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

## DE-FE0026919

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**The Ohio State University**

**2017 NETL $CO_2$ Capture Technology Project Review Meeting**
**Pittsburgh, PA, August 21 – 25, 2017**

# Project Objective

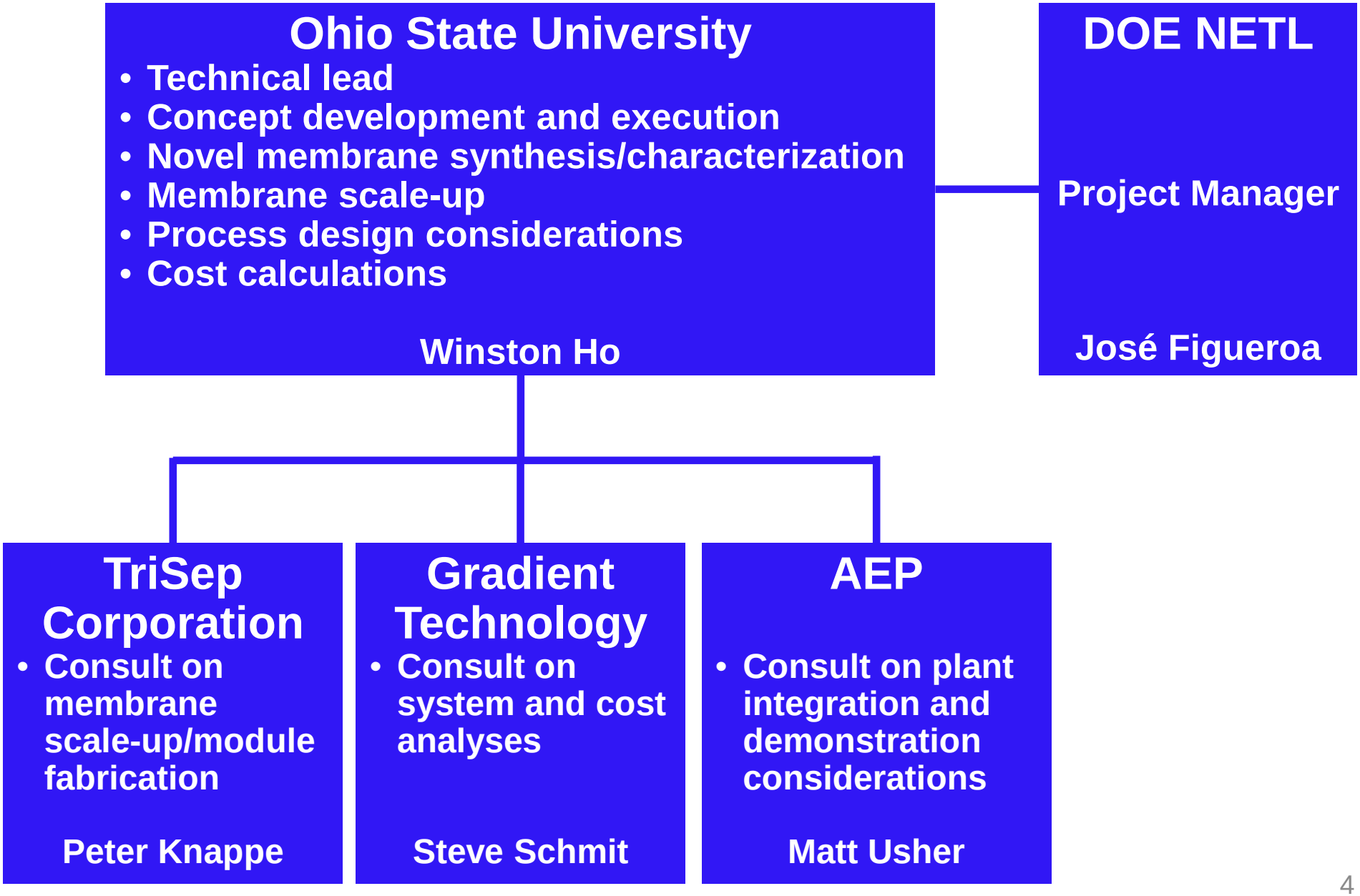
- **Develop a novel cost-effective membrane and design of membrane modules that capture $CO_2$ from <1% $CO_2$ sources**
  - **90% $CO_2$ Capture**
  - **95% $CO_2$ Purity**

