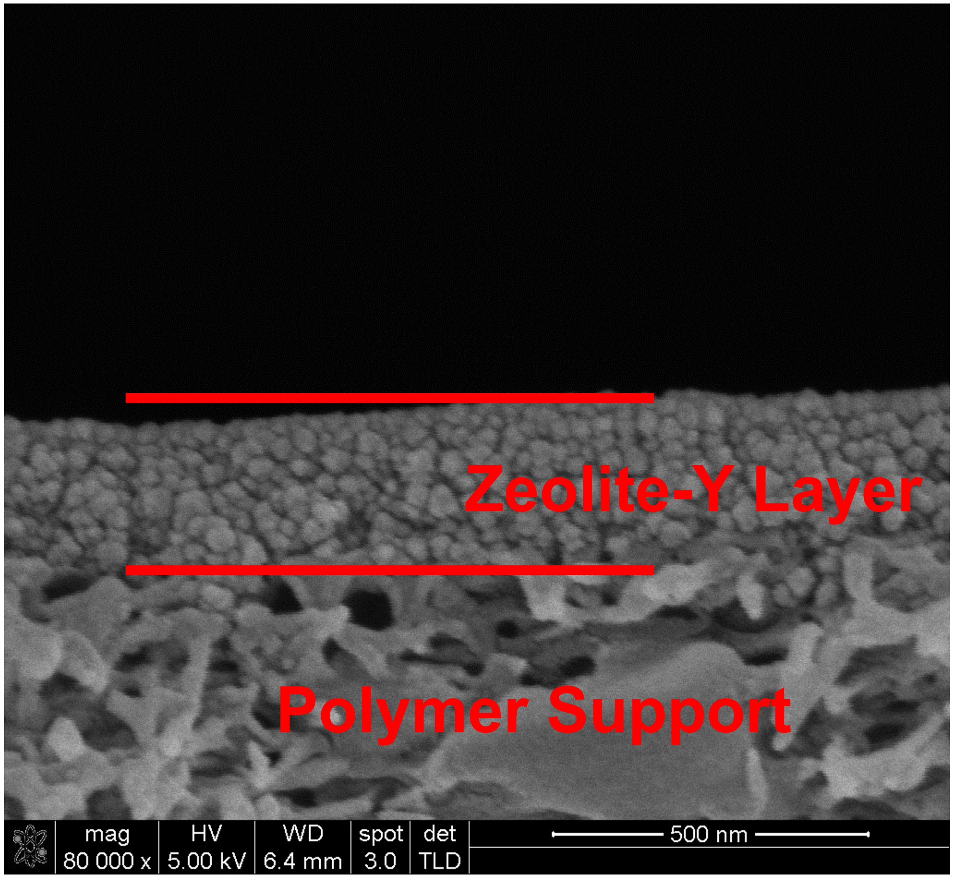
- **Effects of SO_2 and CO_2/SO_2 Mixture on Amine Carriers being Studied by in-situ FTIR**
  - **SO_2 permeated with CO_2**
  - **Amine regenerated by air sweep at 57°C – Confirmed by in-situ FTIR**

Approach 1: Zeolite Nanoparticles Deposited on Polymer Support Successfully

Top View

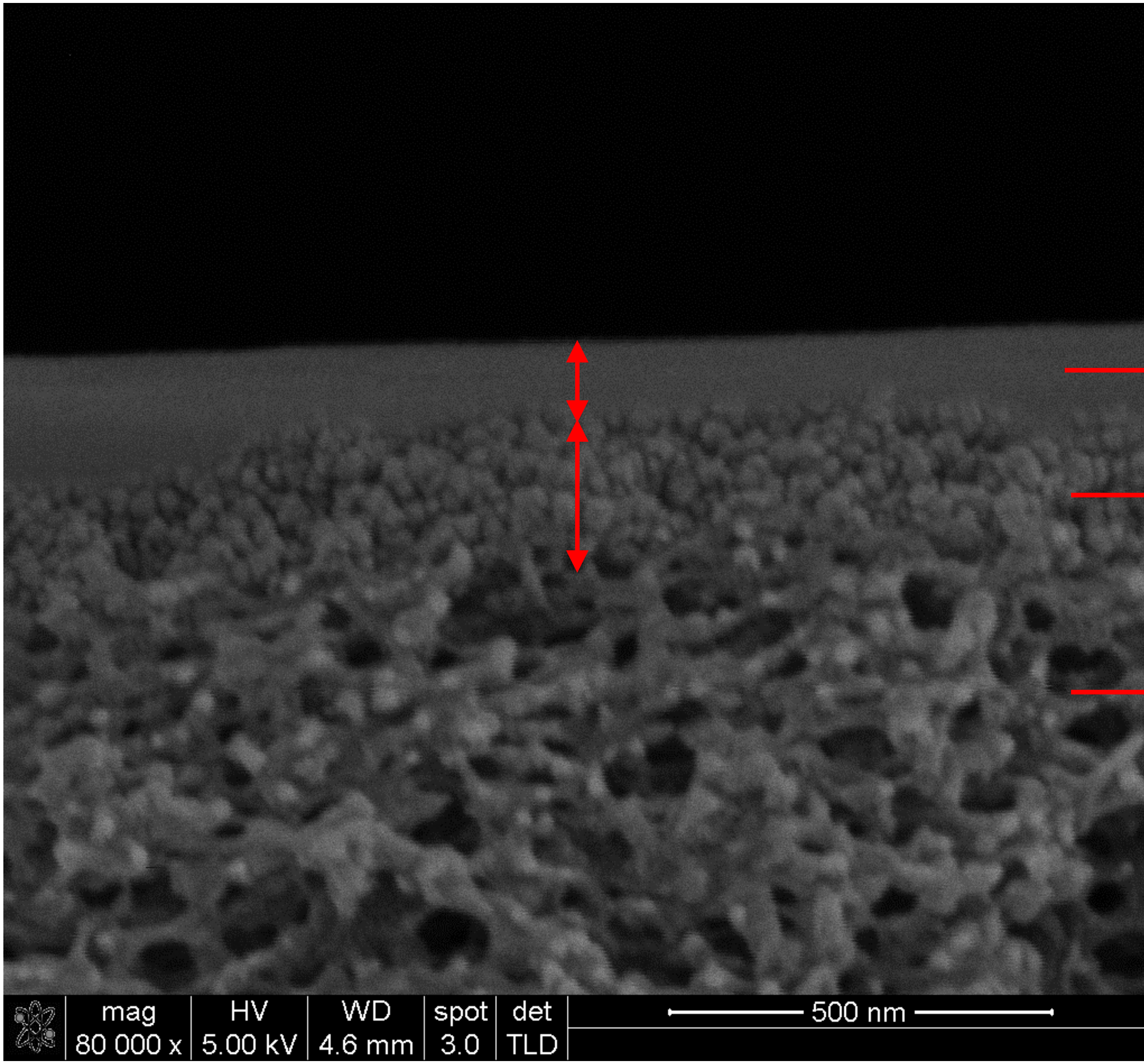


Cross-section



- **High quality deposition with good repeatability**

Amine/Zeolite Seed Layer/Polymer Support



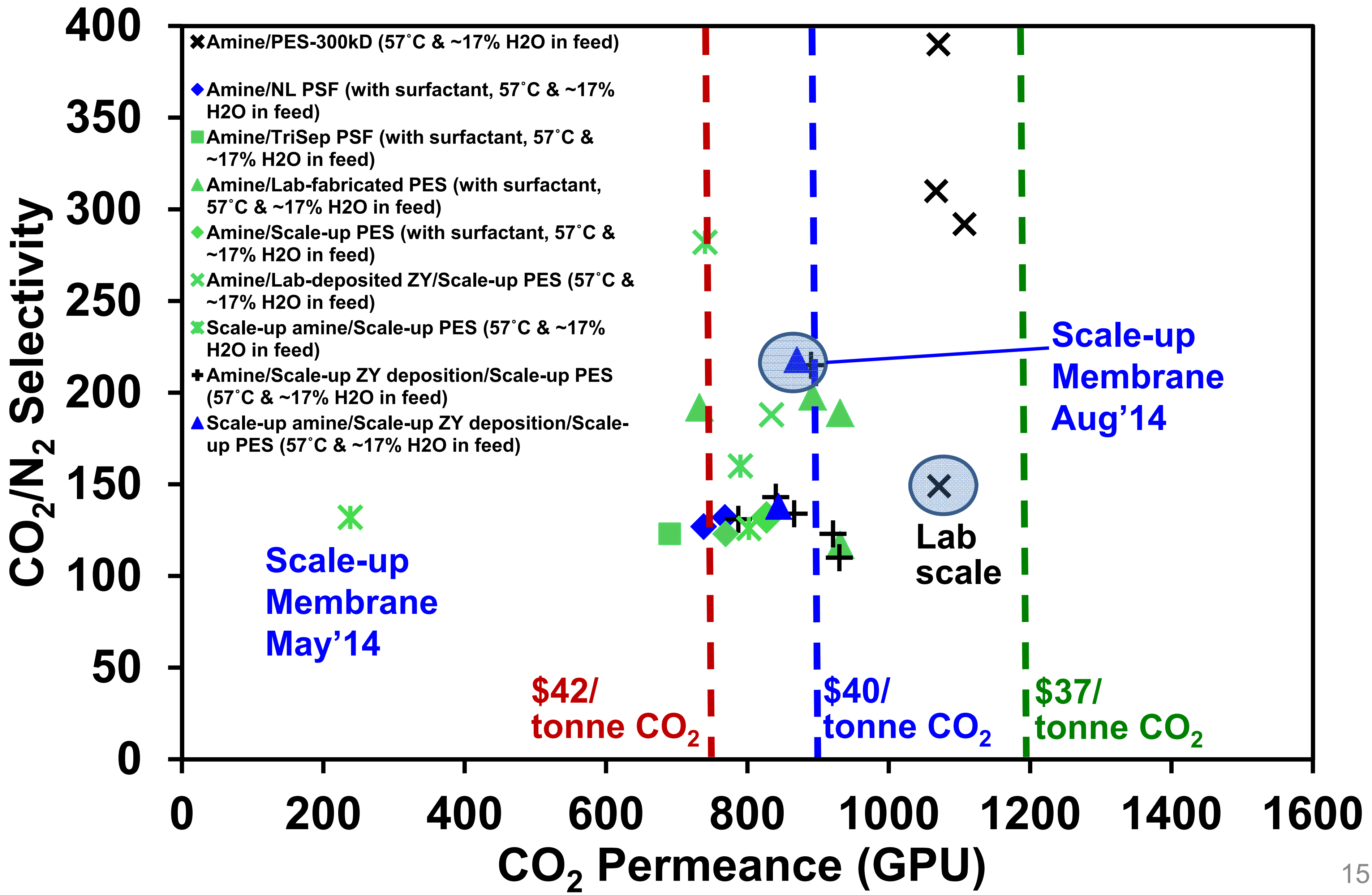
Amine cover layer ~ 205 nm

Zeolite-Y 40 nm seed layer ~ 245 nm

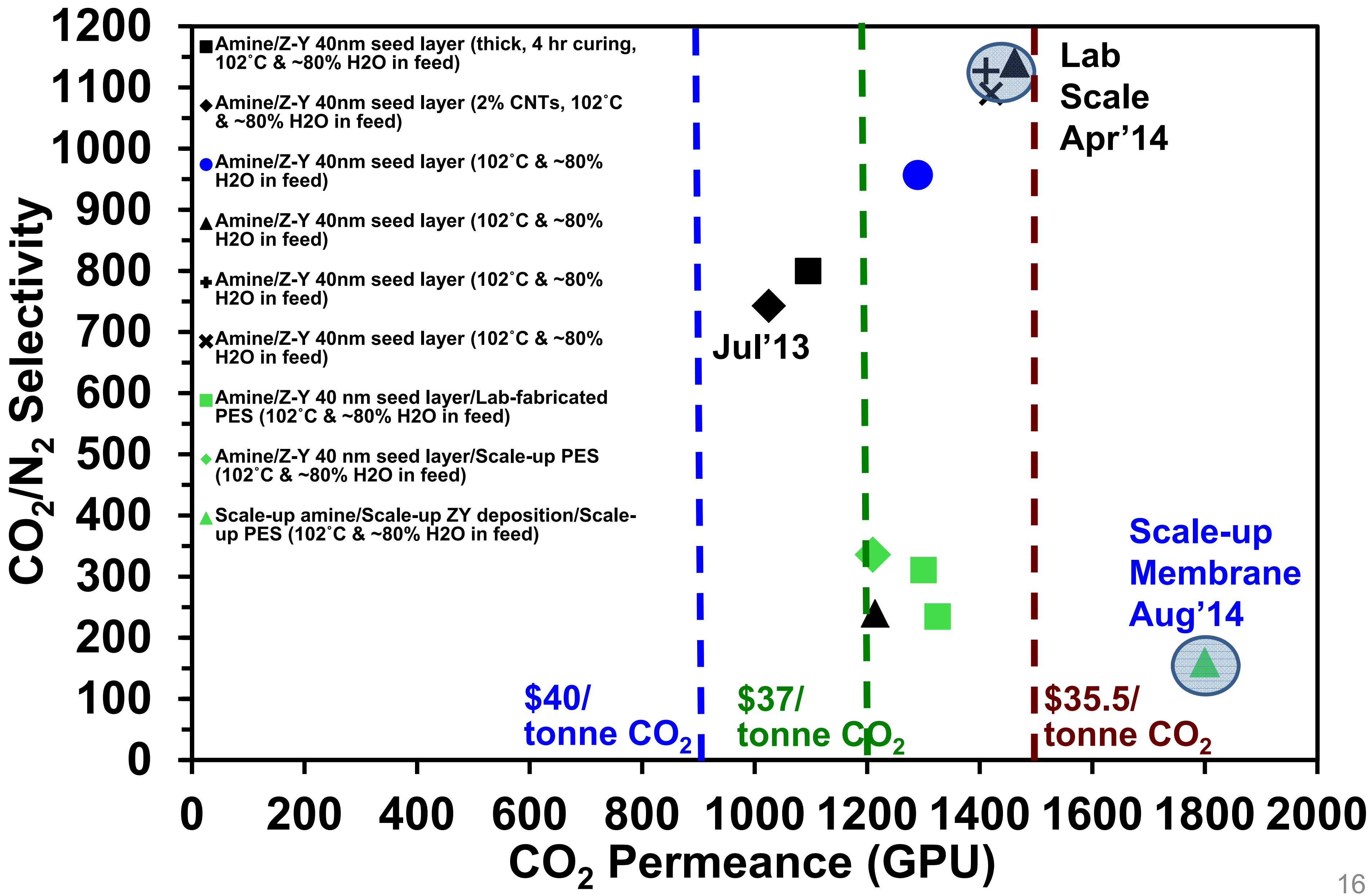
PES support

870 GPU
218 CO_2/N_2 selectivity
At 57°C

Approach 1: Zeolite/Polymer Composite Membranes Containing Amine Cover Layer at 57°C



Approach 1: Zeolite/Polymer Composite Membranes Containing Amine Cover Layer at 102^{o}C

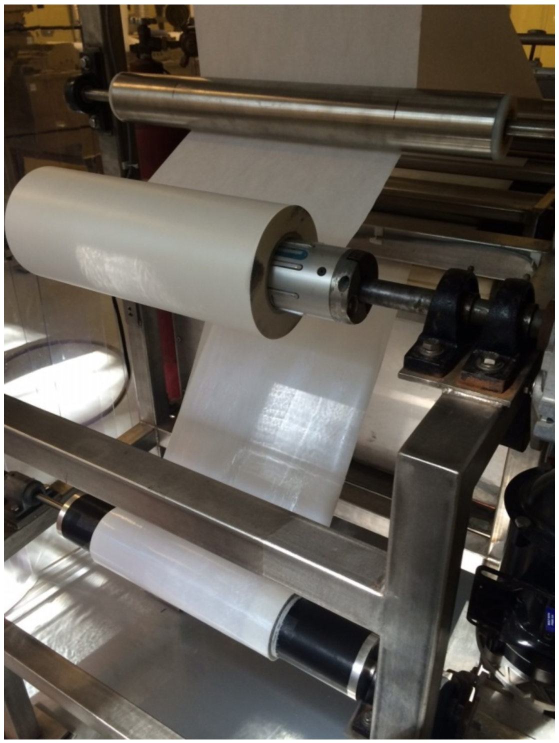


Membrane Scale-up: Usable for Approaches 1 and 2

Continuous Membrane Fabrication Machine at OSU

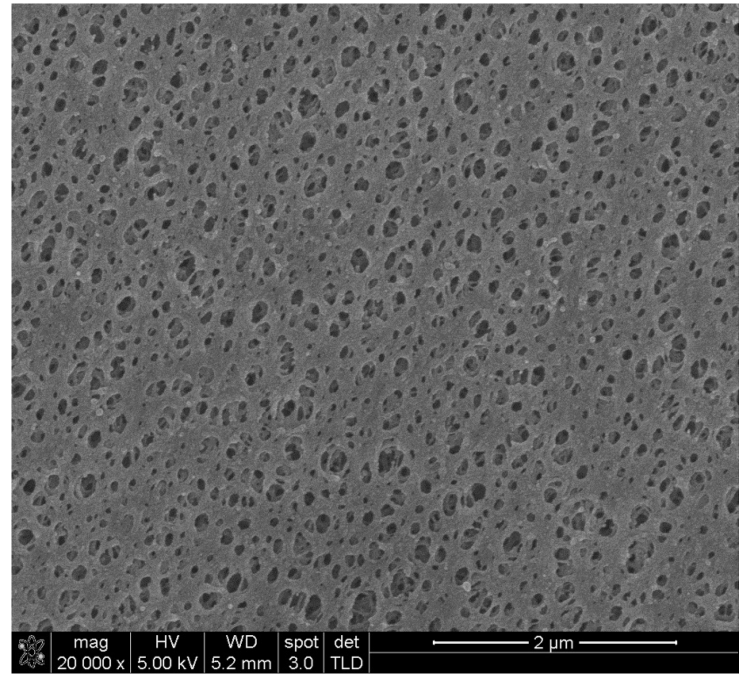
Successful Continuous Fabrication of Affordable PES Support (applicable to Approaches 1 and 2)

Casting Machine



14-inch PES Support

SEM – Top View

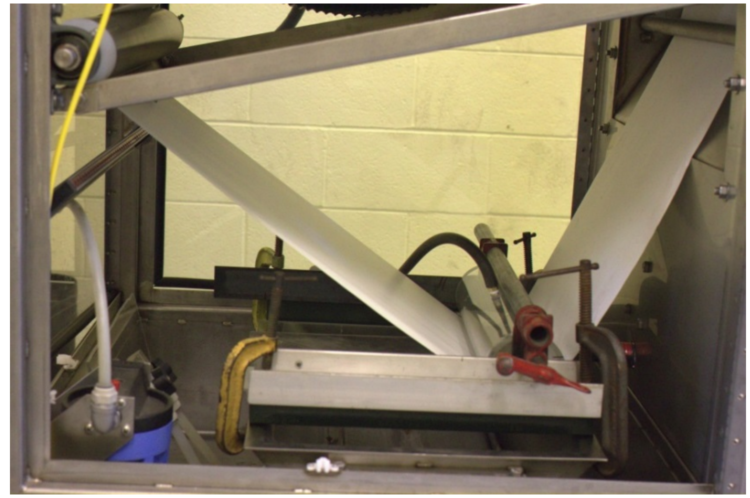


- **Manufacturer could not supply PES needed for scale-up**
- **PES synthesized/developed at OSU to resolve supply issue**
- **Technology transfer to TriSep**