# 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**

# Project Organization and Roles



# Funding and Performance Dates

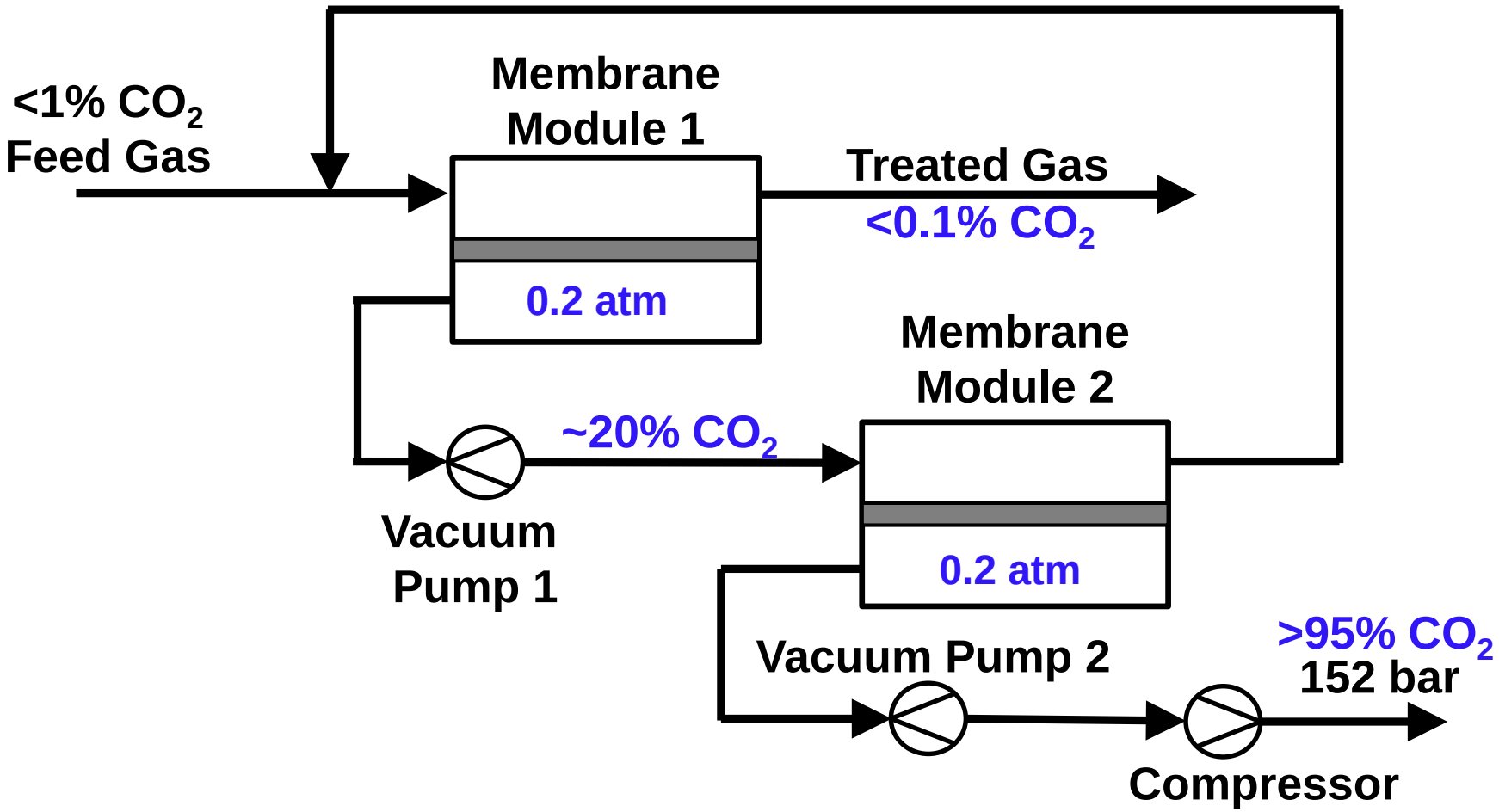
- **Total Budget: 03/01/2016 – 02/28/2019**
  **DOE: $1,248,278; OSU: $372,864 (23% cost share)**