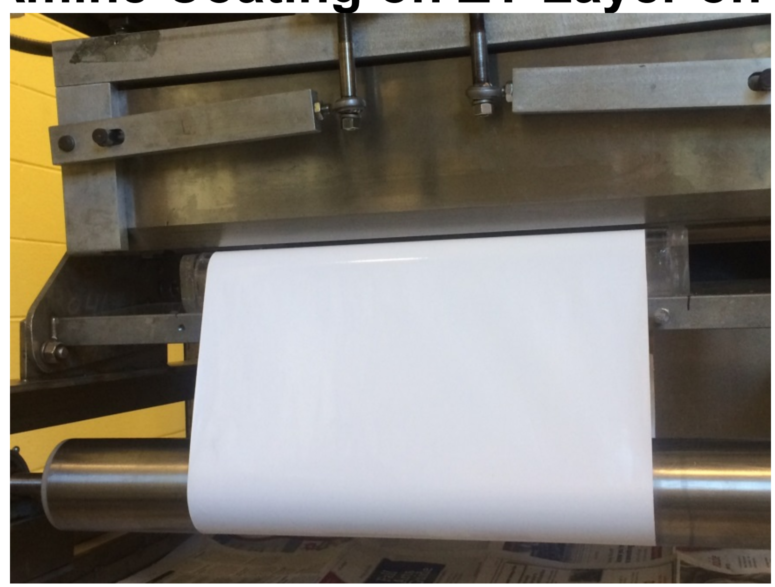
Approach 1: Scale-up Zeolite-Y Deposition and Amine Coating

14-inch PES Support

14" ZY Deposition on PES Support

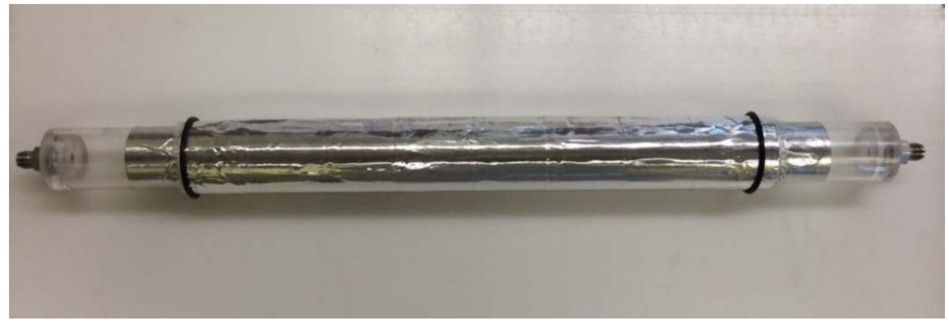


14" Amine Coating on ZY Layer on PES

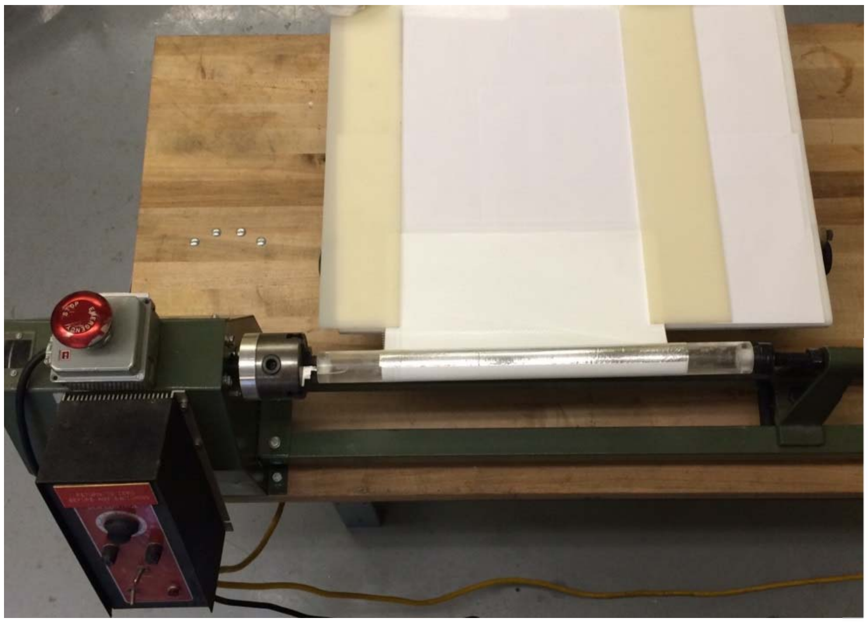


Approach 1: Membrane Element Fabrication

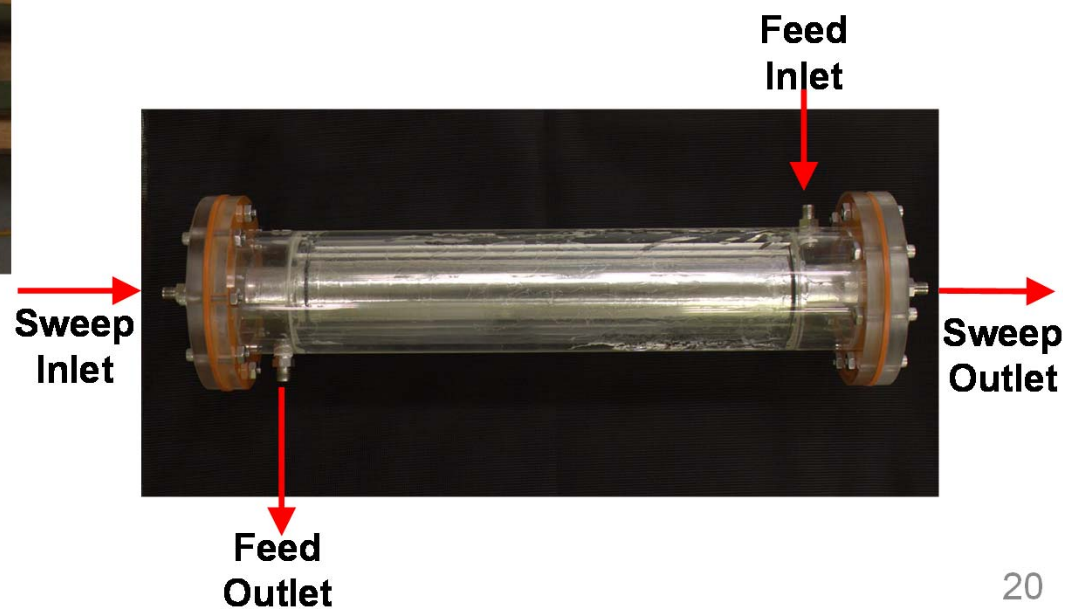
Spiral-Wound Membrane Element



Element Rolling Machine



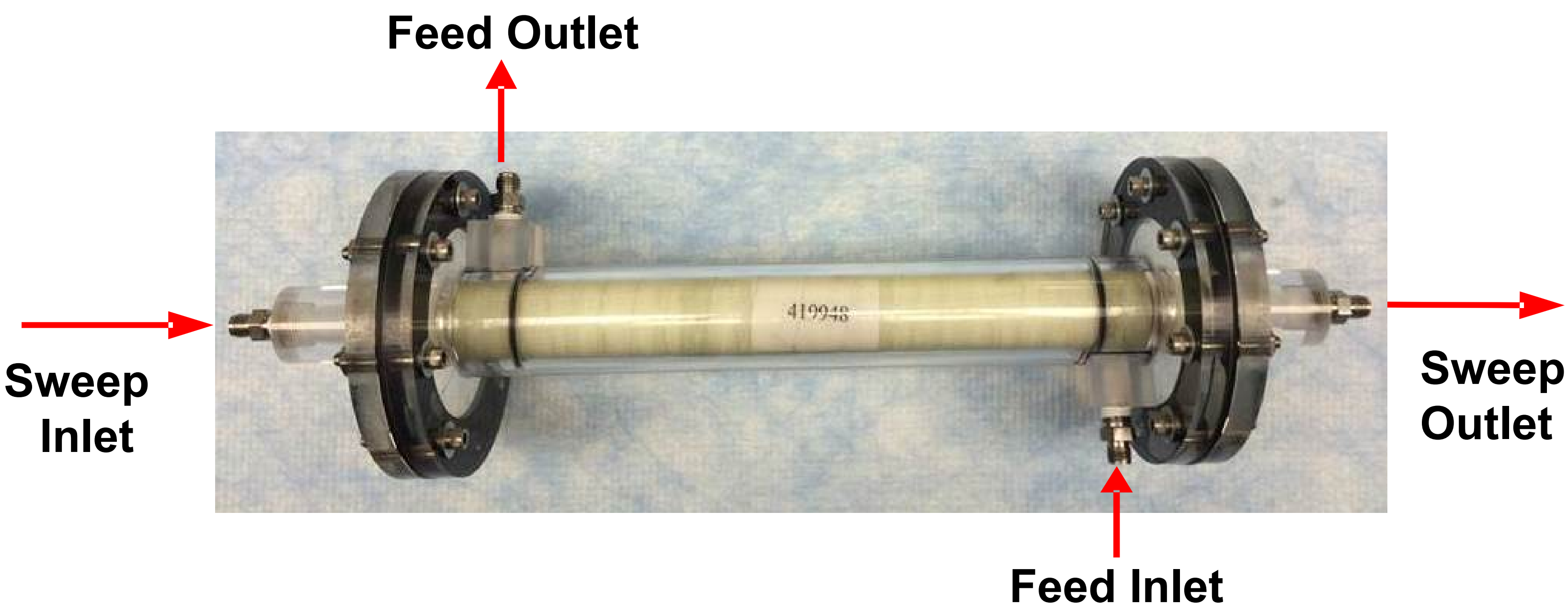
Membrane Module



Approach 1: TriSep also Made Elements for us

Spiral-Wound Membrane Element Made by TriSep

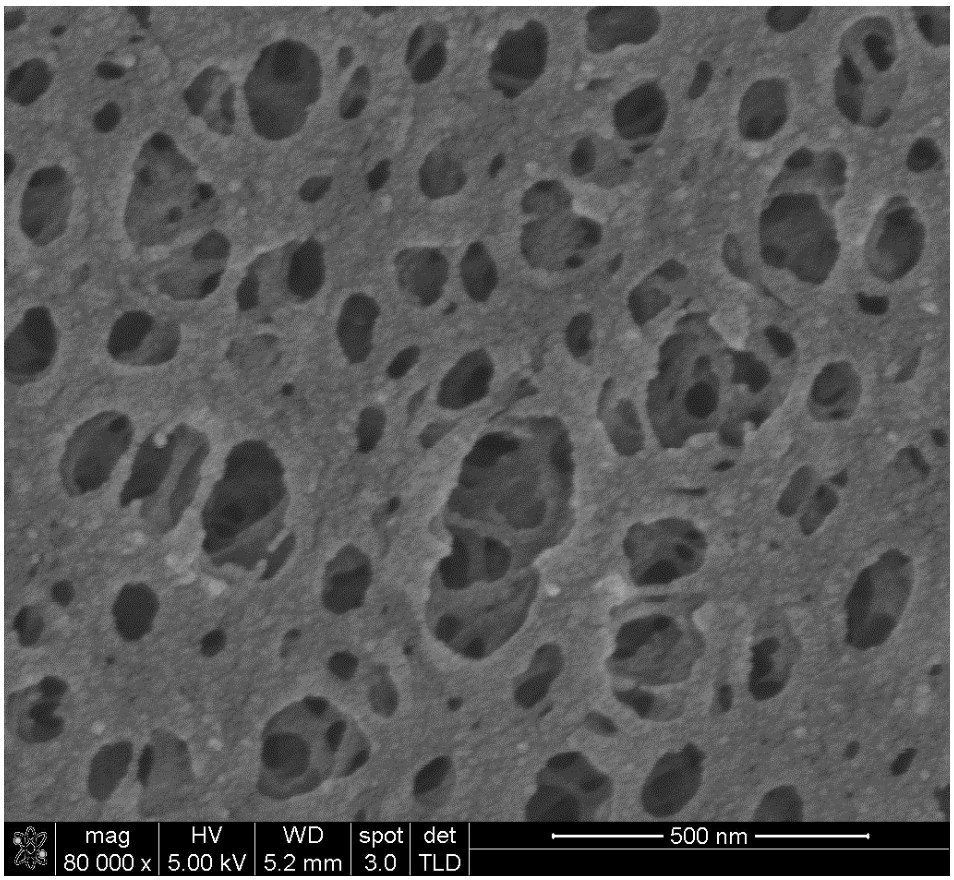
Membrane Module: Element Made by TriSep in our Housing

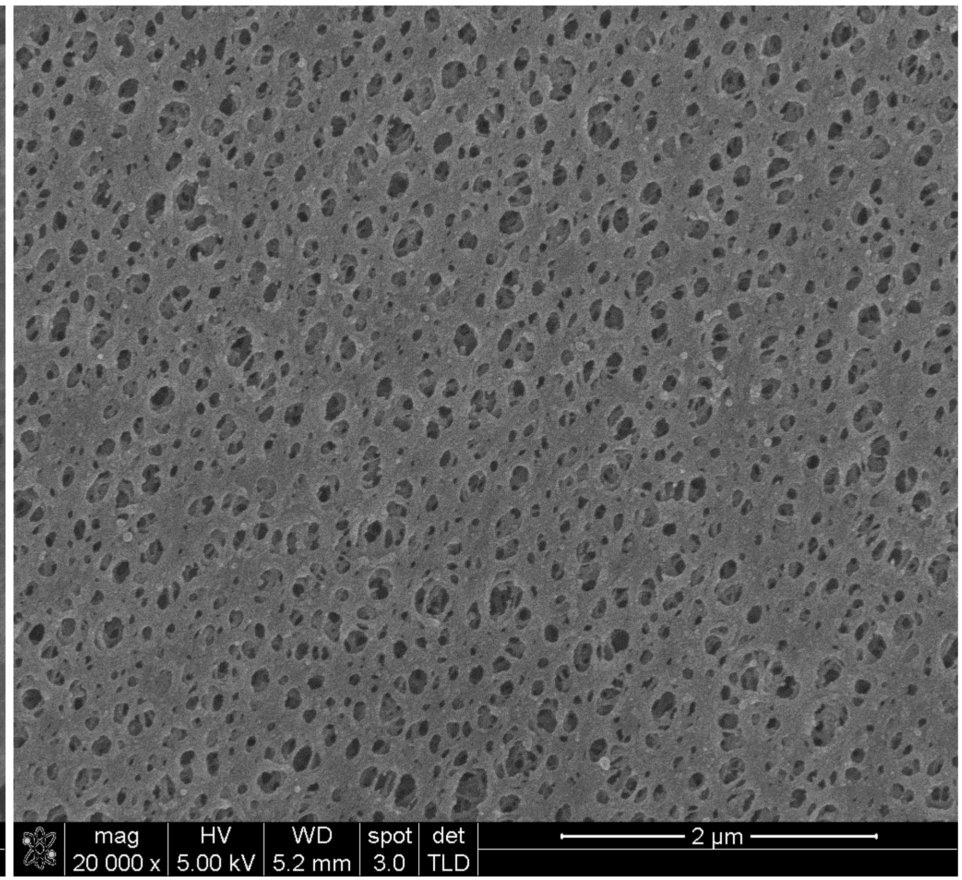


Technical Details – BP2

Successful Continuous Fabrication of Affordable PES Support (applicable to Approaches 1 and 2)

SEM Analysis of 14-inch PES Support



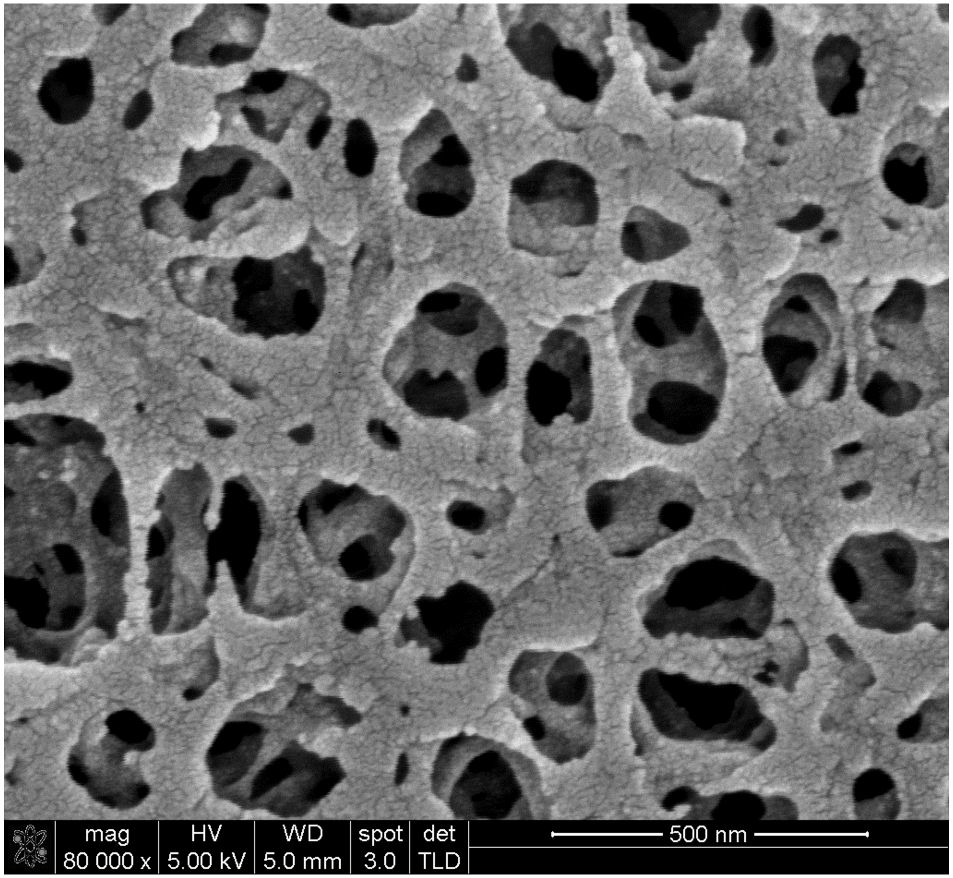


Ave. pore size = 69.5 nm, Porosity = 16.9%

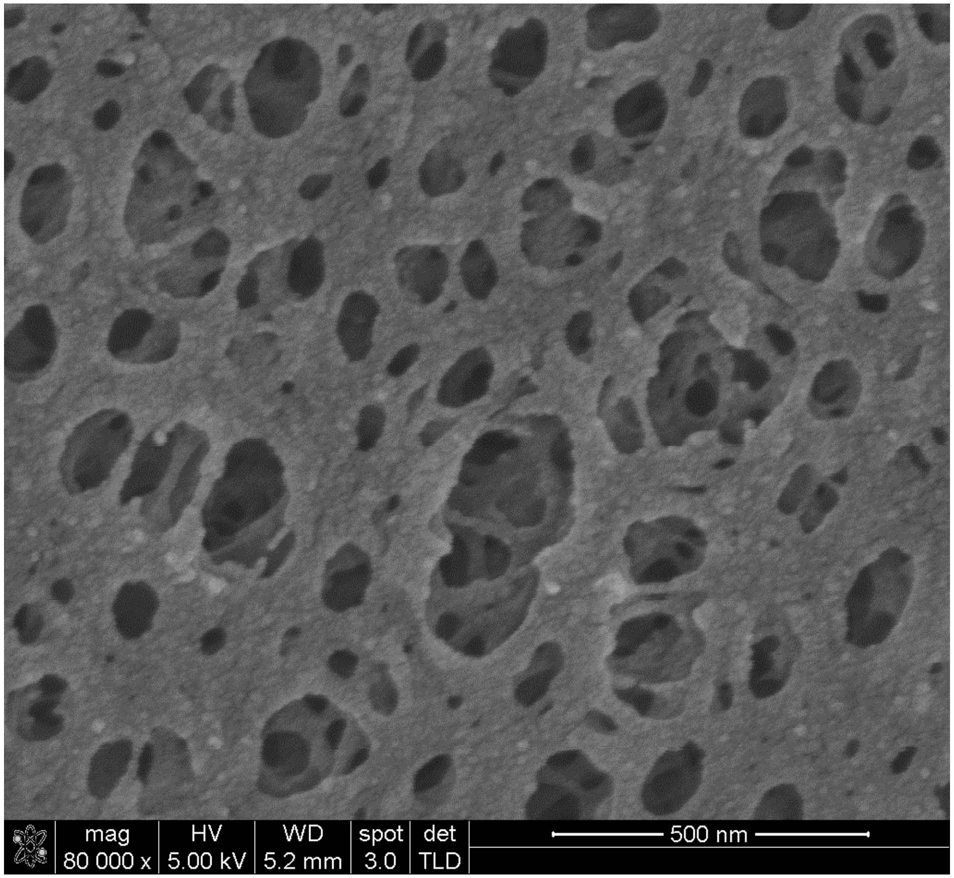
Comparison between Commercial PES-300kD and 14-inch Scale-up PES

Large magnification (80,000 x)

PES-300kD



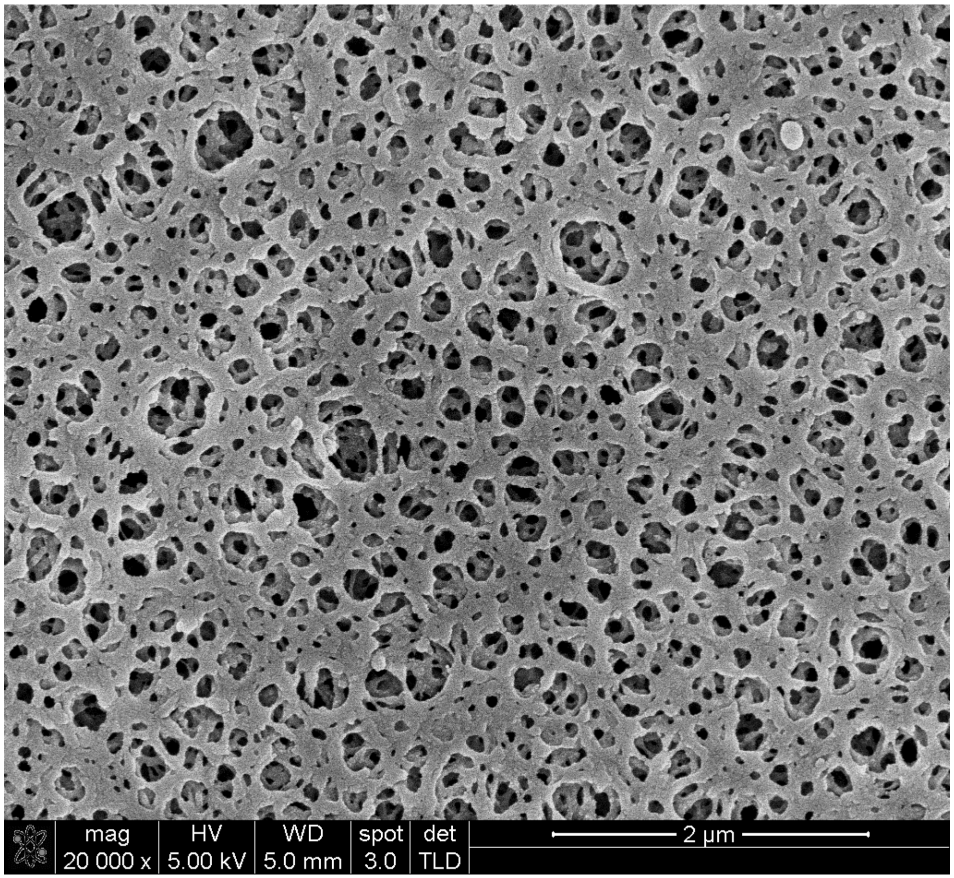
14-inch PES



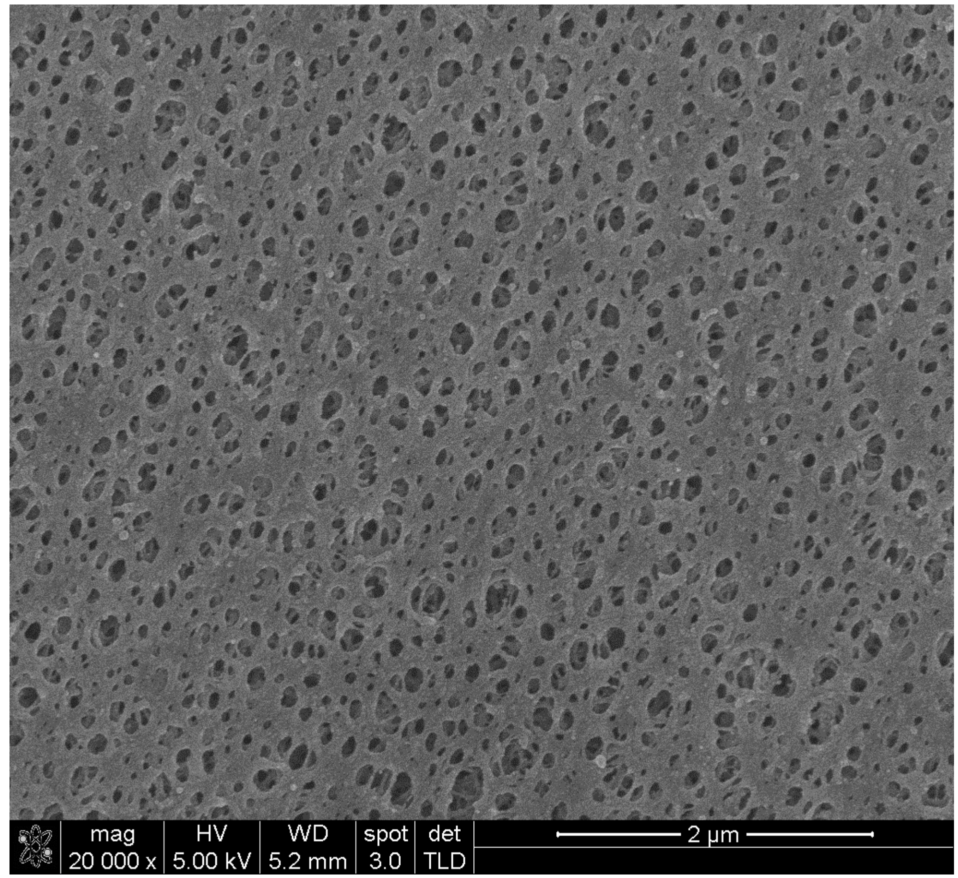
Comparison between Commercial PES-300kD and 14-inch Scale-up PES

Small magnification (20,000 x)

PES-300kD



14-inch PES



Ave. pore size (nm)	72.3	69.5
Porosity (%)	15.8	16.9
Ave. roughness (nm)	17.0	14.0

- Support surface morphology close to that of PES-300kD

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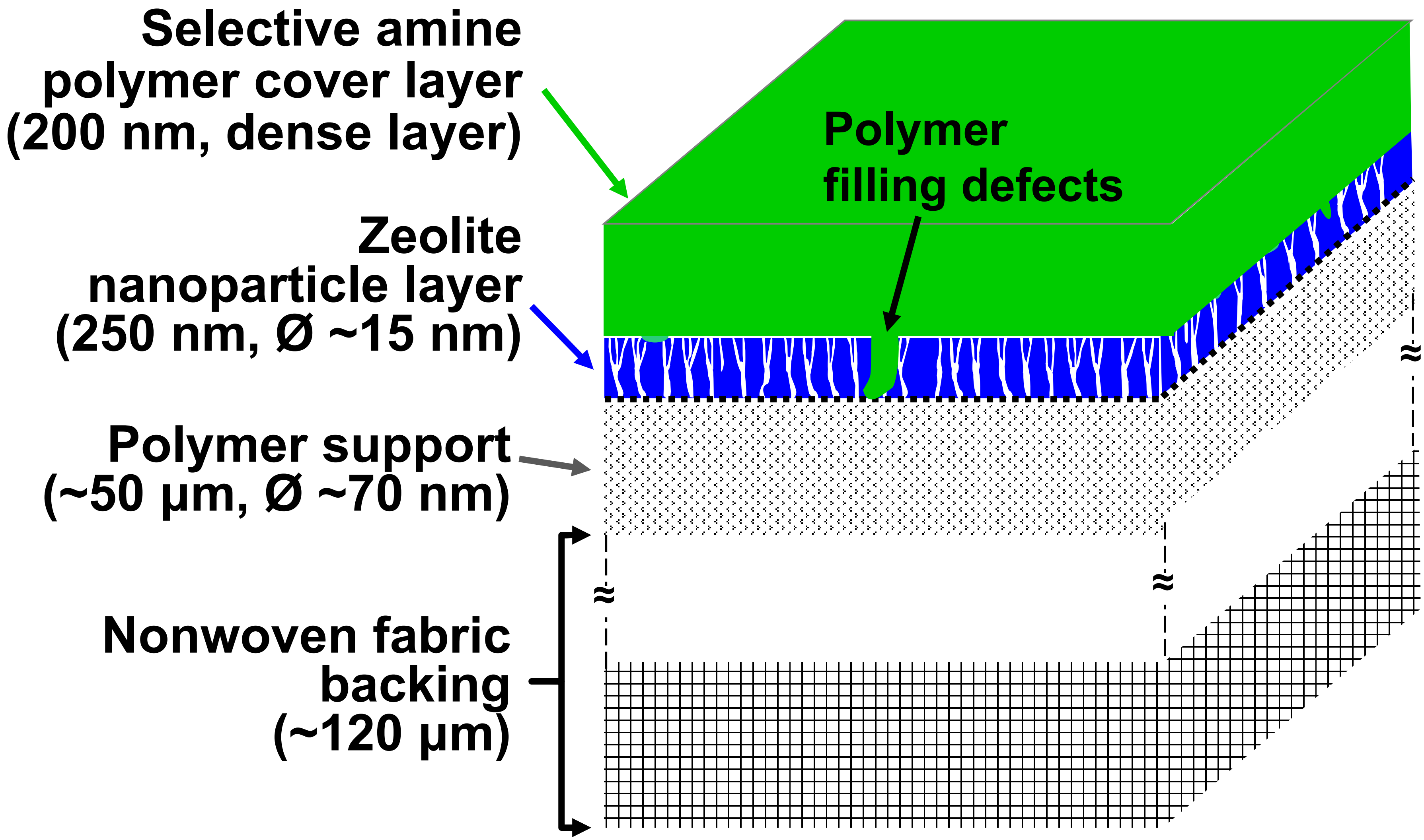
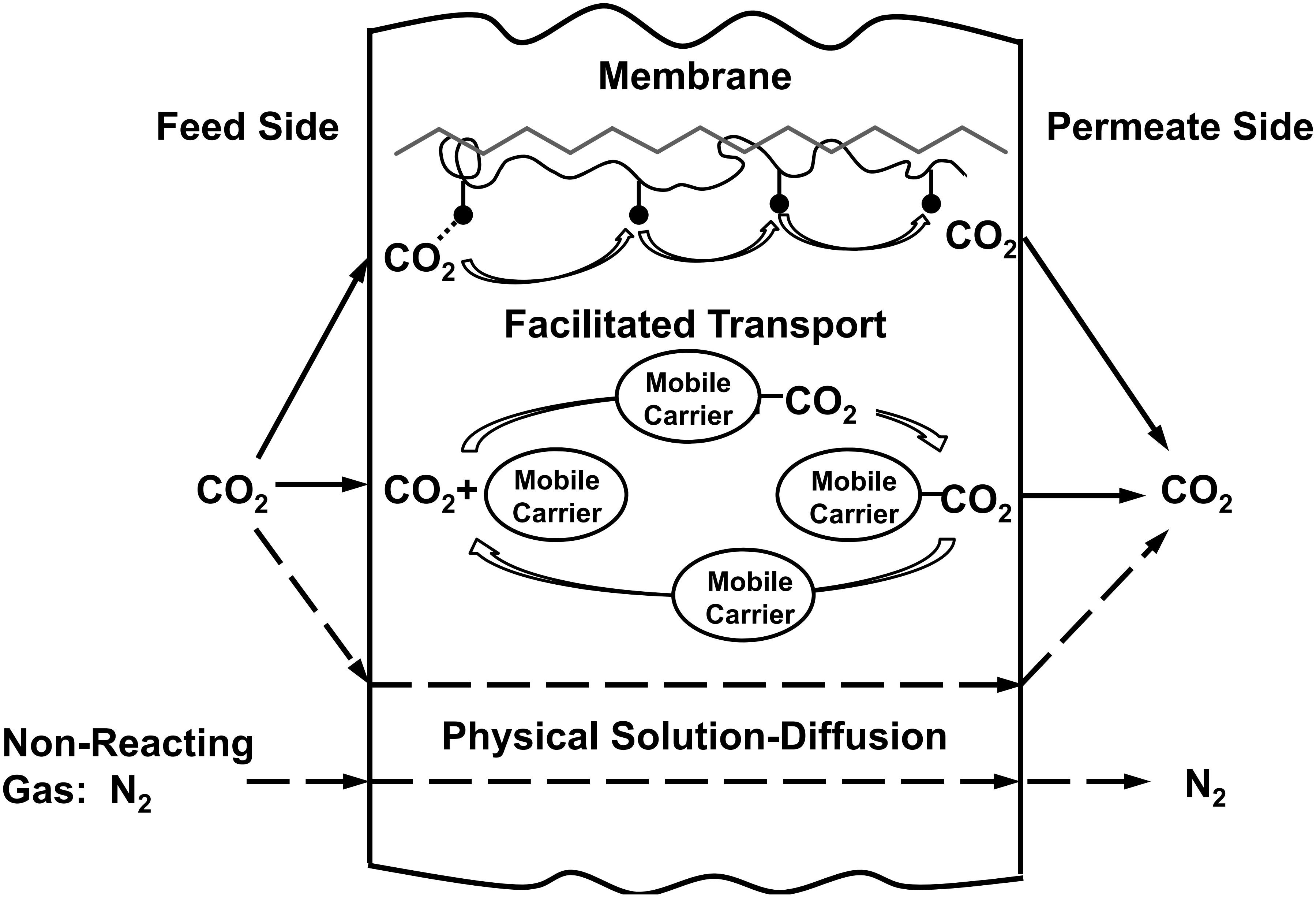
High Inorganic Performance and Low-Cost Polymer Processing Benefits

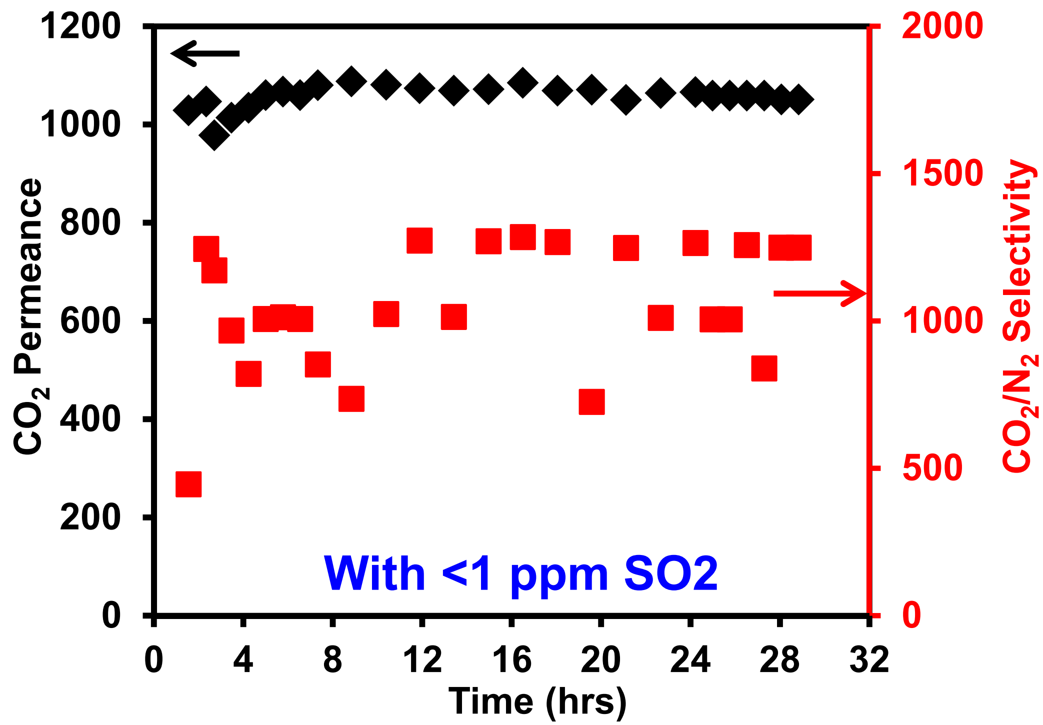


Approach 1: Amine Cover Layer Contains Mobile and Fixed Carriers



Approach 1: SO_2 Effects on Amine-containing Membranes

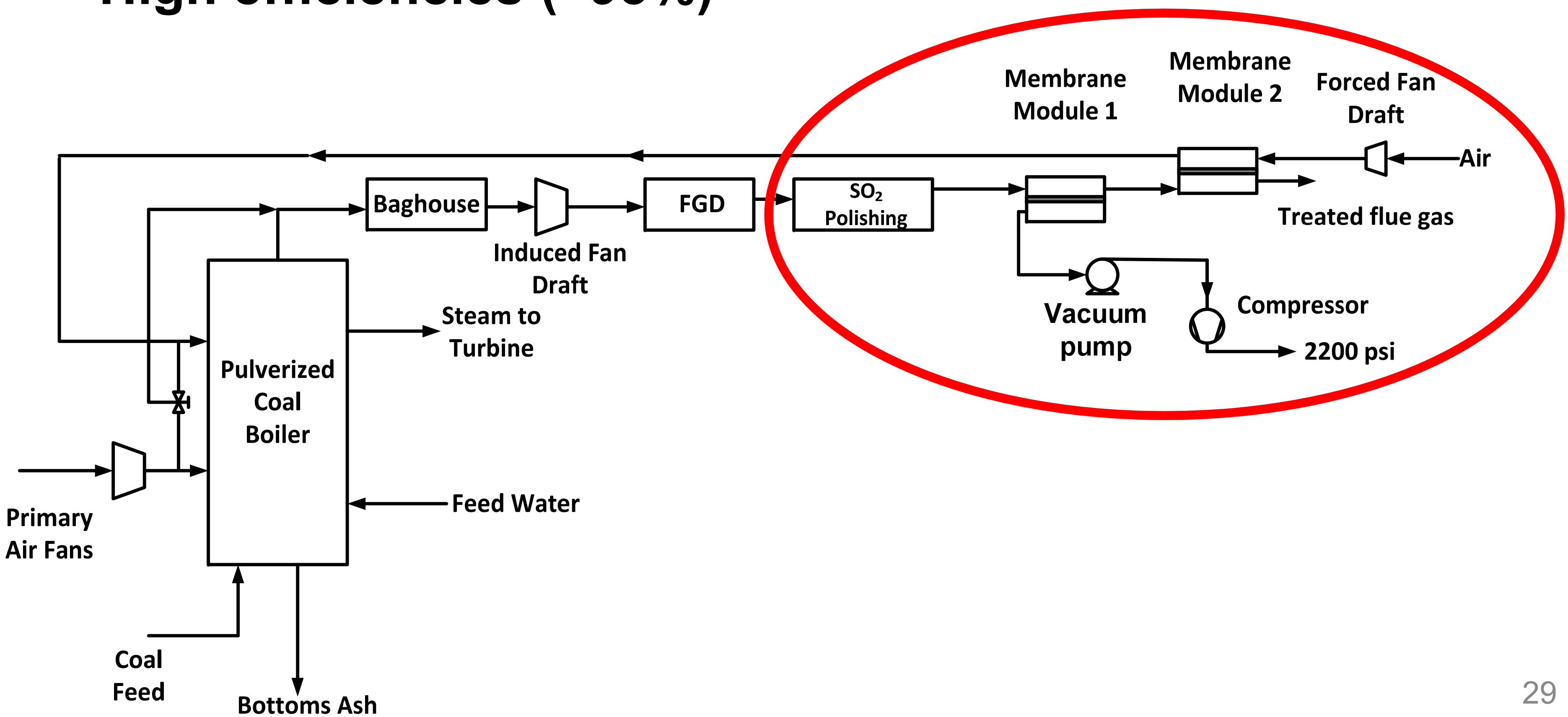
- SO_2 Effects
  - SO_2 at ≤1 ppm appeared not to affect stability of membrane with amine cover layer
  - More study underway between 1 – 43 ppm SO_2