  - **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**

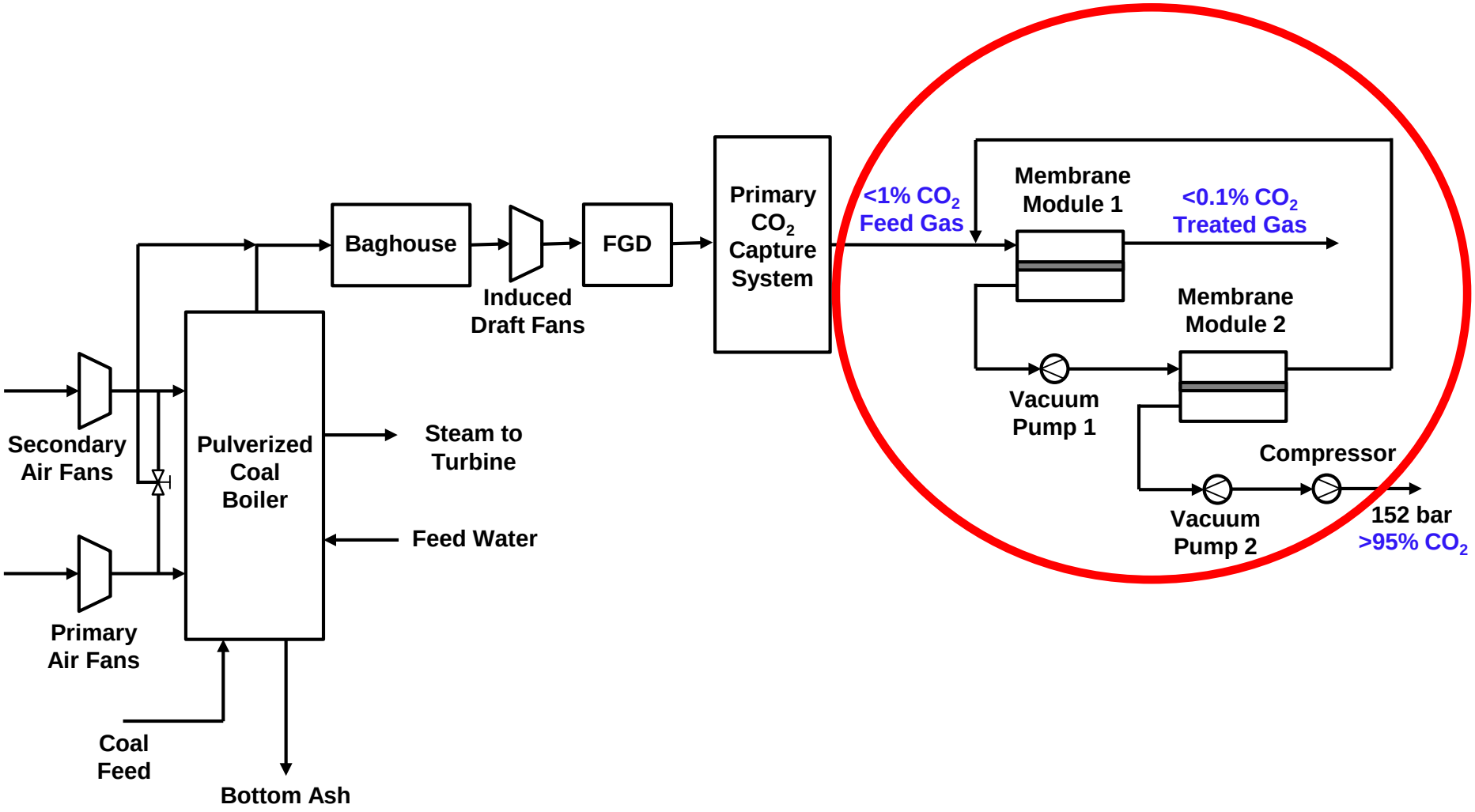
  - **BP3: 03/01/2018 – 02/28/2019**
    **DOE: $421,034; OSU: $125,764**