- Propose SO_2 Polishing Step before membrane

Approach 1: SO_2 Membrane Mitigation

- **Absorption into 20 wt% NaOH Solution**
  - Polishing step based on NETL baseline document
    - Estimated to be about $4.3/tonne CO_2 (6.5% COE increase)
  - Non-plugging, low-differential-pressure, spray baffle scrubber
  - High efficiencies (>95%)



Breakthroughs to Make Approach 1 Feasible

- Speeding up Synthesis of Nanozeolites
- Atomic Force Microscopy for Optimization of PES Support
- Influence of SO_2 on Membrane Components

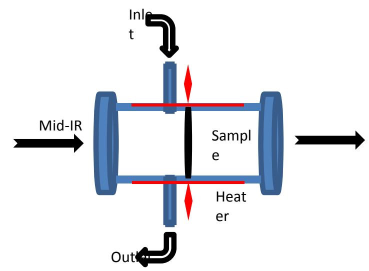
Approach 1: Interaction of SO_2 with Membrane

Objectives

- Investigate each component separately and then their combinations
- Understand interaction of CO_2/SO_2 with amine membranes
- correlate the membrane performance/degradation in the presence of SO_2 and suggest ways to circumvent any negative effects

Experimental setup

Perkin-Elmer Spectrum 400 FT-IR/FT-NIR spectrometer



transmission gas cell

Procedure

Exposed in two temperatures: 102℃ and 57℃

Dry Ar

Obtain background

Wet CO_2

Wet SO_2

Wet SO_2 /CO_2

In-situ measurement

Dry N_2 purge

Study regeneration

Approach 1: Chemical Reactions of CO_2/SO_2 with Membrane Components

- **Reactions with CO_2**

For primary and secondary amine

$CO_2 + RNH_2 \rightleftarrows RNH_2^+COO^-$ (zwitterion)

$RNH_2^+COO^- + B \rightarrow RNHCOO^- + BH^+$ (carbamate)

If sterically hindered,

$RNH_2^+COO^- + H_2O \rightarrow HCO_3^- + RNH_3^+$ (bicarbonate)

For tertiary amine

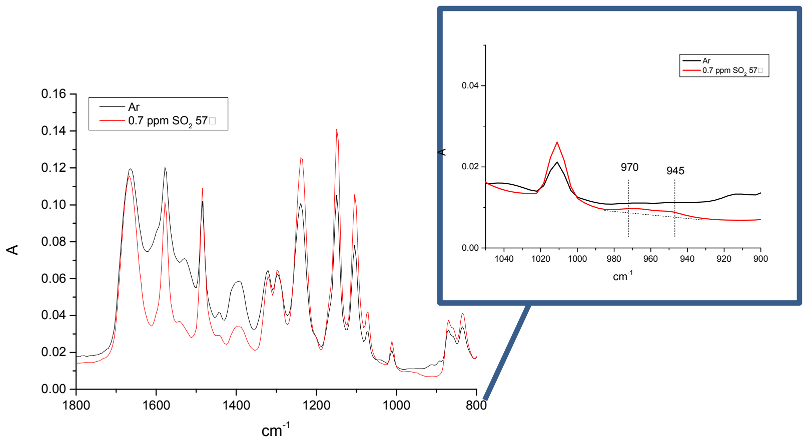
$R_3N + H_2O + CO_2 \rightarrow R_3N^+H + HCO_3^-$

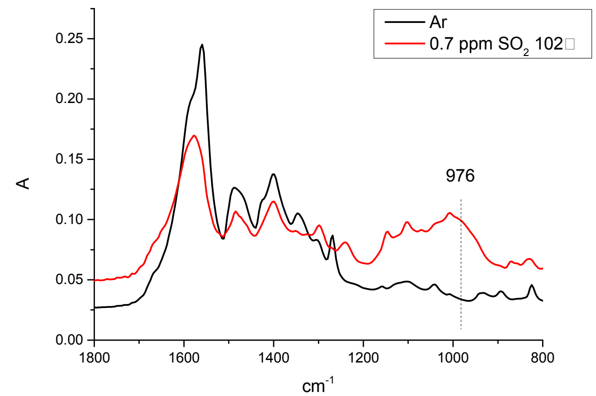
- **Reactions with SO_2**

$R\text{-}NH_2 + SO_2 + H_2O \rightarrow R\text{-}NH_3^+ + HSO_3^-$ (sulfite)

Approach 1: SO_2 Exposed Membranes Characterized by Infrared Spectroscopy

Two sets of membrane samples

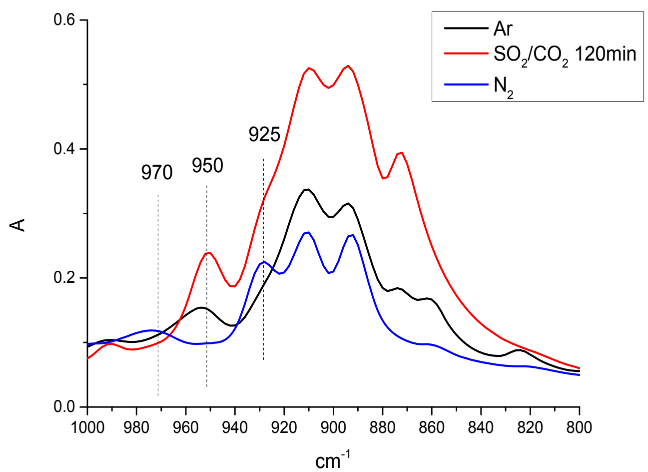




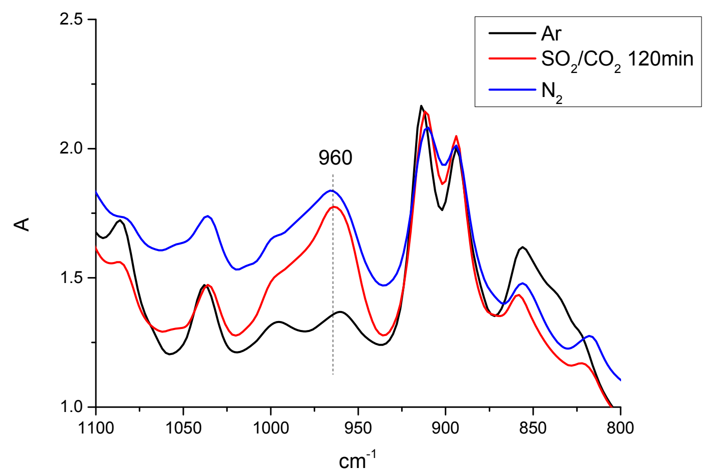
- **Membrane 1 exposed to 0.7 ppm SO_2 57℃**
  - ➢ **Weak bands for sulfite species**

- **Membrane 2 exposed to 0.7 ppm SO_2 at 102℃**
  - ➢ **Strong band of adsorbed sulfite species**

Approach 1: IR Spectrum of Amine at 57°C and 102°C (45 ppm SO_2/10% CO_2)

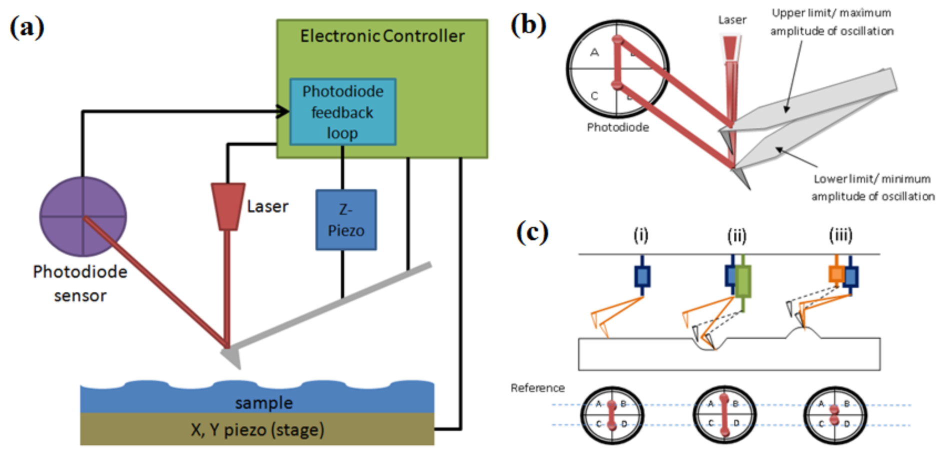


57°C : SO_2 primarily in adsorbed form, removed with N_2 or air purge >1 hour

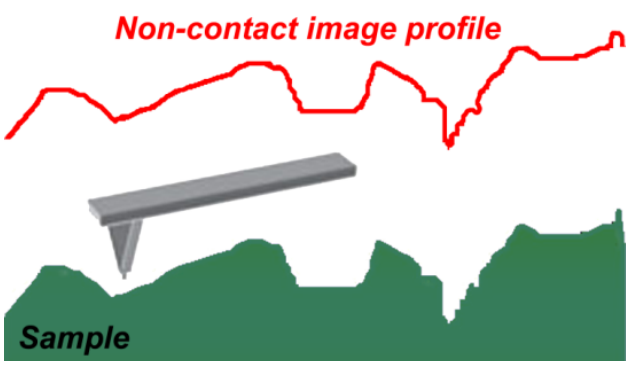


102°C : SO_2 primarily in reacted form, not removed with N_2 or air purge > 1hour

Approach 1: Measuring Surface Roughness of PES Synthesized at Ohio State



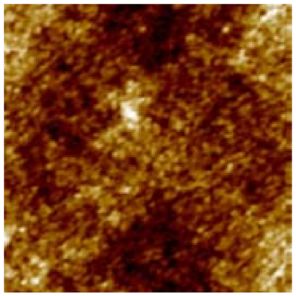
- The AFM generates surface topography (e.g roughness) of membrane
- Roughness measurement
  => membrane quality control



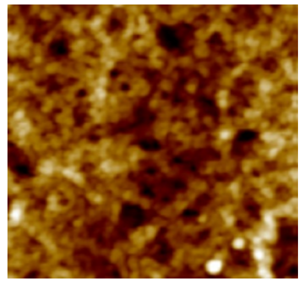
Polymer Characterization with the Atomic Force Microscope
By U. Maver, T. Maver, Z. Peršin, M. Mozetič, A. Vesel, M. Gaberšček and K. Stana-Kleinschek ,Polymer Sc, Chapter 4

Approach 1: Support Roughness Characterized by AFM

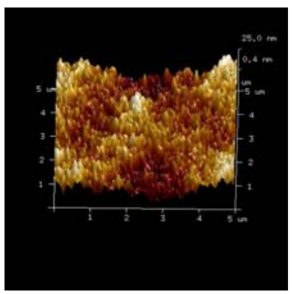
PES support



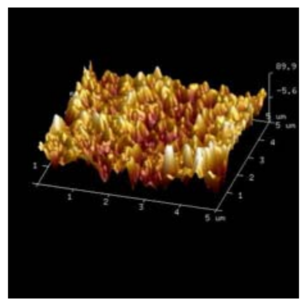
Sample A (top)



Sample B (top)



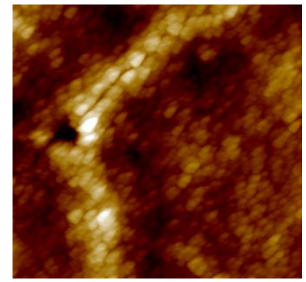
Sample A (3D)

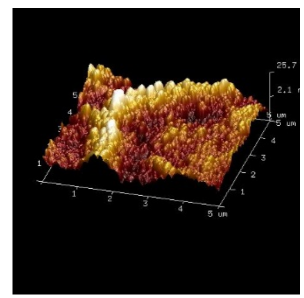


Sample B (3D)

Sample name	Avg roughness
Sample A	8 nm
Sample B	28 nm

Nanozeolite coated PES membrane

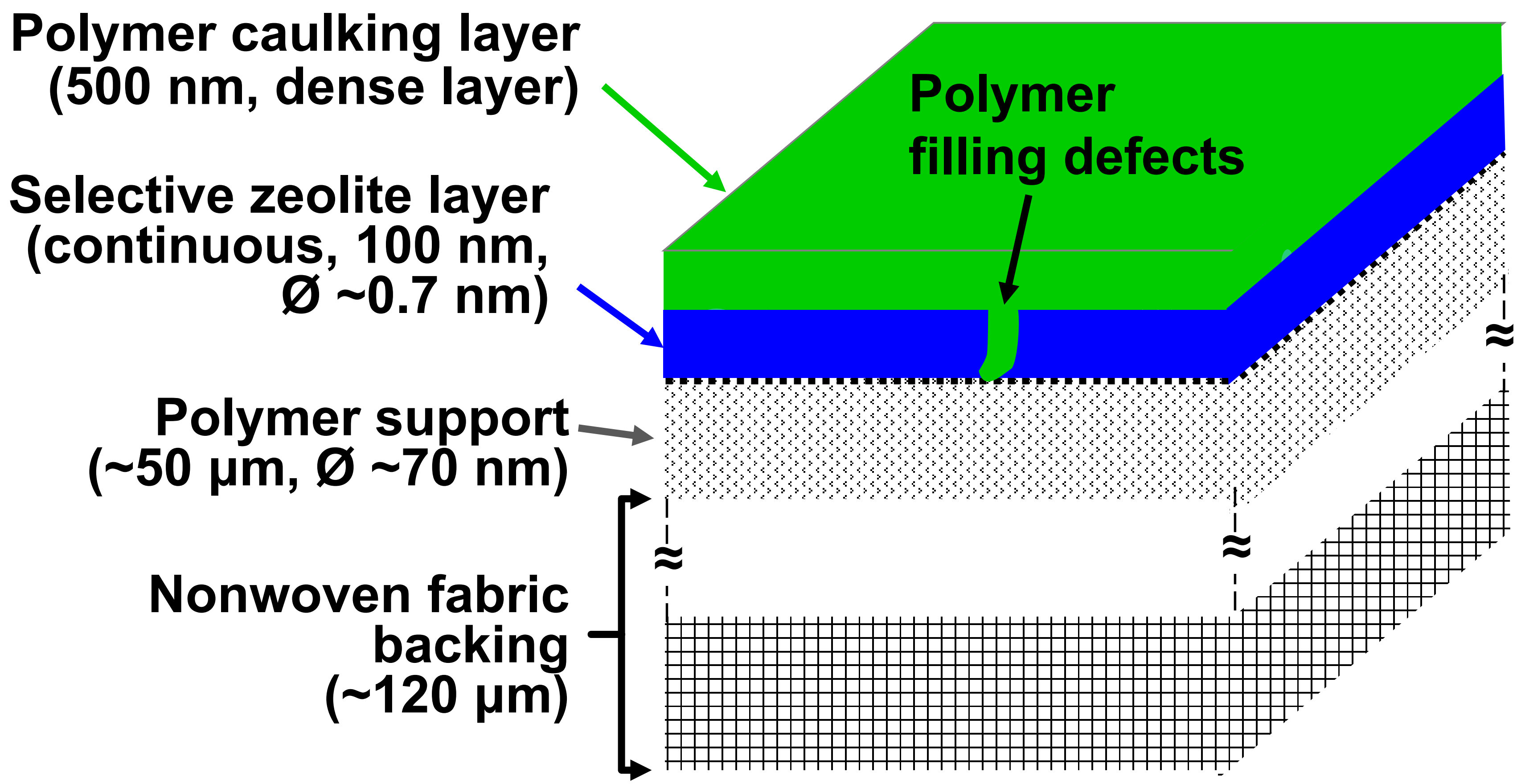




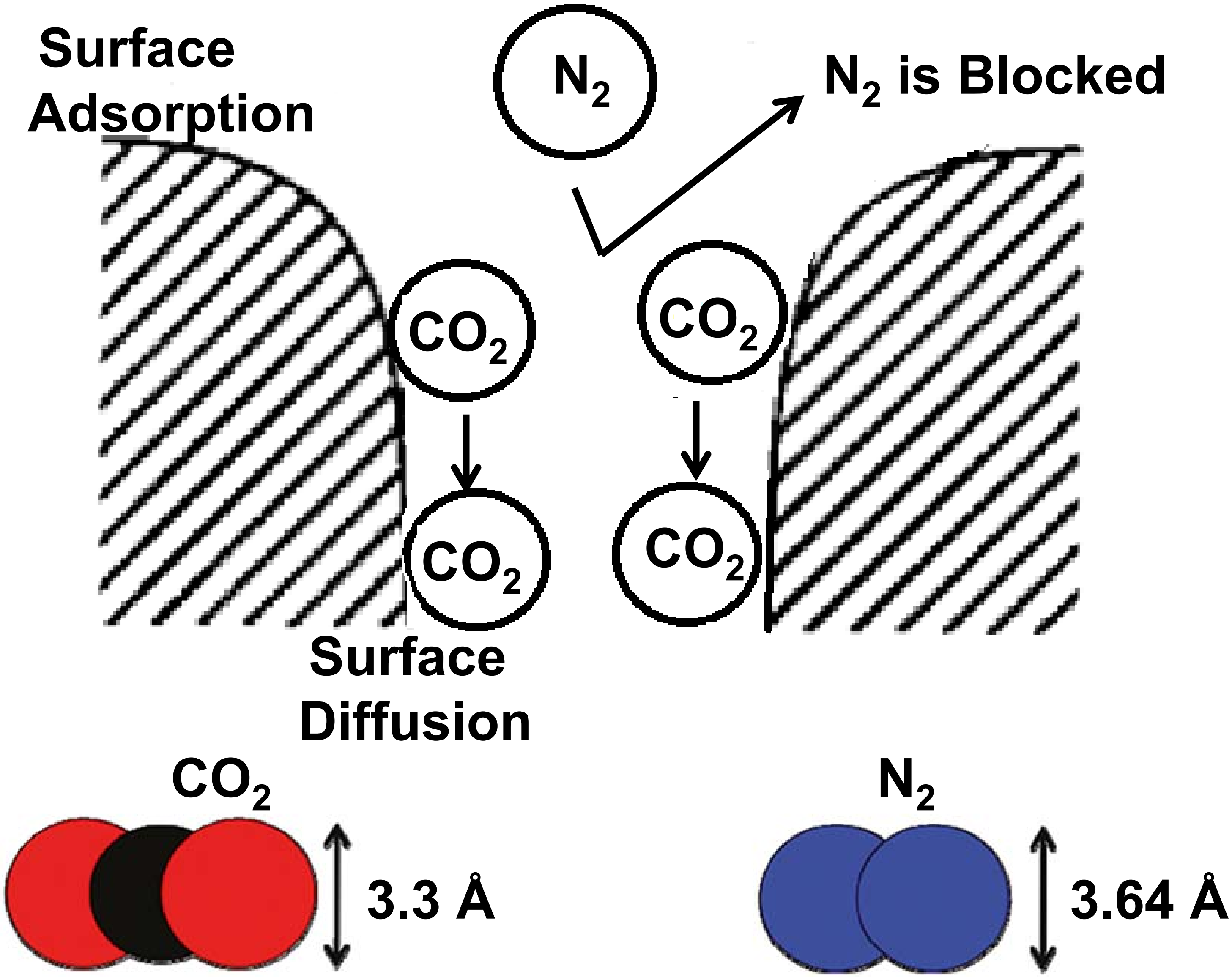
Sample name	Avg roughness
Nano y coated	6 nm

Approach 2: Polymer Caulking Layer / Selective Zeolite Membrane / Polymer Support

High Inorganic Performance and Low-Cost Polymer Processing Benefits



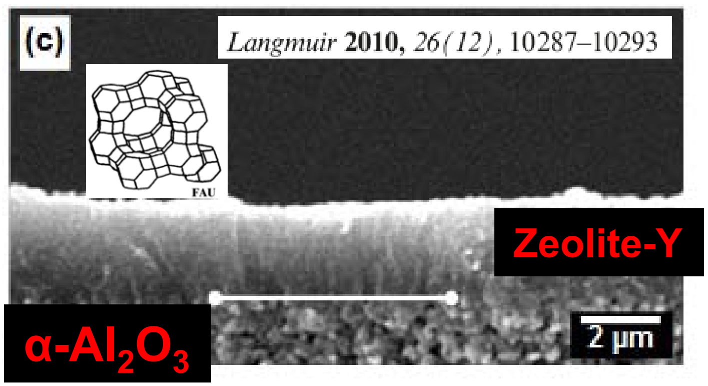
Approach 2: Transport Mechanism through Zeolite

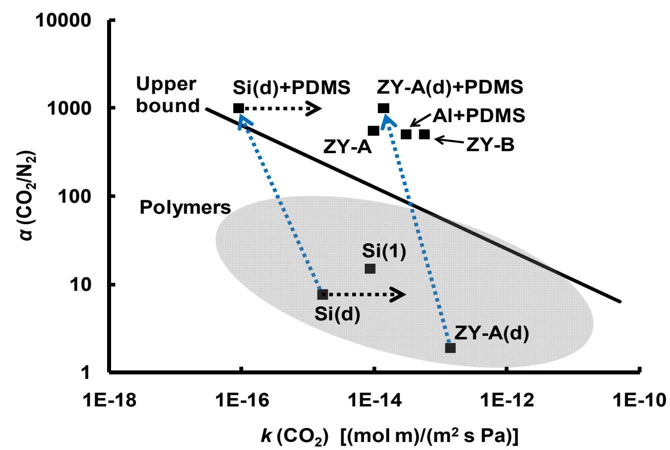


$Q_{CO_2} = -13.67 \times 10^{-40}$ C m^2

$Q_{N_2} = -4.67 \times 10^{-40}$ C m^2

Precedence to Approach 2

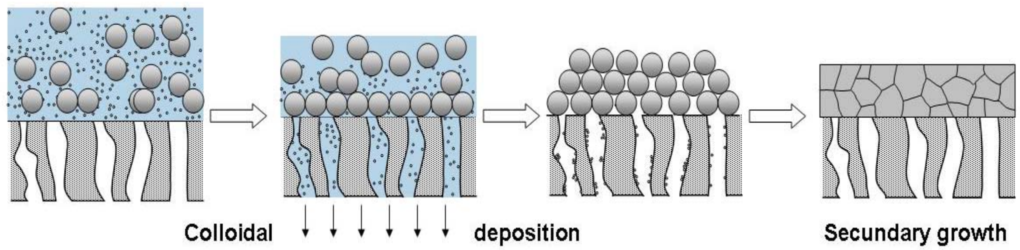




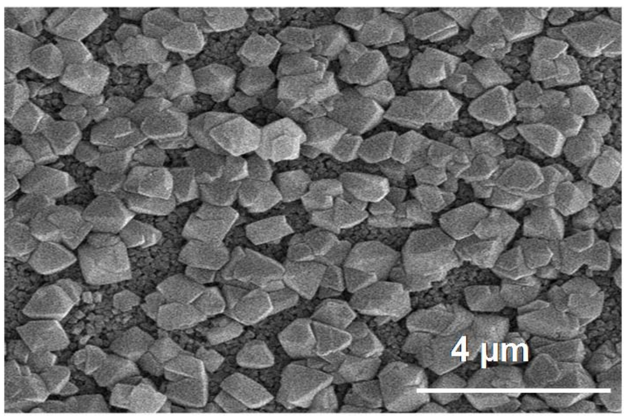
Journal of Membrane Science 421–422 (2012) 299–310

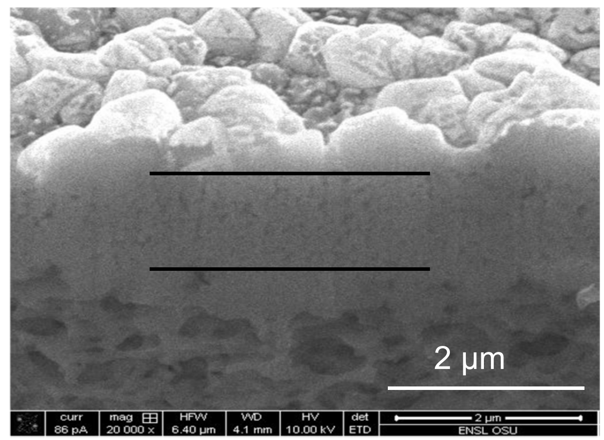
- Zeolite Y on alumina support
- 4-day synthesis
- GPU 328, Permenace 29 (CO_2/N_2)
- Synthetic protocols limit practical application
- Change to Polymer support and speed up zeolite synthesis

Approach 2: First Step – Polymer Support



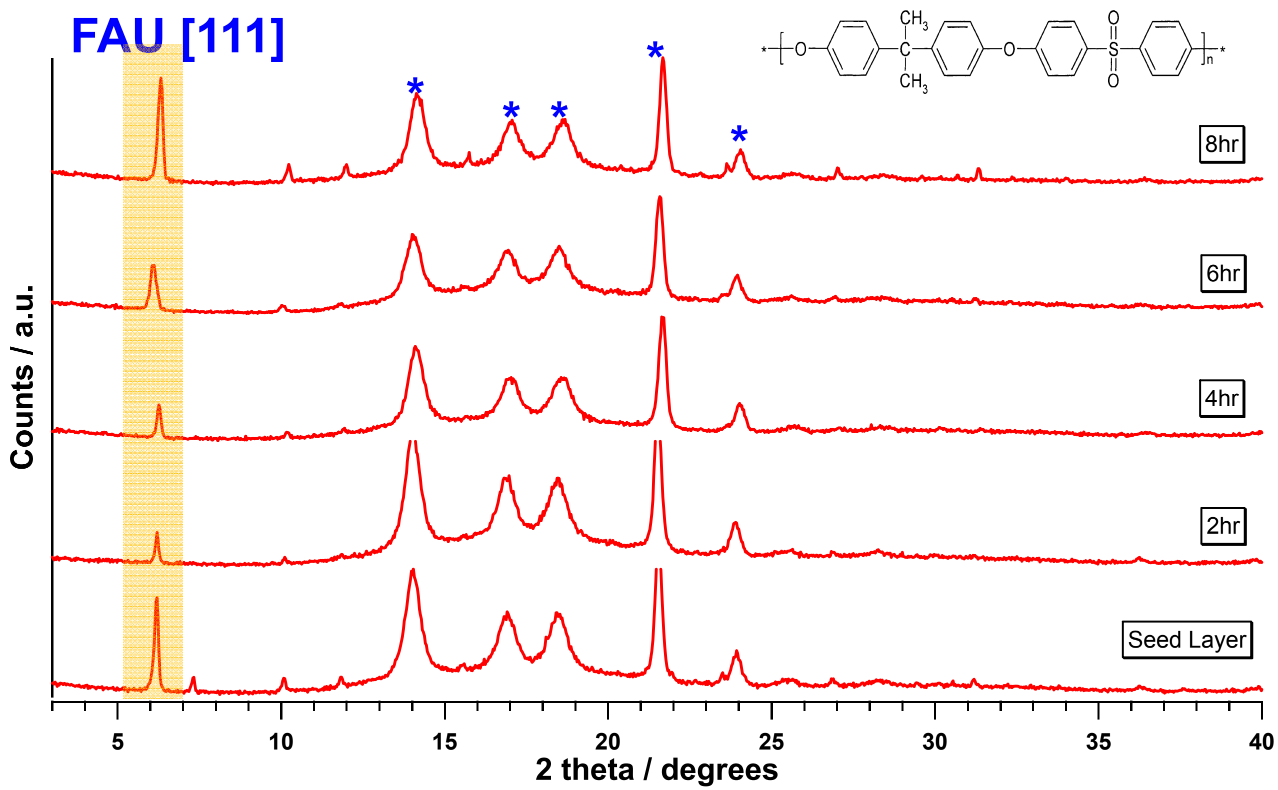
$17Na_2O:Al_2O_3:12.8SiO_2:975H_2O$





Growth Process takes 8 hours : Impractical

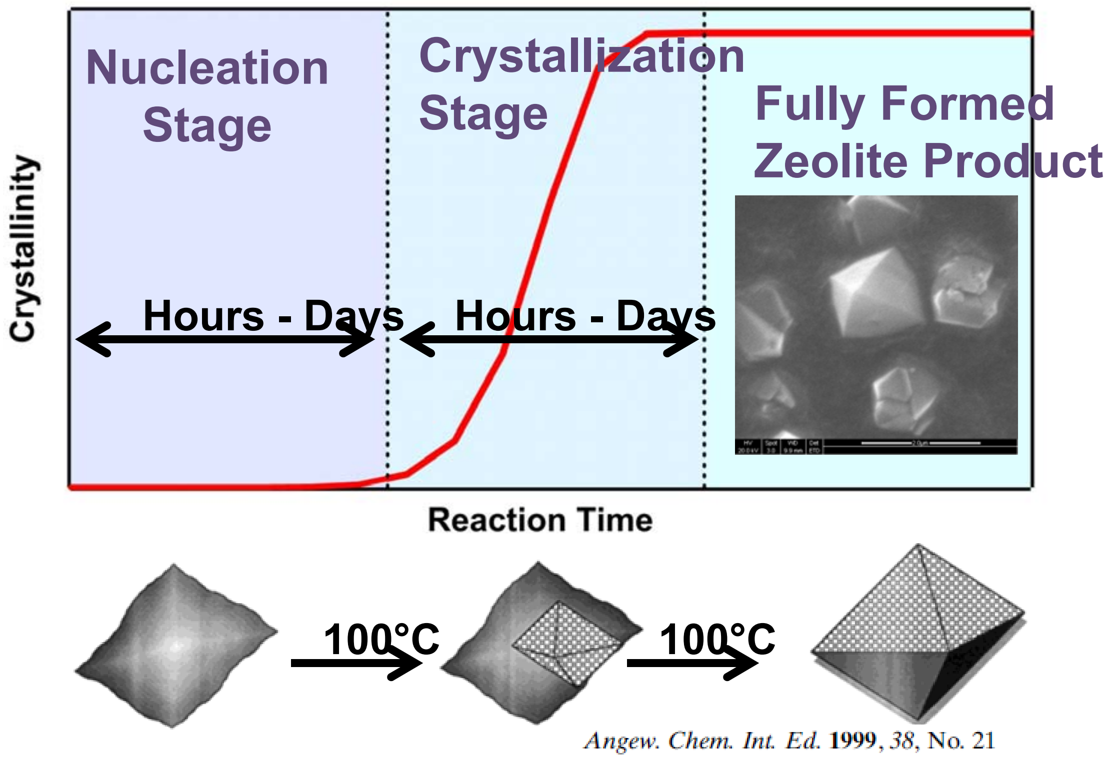
Approach 2: Conventional Zeolite Membrane Growth vs. Time



Poor physical adhesion and partial dissolution limit the membrane quality.

Approach 2: Decrease Zeolite Synthesis Time

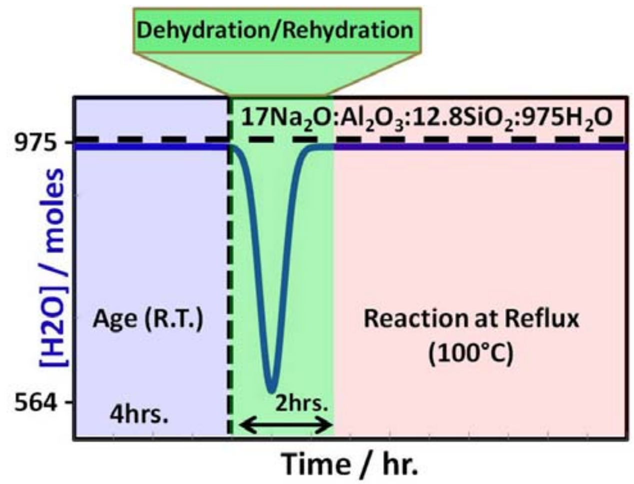
Traditional zeolite synthesis requires long reaction times at high temperatures.

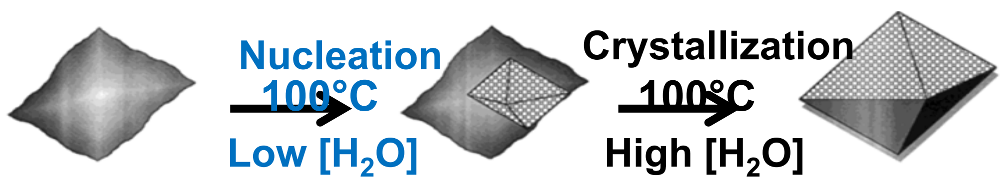


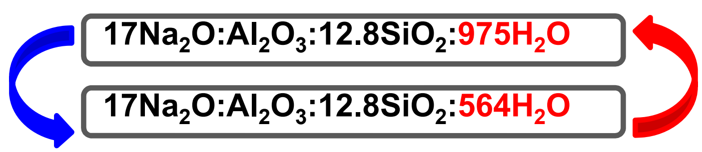
Approach 2: Novel Zeolite Synthesis Approach

<u>Rapid Synthesis</u>

- Open system
- Control water concentration
- Remove H_2O (nucleation)
- Re-add H_2O (crystallization)

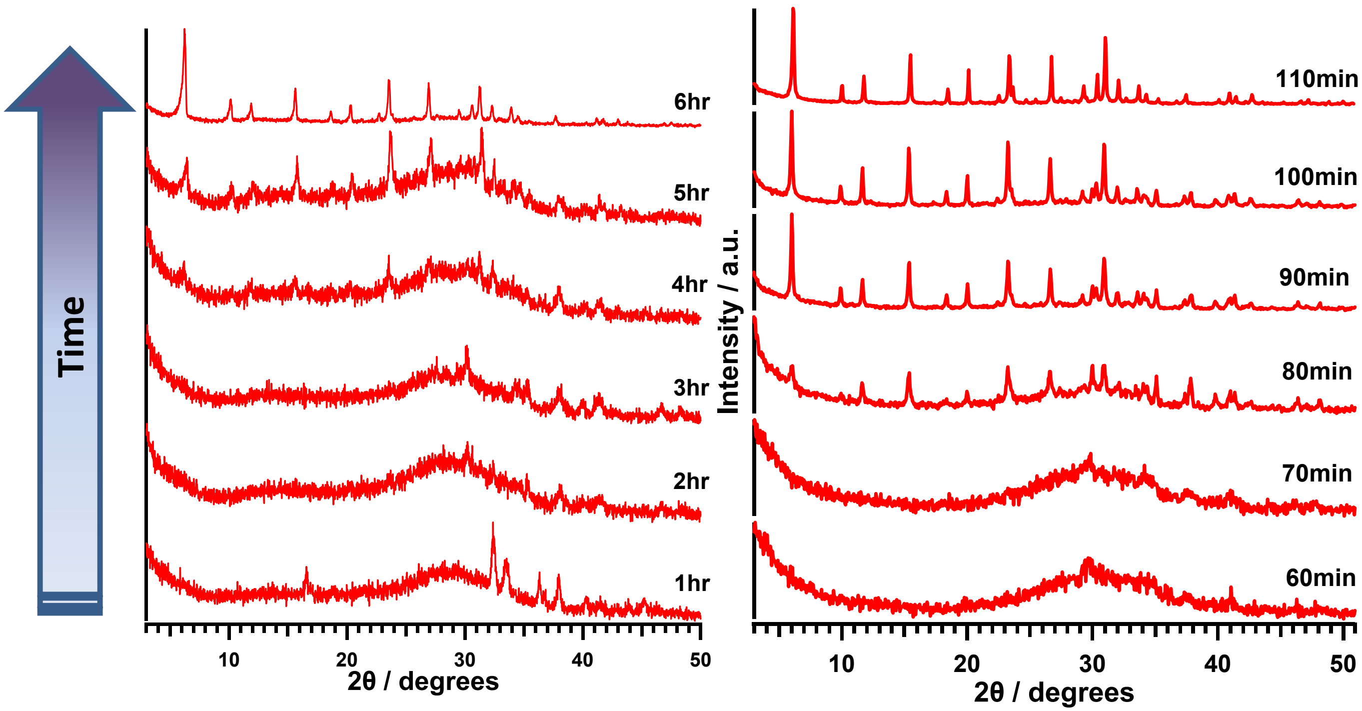






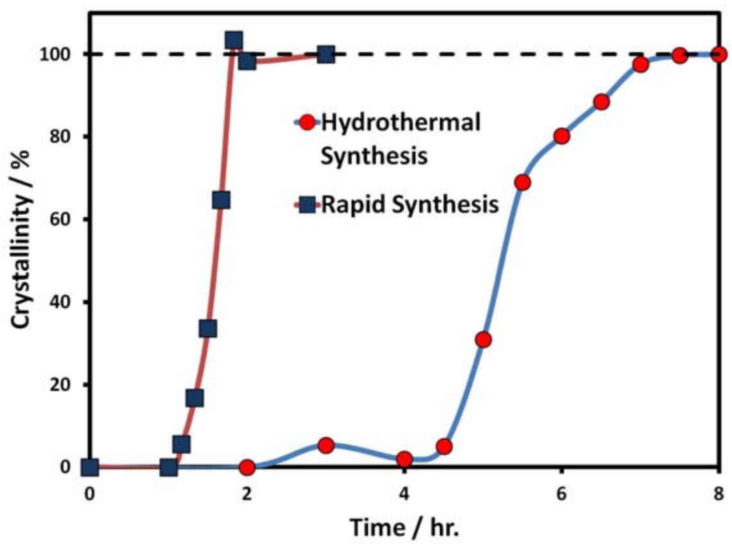
Approach 2: Rapid Synthesis of Zeolite Powders

Hydrothermal Synthesis $17Na_2O:1Al_2O_3:12.8SiO_2:975H_2O$ Rapid Synthesis



Rapid synthetic method yields pure crystalline zeolite powder in 110min

Approach 2: Zeolite Powder Formation Kinetics

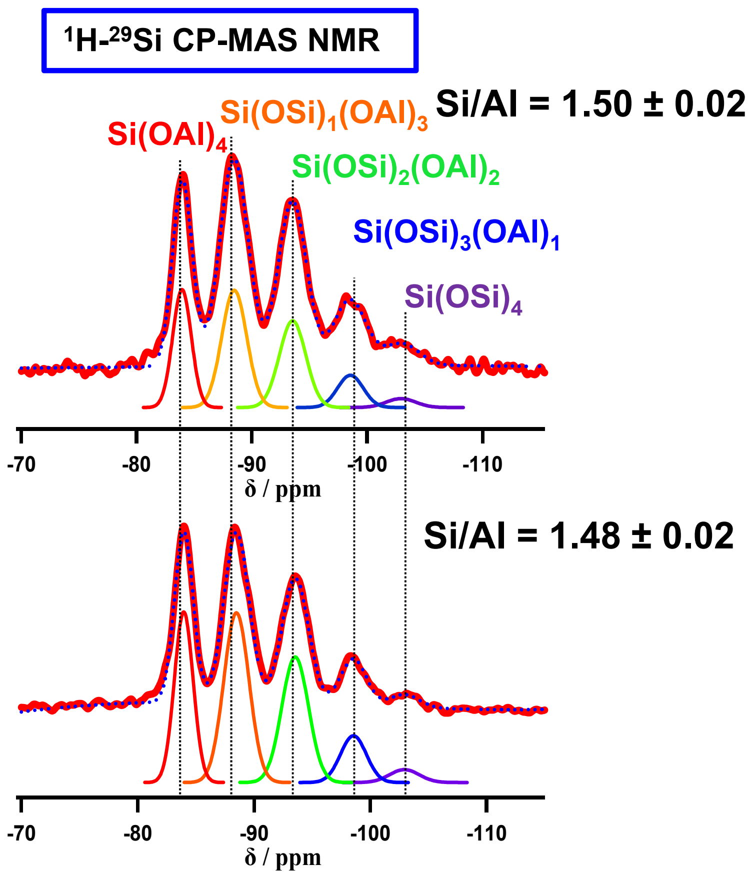


$17Na_2O:Al_2O_3:12.8SiO_2:975H_2O$

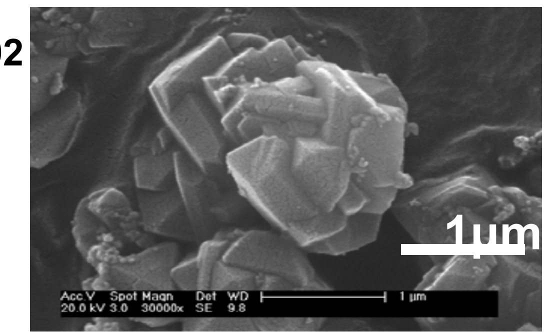
$17Na_2O:Al_2O_3:12.8SiO_2:564H_2O$

Crystallization in 2hrs. vs. 8hrs.

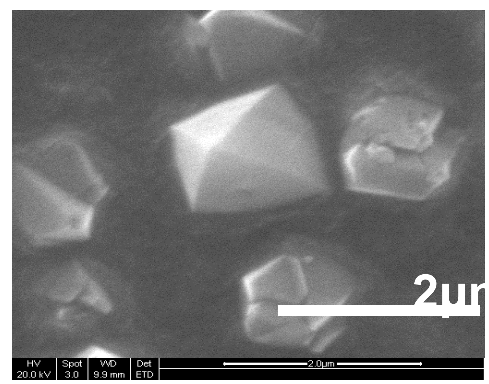
Approach 2: Comparing Rapid and Conventional Processes



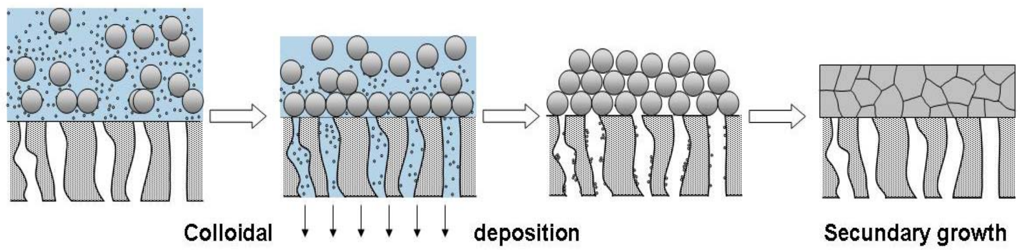
Rapidly grown product

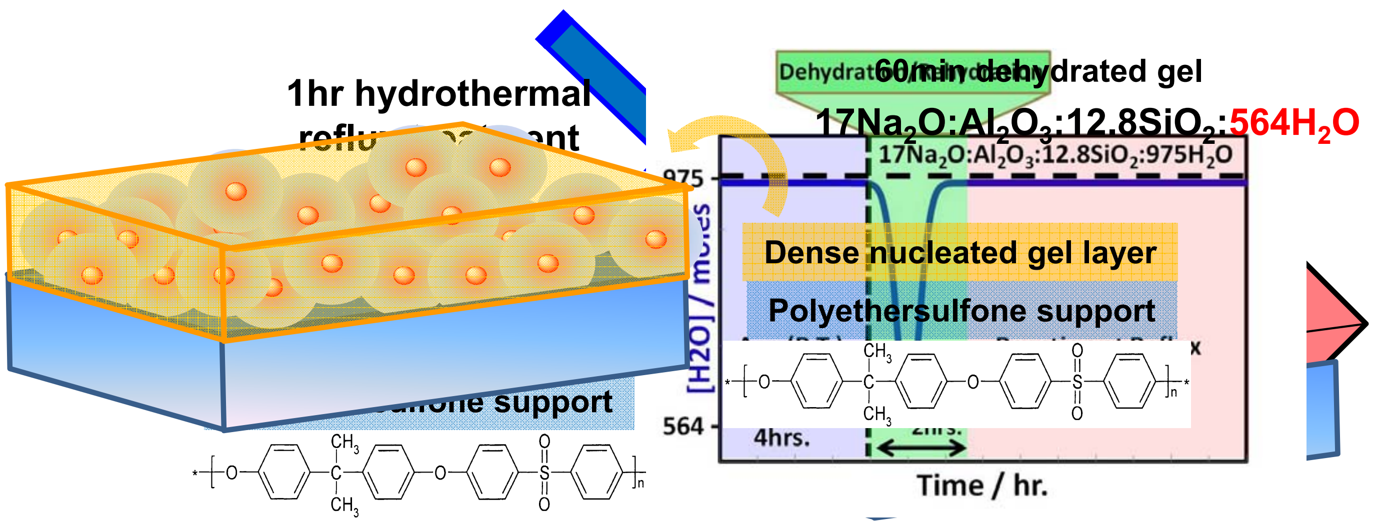


Hydrothermal product

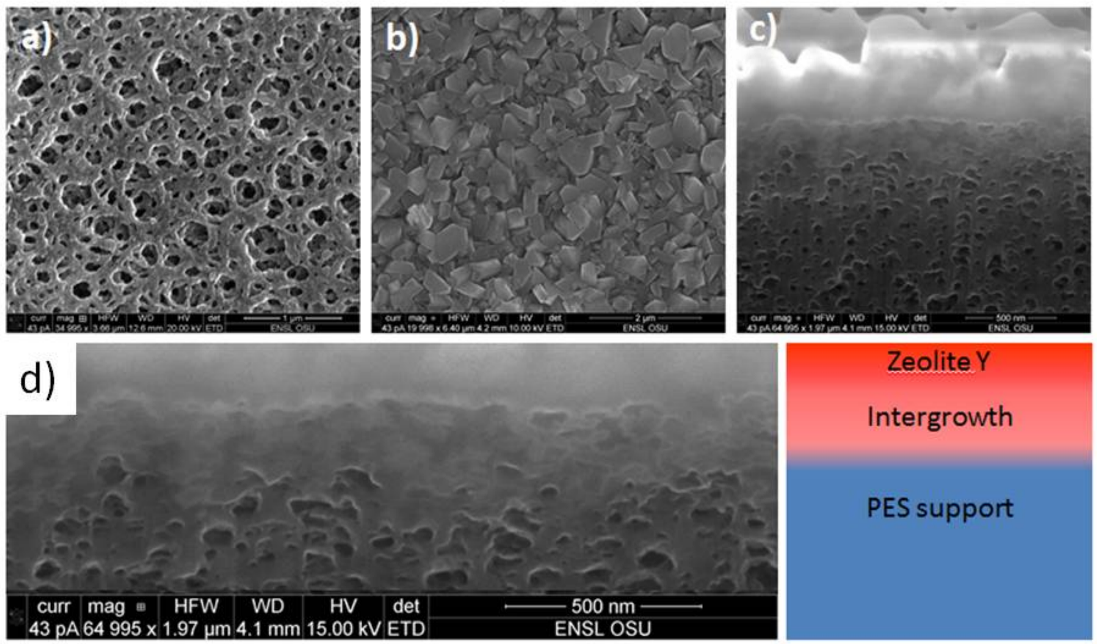


Approach 2: Application of Nucleated Gel to Membrane Growth

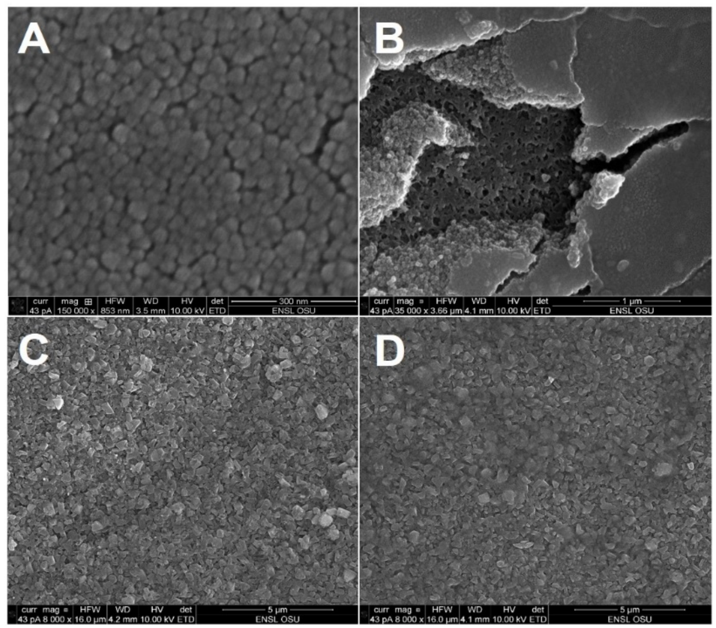




Approach 2: Characteristics of Membrane Grown by Rapid Process – 1 hour



Approach 2: Characteristics of Membrane Grown by Rapid Process – Tape Test

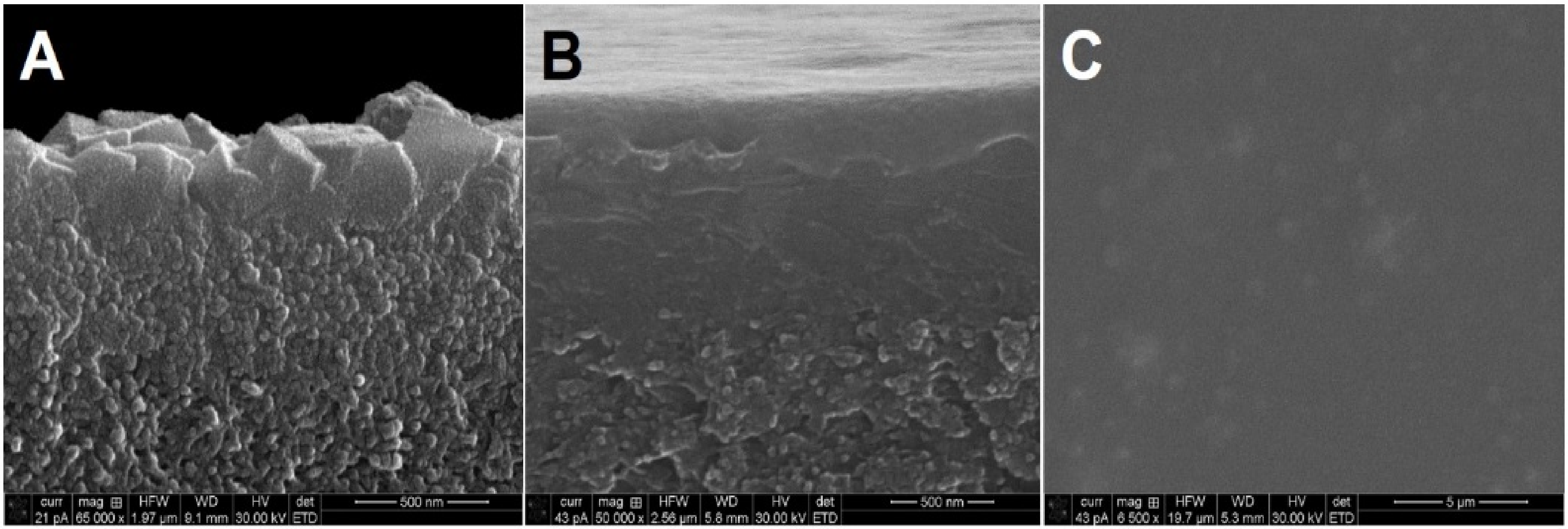


Seeded zeolite on PES support

Zeolite membrane on PES support

Before Tape test **After Tape test**

Approach 2: PDMS/Zeolite/PES Membrane Synthesized



A.Membrane

B. PDMS caulking layer

C: Top view

Techno-Economic Calculations (applicable to Approaches 1 and 2)

Performed by Gradient Technology (based on 2007$)

- **Scale-up Prototype Membrane Results**
  - **870 GPU and 218 Selectivity at 57°C**
    - **\$40.4/tonne CO_2 – Nearly meet DOE target of \$40/tonne CO_2**
    - **57.2% Increase in cost of electricity (COE)**
  - **1800 GPU and 160 Selectivity at 102°C**
    - **\$34.4/tonne CO_2 – Exceed DOE target of \$40/tonne CO_2**
    - **47.1% Increase in cost of electricity (COE)**
- **Lab-Size Membrane Results: 1100 GPU & 140 Selectivity at 57°C**
  - **\$37.5/tonne CO_2 – Exceed DOE target of \$40/tonne CO_2**
  - **52.2% Increase in COE**

- **If:**
  - **CO_2 Permeance = 3000 GPU and 140 CO_2/N_2 Selectivity**
    - **\$30.9/tonne CO_2 – Exceed DOE target of \$40/tonne CO_2**
    - **44% COE increase**

- **Significantly Lower Cost than Amine Scrubbing**

BP1 Milestone Status Report

Milestone Title Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Task 1	09/30/12			
No-cost extension requested	09/30/12	08/23/12	Project Manager	Additional time for meeting BP1 target
PI change	12/31/12	12/05/12	Project Manager	Change PI/Co-PI
Task 2	01/31/13			
Polymer support source selected	09/30/12	09/30/12	Performance data	Identified PES and PSF supports
Cover layer composition	01/31/13	--	Performance data	BP1 target met, continue BP2 and BP3
Protocol ceramic support >3000 GPU	04/01/12	09/30/12	Performance data	Completed; protocol delivered in Q3
Meso-porous scaffold	09/30/12	09/30/12	Performance data	Support blocking solved (see the above milestone)
Task 3	03/31/13			
Membrane benchmark for polymer supports	03/15/13	03/15/13	Transport measurement	BP1 target met
Membrane benchmark for ceramic supports	09/30/12	09/30/12	Transport measurement	Ceramic supports are no longer pursued.
Task 4	03/01/13			
Model incorporated in ASPEN Plus program	03/01/13	03/01/13	Model calculations	Model in ASPEN Plus program completed
Task 5	05/01/13			
Quarterly reports	Q1 – Q6 + 30 days	Q1: 01/31/2012 Q2: 05/01/2012 Q3: 07/31/2012 Q4: 10/26/2012 Q5: 01/31/2013 Q6: 04/30/2013 Q7: 08/14/2013	Project Manager	Mostly on schedule
Task 6	07/01/13			
Budget Period 1 report	07/01/13	06/14/13	Project Manager	On schedule

BP2 Milestone Status Report

Milestone Title Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Task 7	08/31/14			
3-Month no-cost extension requested	08/31/14	05/31/14	Project Manager	Additional time for completing BP2 tasks
Task 8	08/31/14			
Improved Membrane Synthesis	08/31/14	08/01/14	Performance data	
Continuous Deposition Procedure	08/31/14	08/01/14	Performance data	
Task 9	08/31/14			
Membrane Characterization	08/31/14	08/01/14	Transport measurement	
Task 10	08/31/14			
Continuous Membrane Machine Operational	12/31/13	12/31/13	Demonstration	The machine is operational at OSU.
7.5' 14" prototype membrane	08/31/14	08/01/14	Performance data	
Task 11	08/31/14			
Prototype Membrane Characterization	08/31/14	08/01/14	Transport measurement	
Task 12	08/31/14			
Spiral-Wound Membrane Element Rolling	08/31/14	08/01/14	Demonstration	
Task 13	08/31/14			
Pressure Drop Measurements of Membrane Elements	08/31/14		Pressure measurement	
Task 14	08/31/14			
Use and Refining of the System and Cost Analysis	08/31/14		Model calculations	
Task 15	08/31/14			
Quarterly reports	Q8 – Q11 + 30 days	Q8: 10/28/2013 Q9: 01/27/2014 Q10: 04/27/2014 Q10: 07/18/2014	Project Manager	On schedule
Task 16	10/01/14			
Budget Period 2 report	10/01/14		Project Manager	

Changes of BP2 Milestones

- **Zeolite Membrane Growth Time Revision to 1 h**
  - **Over the past two years, we have shortened this time from 8 h to 1 h**
  - **Due to significant amount of time spent in fixing irreproducibility**
    - **Not enough time to decrease zeolite membrane growth time**
  - **Original growth time set for 16 minutes based on minimum web speed of 1'/min for continuous machine provided by manufacturer**
    - **We have found that minimum web speed is actually 0.15'/min**
    - **This translates to 107 min available in this machine**
  - **Investigate strategies for shortening growth to <60 min in BP3**
- **Element/Module Size Revision to 1.8" dia. x 14"**
  - **We have had to develop PES support needed for scale-up**
    - **Due to issues encountered from PES support manufacturer**
    - **This has taken available time and resources**
  - **Our PES support costs much less – membrane cost much reduced**
  - **Due to zeolite growth time issue, limited resources to make zeolite nanoparticles – limited supply of nanoparticles**
    - **New microwave approach will alleviate this obstacle**
  - **Modified Milestone: Fabricate 7.5', in liu of 50' in BP2**
    - **15" x 14" membrane leaf used for element rolling**
  - **Will fabricate >50' membrane in BP3**
    - **Make three 2" dia. x 14" elements/modules in BP3**

Partners Involved in BP3 Tasks

- **Optimized Continuous Membrane Fabrication**
  - Continuous Membrane Fabrication Machine Available at OSU
  - TriSep Membrane Company is Involved

- **Real Flue Gas Testing**
  - Quick Testing at NCCC
    - Membrane module testing with real flue gas
    - For comparison with simulated flue gas results
  - NCCC (Tony Wu, Frank Morton) for Testing
  - AEP is Involved in EH&S and Power Plant integration
  - Gradient is Involved in Modeling and Cost Calculations

- **Gradient Task**
  - Task 24.0 – Use and Refining of System and Cost Analysis

BP3 Budget

Budget Period	Federal Share	Non-Federal Share	Project Total
3	$1,143,566	$420,293	$1,563,859

- **Budget amounts do not change**
  - Not asking for more money for BP3
- **Reallocating funds for proposed technology development acceleration**
- **ODOD cash match of $500,000 cost share**
  - Add 2.5 Ph.D. students to this project
    - Zeolites with different pore openings as compared to Zeolite-Y
    - Subsequent zeolite-polymer composite membranes
  - This should complement and contribute to this project significantly

BP3 Tasks – No Major Changes

Task 17.0 – Project Management and Planning

Task 18.0 – Further Improved Membrane Synthesis
- Subtask 18.1 – Optimiz. of inorg. sel. layer: rapid zeolite membrane growth
- Subtask 18.2 – Optimization of inorganic / polymer membrane

Task 19.0 – Membrane Characterization – *SO_2 Mitigation*

Task 20.0 – Optimized Prototype Membranes Fabrication
- Subtask 20.1 – Fabrication of optimized inorganic selective layer
- Subtask 20.2 – Fabrication of optimized inorganic/polymer membrane
    + At least 50 ft of 14-inch width

Task 21.0 – Optimal Prototype Membrane Characterization

Task 22.0 – Prototype Module Fabrication – 3 Modules (each 2 m^2)
- Subtask 22.1: Spiral-wound module fabrication
- Subtask 22.2: Optimized fabrication w.r.t. pressure drop & packing density

Task 23.0 – Membrane Module Testing
- Subtask 23.1: Bench scale testing using simulated flue gas
- Subtask 23.2: Pressure drop measurements with simulated flue gas

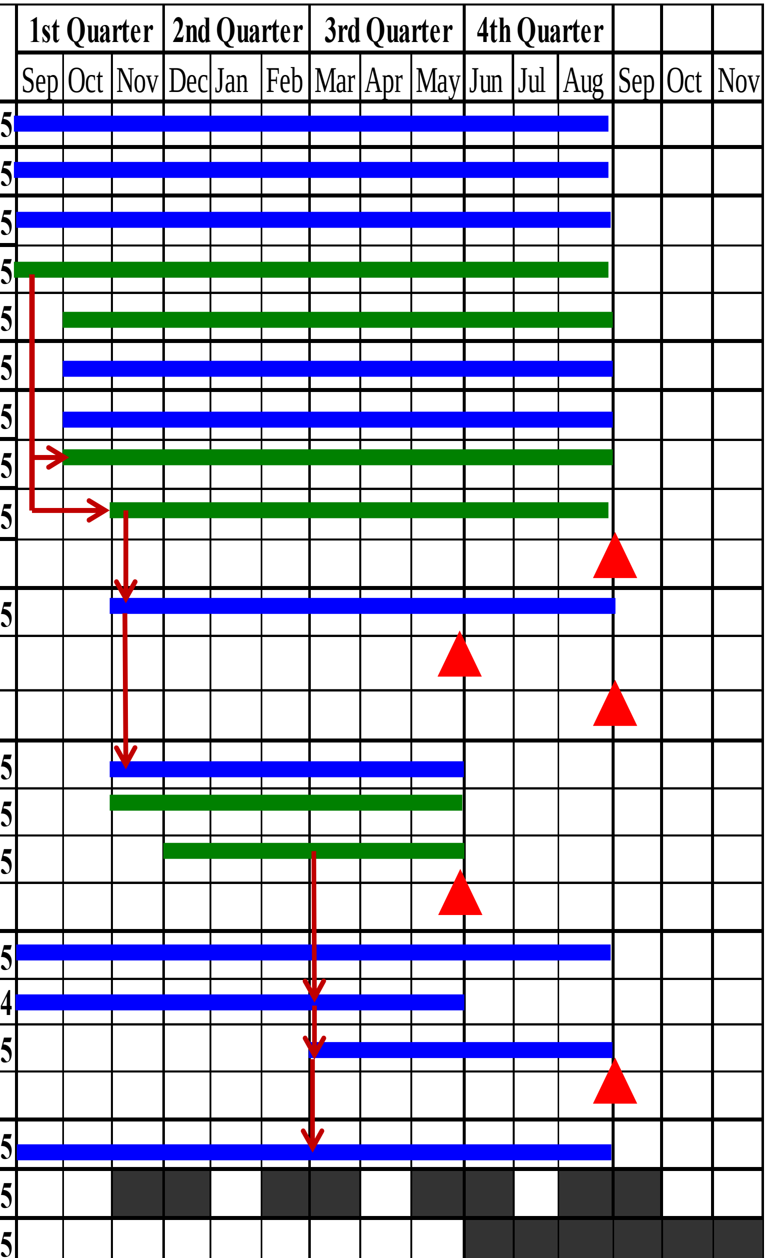
Task 24.0 – Use and Refining of System and Cost Analysis

Task 25.0 – Quarterly Progress Reports

Task 26.0 – Final Technical Report

BP3 Task Schedule

Task Name	Total Cost of Task ($)	Start	Finish
Budget Period 3	1,563,859	**9/1/2014**	**8/31/2015**
Task 17: Project Management and Planning	10,753	**9/1/2014**	**8/31/2015**
Task 18: Further Improved Membrane Synthesis	262,545	**9/1/2014**	**8/31/2015**
Subtask 18.1: Optimization of inorganic selective layer	*131,272*	**9/1/2014**	**8/31/2015**
Subtask 18.2: Optimization of inorganic/polymer membrane	*131,273*	**10/1/2014**	**8/31/2015**
Task 19: Membrane Characterization	149,745	**10/1/2014**	**8/31/2015**
Task 20: Optimized Prototype Membrane Fabrication	300,545	**10/1/2014**	**8/31/2015**
Subtask 20.1: Fabrication of optimized inorganic selective layer	*150,272*	**10/1/2014**	**8/31/2015**
Subtask 20.2: Fabrication of optimized inorganic/polymer membrane	*150,273*	**11/1/2014**	**8/31/2015**
Milestone 6: Successful fabrication of at least 50-ft prototype membrane			
Task 21: Optimal Prototype Membrane Characterization	211,065	**11/1/2014**	**8/31/2015**
Milestone 7: Prototype membrane with $40/tonne CO_2			
Milestone 8: Prototype membrane with $39/tonne CO_2			
Task 22: Prototype Module Fabrication	221,894	**11/1/2014**	**5/31/2015**
Subtask 22.1: Spiral-wound module fabrication	*110,947*	**11/1/2014**	**5/31/2015**
Subtask 22.2: Optimized fabrication w.r.t. pressure drop/packing density	*110,947*	**12/1/2014**	**5/31/2015**
Milestone 9: Successful fabrication of 3 modules of 2-inch dia. by 14 inches			
Task 23: Membrane Module Testing	221,086	**9/1/2014**	**8/31/2015**
Subtask 23.1: Bech scale testing with simulated flue gas	*138,179*	**9/1/2014**	**2/28/2014**
Subtask 23.2: Presure drop measurements with simulated flue gas	*82,907*	**3/1/2015**	**8/31/2015**
Milestone 10: Achieving acceptable pressure drop (0.05 bar)			
Task 24: Use and Refining of the System and Cost Analysis	174,475	**9/1/2014**	**8/31/2015**
Task 25: Quarterly Progress Reports	5,876	**11/1/2014**	**10/1/2015**
Task 26: Final Technical Report	5,875	**6/1/2015**	**12/1/2015**



Field Testing for BP3

- **Prototype Membrane Module Field Testing**
  - NCCC with real flue gas
  - Discussion with NCCC (Tony Wu and Frank Morton) in progress
- **CO_2 and SO_2 will be Measured**
- **After Test, comparative analysis with baseline data**
  - Module will be measured in lab for permeance / selectivity
  - For comparison with the module without exposure
- **Post Mortem Analysis**
- **Any Residues/Contaminants Collected will be Analyzed**
  - Testing on treating flue gas with pretreatment
    - + Filtration using 5-μm filter before membrane
    - + Based on field test data, revisit pretreatment requirements
  - Designing Effective Pretreatment
  - Determining O&M Requirements

Technology Development Roadmap

July 2013	8” x 8” Membrane leaf hand-rolled into element
May 2014	Continuous PES support fabrication
June 2014	Continuous zeolite nanoparticle deposition
July 2014	Continuous amine cover layer on zeolite nanoparticle layer Spiral-wound element fabricated using rolling machine “Model-T” membrane module fabricated
December 2014	Membrane module testing at NCCC
2016 – 2017	1 TPD at NCCC
2019 – 2020	20 TPD (1 MW) at NCCC

Technical and Economic Analysis

- **Aspen Plus modeling software utilized to model the capture process**
- **PC plant has not been modeled**
- **Model has been integrated into a Supercritical PC plant (Case 11) that produces 550 MW of net power**
- **The capture equipment has been sized to capture 90% of the CO_2 at a purity of 95 vol% and compress it to 2,215 psia at 124°F**
- **Economic model is based on the factored cost estimating technique (distributive percentages)**
  - **Recognized by American Association of Cost Engineers (AACE)**
- **Technical & economic analysis conducted similarly to the analysis completed in the NETL report**
  - ***Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, Nov. 2010***

Technical & Economic Analysis (Cont'd)

- 27 different cases utilizing the Aspen Plus and economic model were conducted
- Report details the results and includes stream tables, process flow diagrams, equipment size and cost information, capital cost summaries, variable and fixed cost summaries, and all performance and cost metrics
- Primary parameters investigated:
  - ✓Flue gas feed pressure to the membrane-based CO_2 capture unit
  - ✓First-stage membrane permeate pressure
  - ✓CO_2 permeance
  - ✓CO_2 / N_2 selectivity
  - ✓H_2O / CO_2 selectivity

Technical & Economic Analysis
Case Parameters

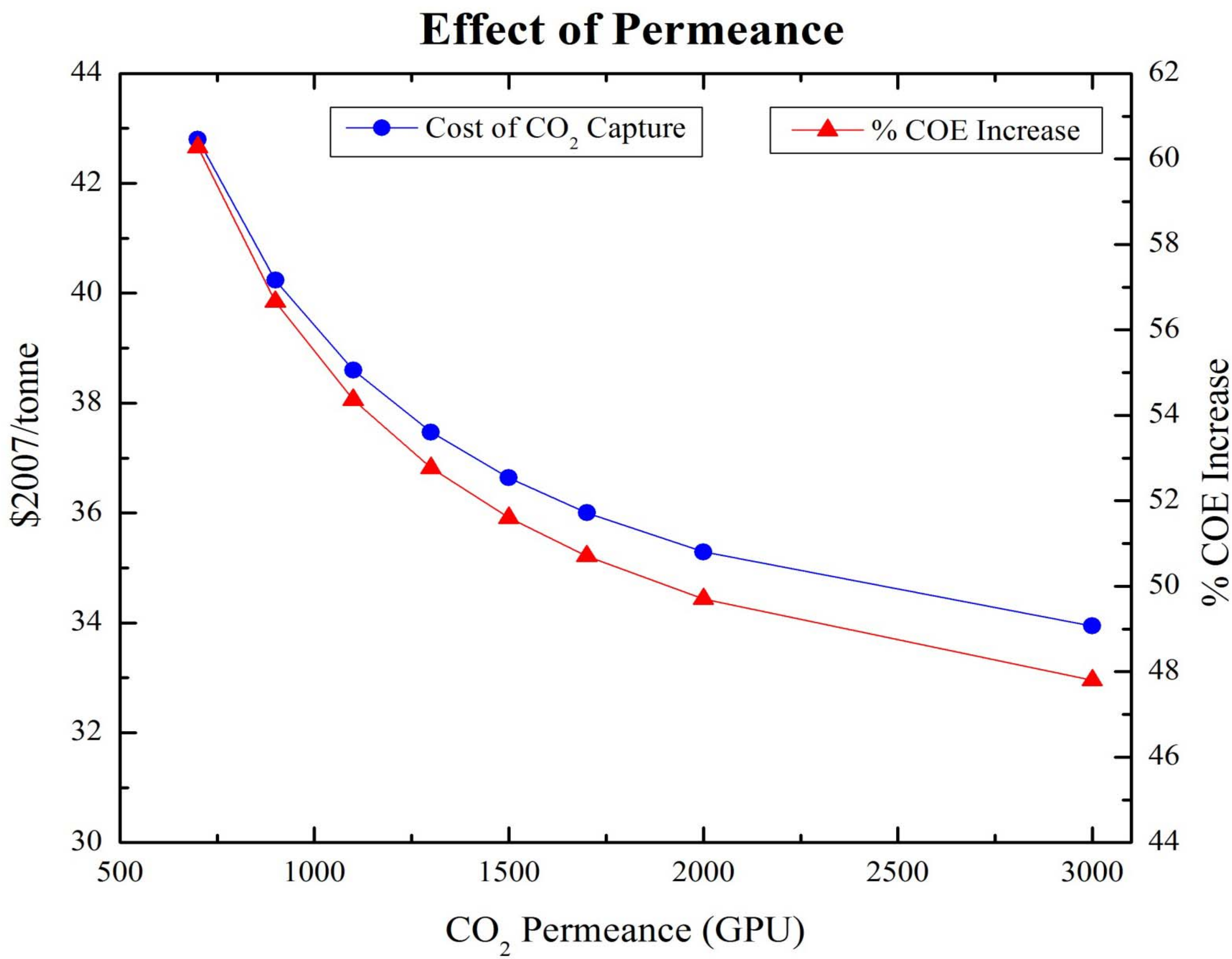
	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H	Case I	Case J
Flue Gas Pressure (atm)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Membrane 1 Permeate Pressure (torr)	150	150	150	150	150	150	150	150	150	150
Membrane 2 Air Sweep (%)	80	80	80	80	80	80	80	80	80	80
Air Sweep Gas Pressure (atm)	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
CO_2 Permeance (GPU)	1100	1300	1500	1700	2000	3000	1100	1100	1100	1100
H_2O:CO_2 Permeance	1	1	1	1	1	1	1	1	1	1
CO_2:N_2 Permeance	140	140	140	140	140	140	160	180	200	300
H_2O Permeance (GPU)	1100	1300	1500	1700	2000	3000	1100	1100	1100	1100
N_2 Permeance (GPU)	7.9	9.3	10.7	12.1	14.3	21.4	6.9	6.11	5.5	3.7
SO_x and NO_x Permenace (GPU)	0	0	0	0	0	0	0	0	0	0
MB-02 Sweep Side Pressure	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Turboexpander	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cost of Electricity Increase (%)	54.36%	52.77%	51.60%	50.71%	49.70%	47.80%	53.85%	53.57%	53.41%	53.47%
Cost of CO_2 Capture	38.60	37.47	36.64	36.00	35.29	33.94	38.29	38.12	38.05	38.17

	Case K	Case L	Case M	Case N	Case O	Case P	Case Q	Case R	Case S	Case T
Flue Gas Pressure (atm)	1.6	1.4	1.3	1.2	1.1	1.07	1.054	1.5	1.5	1.5
Membrane 1 Permeate Pressure (torr)	150	150	150	150	150	150	150	170	150	150
Membrane 2 Air Sweep (%)	80	80	80	80	80	80	80	80	80	80
Air Sweep Gas Pressure (atm)	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
CO_2 Permeance (GPU)	1100	1100	1100	1100	1100	1100	1100	1100	900	700
H_2O:CO_2 Permeance	1	1	1	1	1	1	1	1	1	1
CO_2:N_2 Permeance	140	140	140	140	140	140	140	140	140	140
H_2O Permeance (GPU)	1100	1100	1100	1100	1100	1100	1100	1100	900	700
N_2 Permeance (GPU)	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	6.4	5.0
SO_x and NO_x Permenace (GPU)	0	0	0	0	0	0	0	0	0	0
MB-02 Sweep Side Pressure	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Turboexpander	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Cost of Electricity Increase (%)	54.26%	55.01%	56.46%	60.38%	74.43%	90.72%	157.98%	53.52%	56.66%	60.28%
Cost of CO_2 Capture	38.31	39.30	40.61	43.75	54.29	66.04	115.13	38.13	40.24	42.80

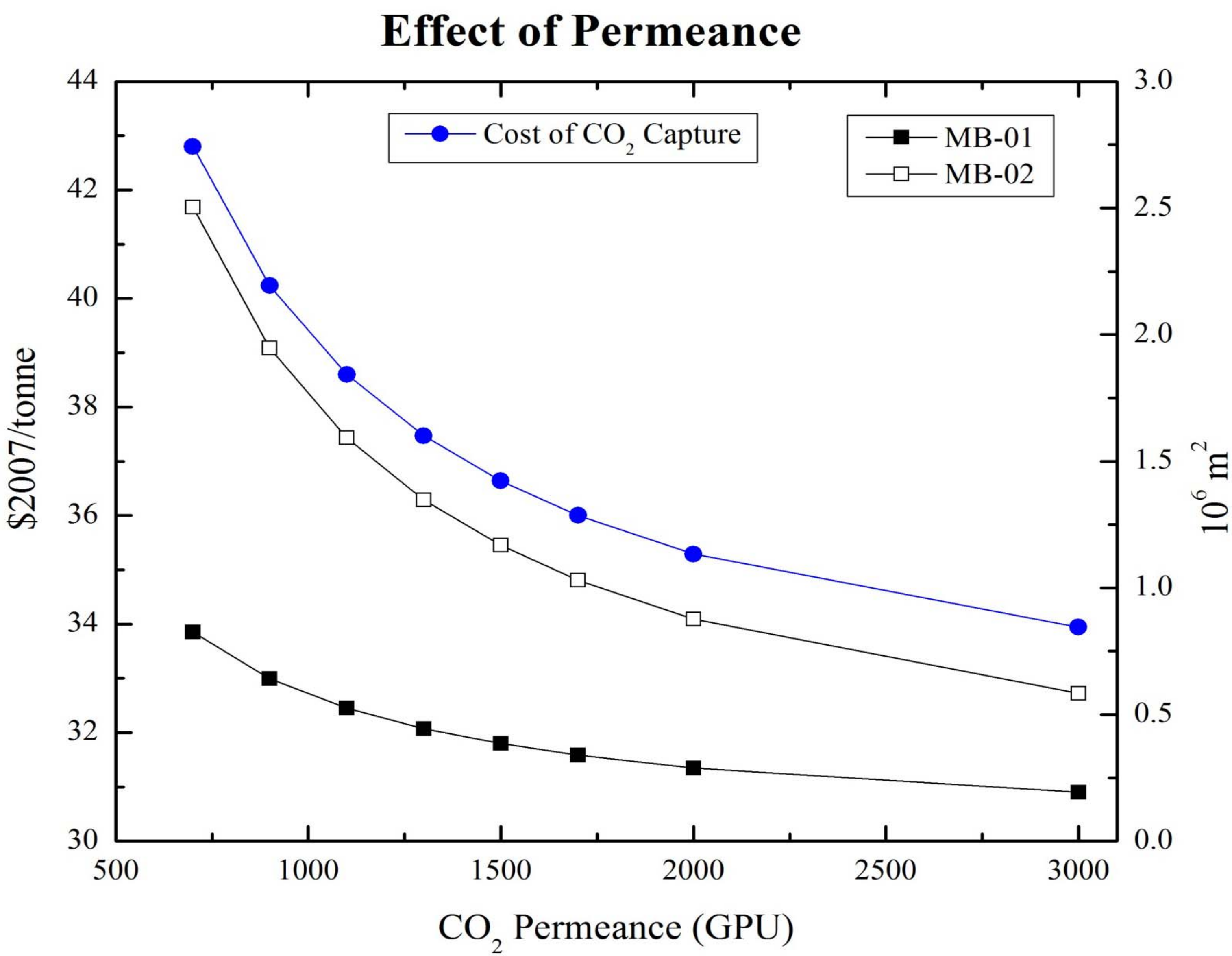
Technical & Economic Analysis Case Parameters

	Case U	Case V	Case W	Case X	Case Y	Case Z	Case AA
Flue Gas Pressure (atm)	1.7	1.5	1.5	1.5	1.5	1.5	1.6
Membrane 1 Permeate Pressure (torr)	150	130	190	210	230	170	150
Membrane 2 Air Sweep (%)	80	80	80	80	80	80	80
Air Sweep Gas Pressure (atm)	1.05	1.05	1.05	1.05	1.05	1.05	1.05
CO_2 Permeance (GPU)	1100	1100	1100	1100	1100	900	900
$H_2O:CO_2$ Permeance	1	1	1	1	1	1	1
$CO_2:N_2$ Permeance	140	140	140	140	140	140	140
H_2O Permenace (GPU)	1100	1100	1100	1100	1100	900	900
N_2 Permenace (GPU)	7.9	7.9	7.9	7.9	7.9	6.4	6.4
SO_x and NO_x Permenace (GPU)	0	0	0	0	0	0	0
MB-02 Sweep Side Pressure	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Turboexpander	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cost of Electricity Increase (%)	54.46%	56%	53%	53%	52%	56%	56%
Cost of CO_2 Capture	38.2	39.5	37.8	37.6	37.5	39.8	39.7

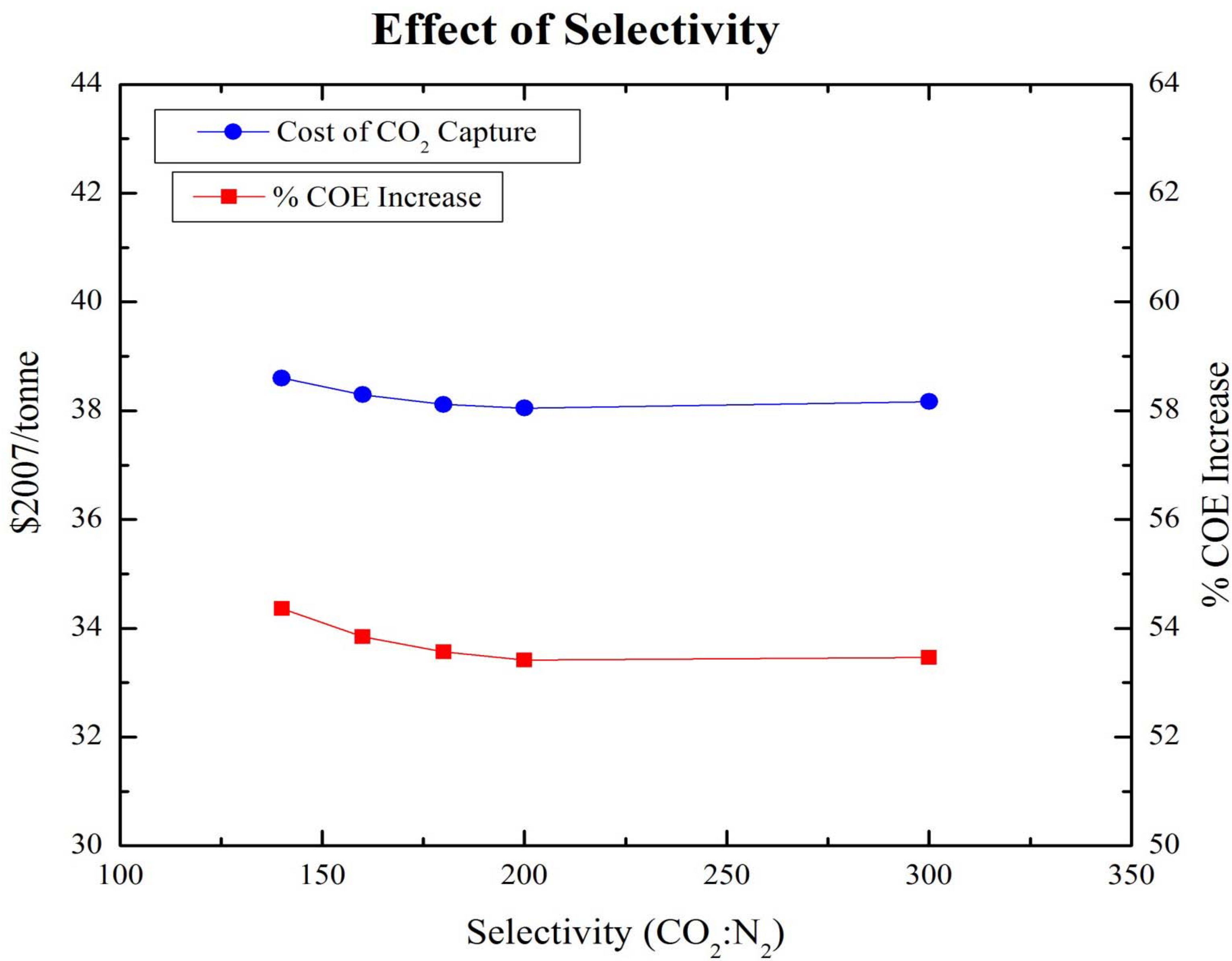
Technical & Economic Analysis Results



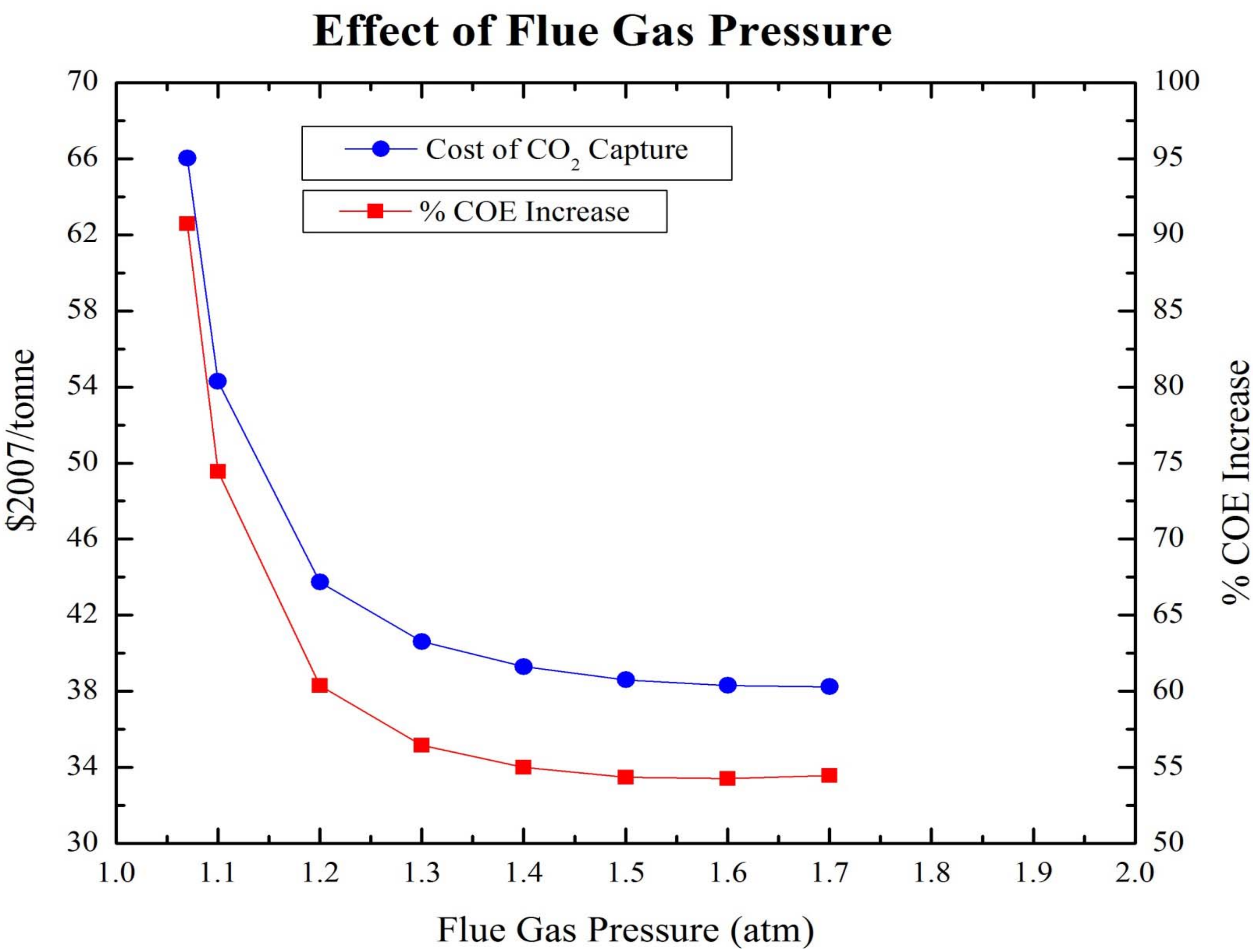
Technical & Economic Analysis Results



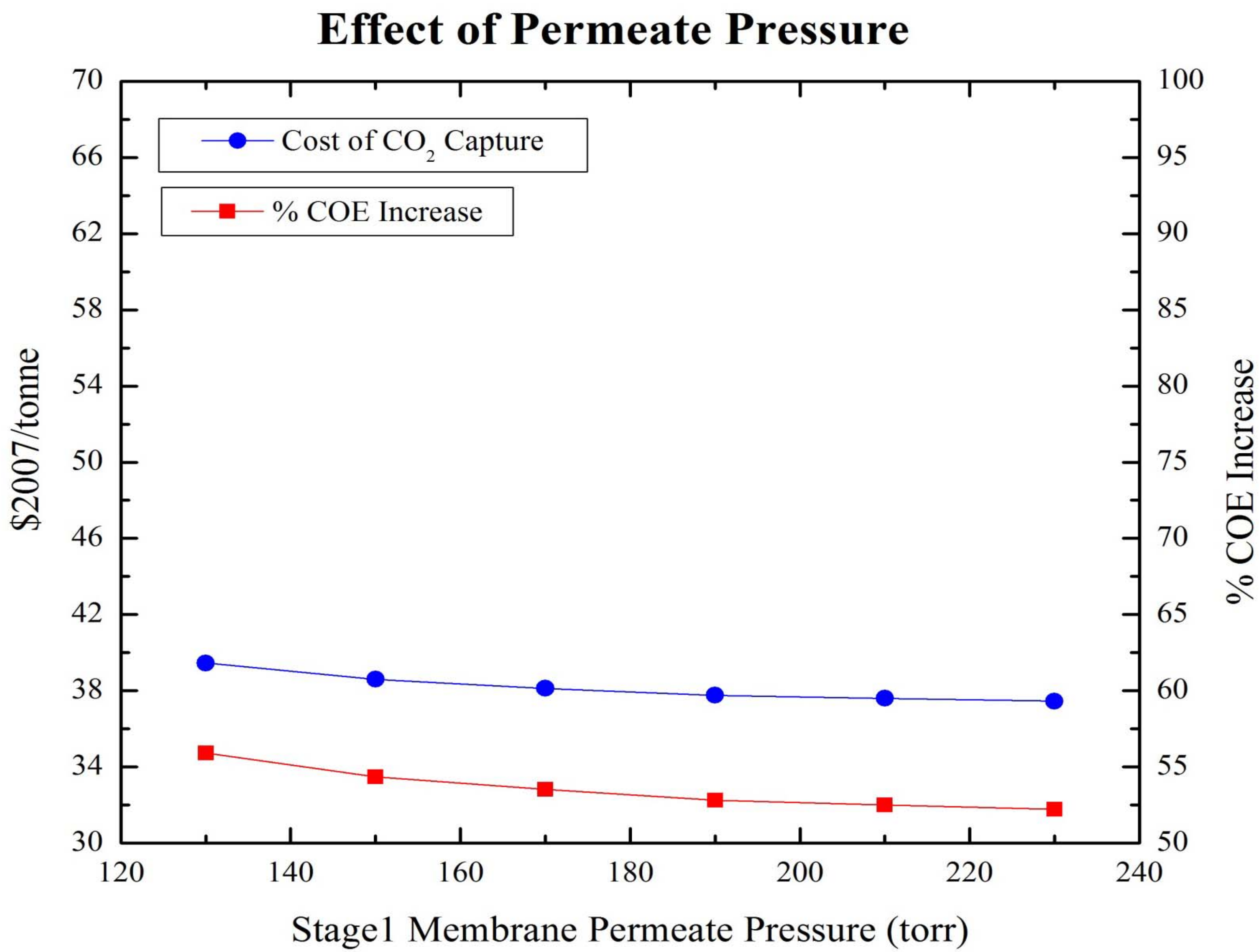
Technical & Economic Analysis Results



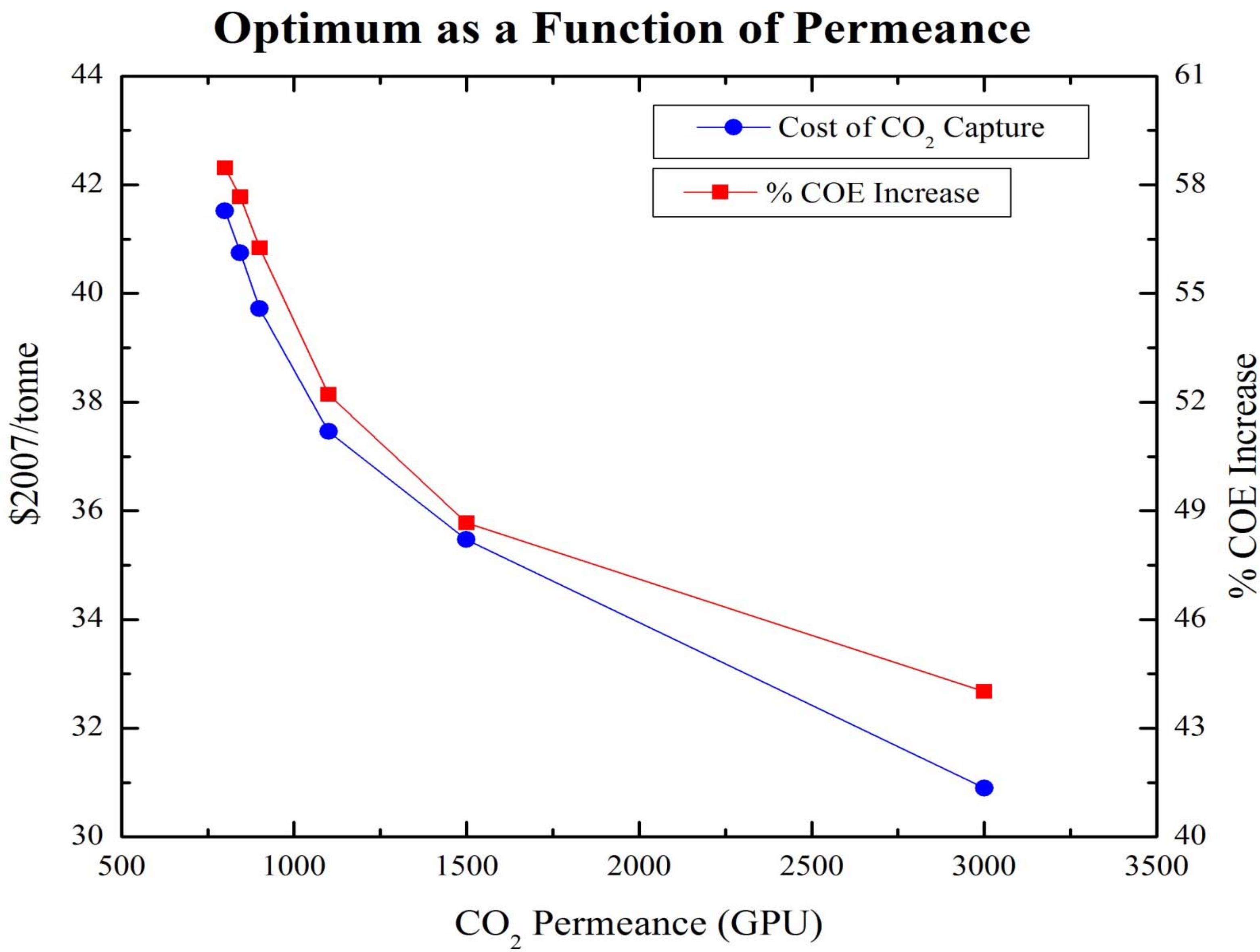
Technical & Economic Analysis Results



Technical & Economic Analysis Results



Technical & Economic Analysis Results



Technical & Economic Analysis Results

- **Effect of CO_2 permeance**
  - **Improved permeance reduces membrane areas and, hence, cost**
- **Effect of CO_2 / N_2 selectivity**
  - **Selectivity (>140) has negligible impact on economics**
- **Effect of Flue Gas Pressure**
  - **Flue gas pressure optimum approximately 1.5 – 1.6 atm and decreases with increasing permeance**
- **Effect of Permeate Pressure (Stage 1)**
  - **Increased permeate pressure slightly improves economics due to reduced vacuum demand**

Technical & Economic Analysis Summary

- **Technical & economic analysis has shown that the cost of carbon capture can be reduced to less than $40/tonne**

- **SO_2 removal equipment has been included to reduce SO_2 to less than 10 ppm**

- **Improved economic analysis will require additional equipment design and quotations**

Summary

- Achieved milestones/success criteria for BP2
  - Scale-up prototype membrane results
    - + CO_2 permeance = 870 GPU, CO_2/N_2 selectivity = 218 at 57°C
      - ++ Capture cost = \$40.4/tonne CO_2 – Nearly meet DOE target of \$40/tonne
    - + CO_2 permeance = 1800 GPU, CO_2/N_2 selectivity = 160 at 102°C
      - ++ Capture cost = \$34.4/tonne CO_2 – Exceed DOE target of \$40/tonne
  - Lab-size membrane with CO_2 permeance = 1100 GPU, CO_2/N_2 selectivity = ~140 at 57°C
    - + Capture cost of \$37.5/tonne CO_2 – Exceed DOE target of \$40/tonne
- Updated techno-economic analysis
- Proposed BP3 tasks
  - Accelerating technology development
- Received $500K Matching funds from Ohio Coal Office
- Asking NETL to authorize proposed BP3 research, budget, and schedule