# Process Proposed for $CO_2$ Capture from <1% $CO_2$ Sources



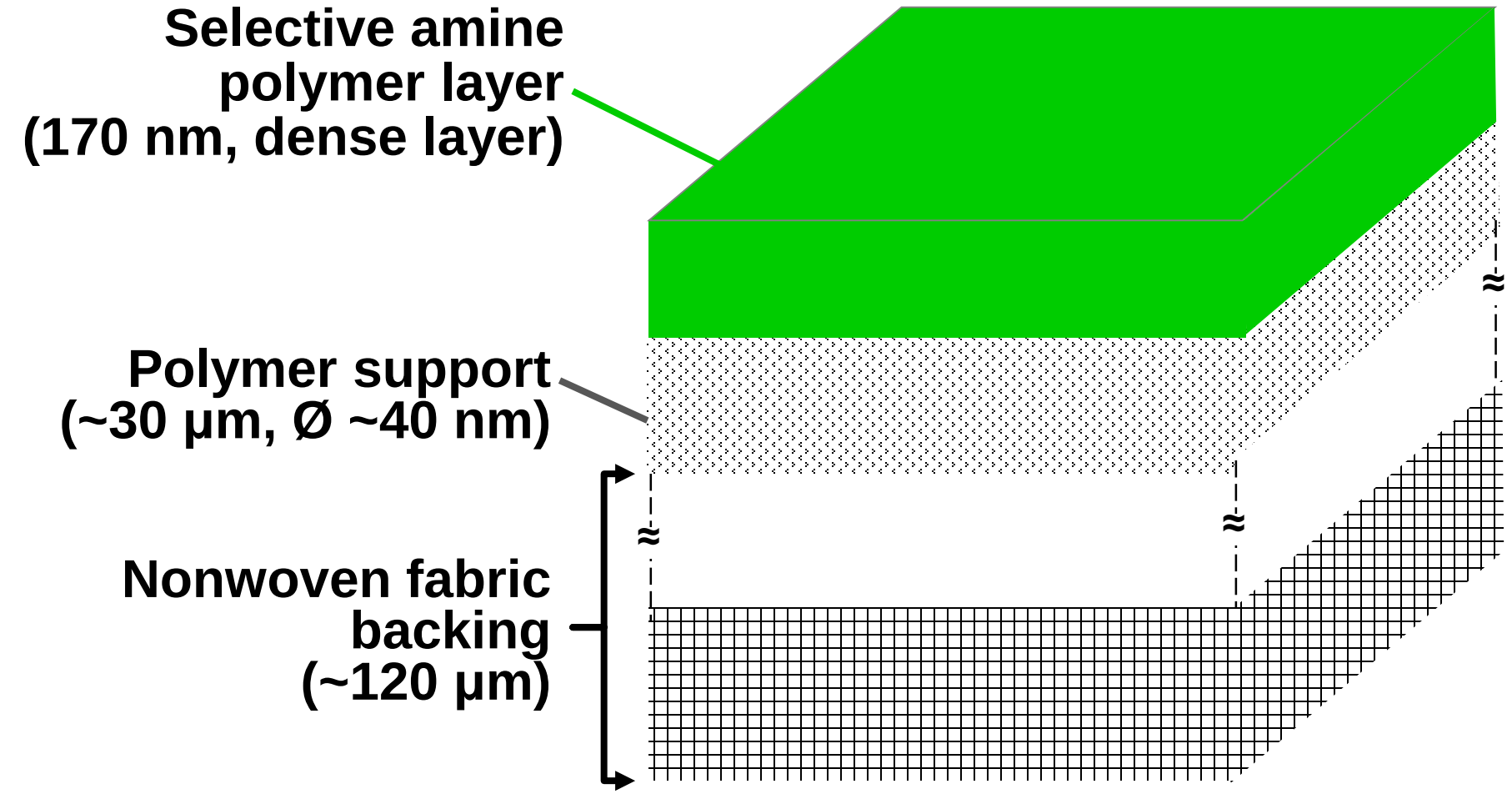

- **Proposed membrane process does not require cryogenic distillation (compared to competition)**

# 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**

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

  - **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% $CO_2$ concentration feed gas due to carrier saturation phenomenon**
- **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 – 6-Month Accomplishments

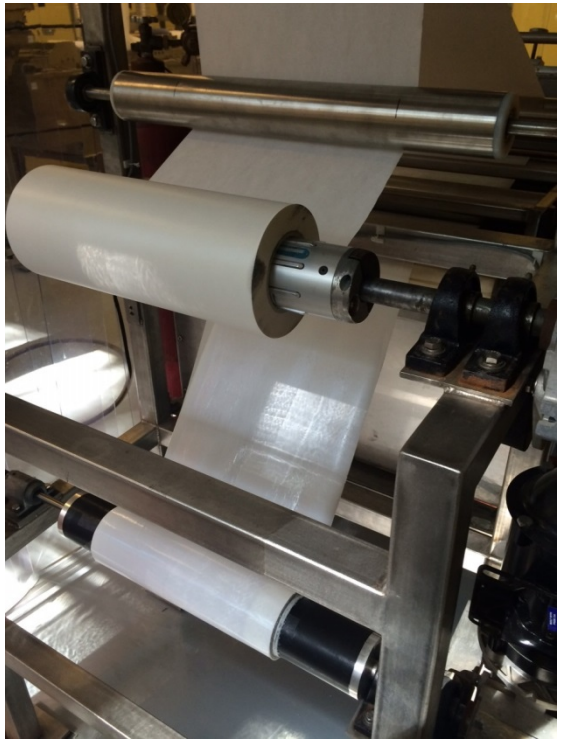
- **Improved 14”-wide PES Polymer Support Fabricated with Continuous Machine**
  - **Very high $CO_2$ permeance of 22500 GPU obtained**
- **Pilot Composite Membranes Synthesized**
  - **Membrane scaled up to 14” by roll-to-roll successfully**
  - **1400 GPU with 220 $CO_2/N_2$ selectivity obtained at 57°C using 1% $CO_2$ concentration feed gas**
- **Plate-and-Frame and Spiral-Wound Modules Fabricated**
  - **Both showed ~1000 GPU with ~220 selectivity at 57°C**
  - **Good membrane module stability obtained (3 ppm $SO_2$)**
- **High-Level Techno-economic Analysis Showed Capture Cost of ~$280/tonne $CO_2$ (in 2011 $)**
  - **~20% increase in COE**
- **2 U.S. Patent Applications and 2 Provisional Patent Appl’s Filed – New Membrane Compositions**

# Affordable Fabrication of PES Support and Composite Membrane

## Continuous Membrane Fabrication Machine at OSU

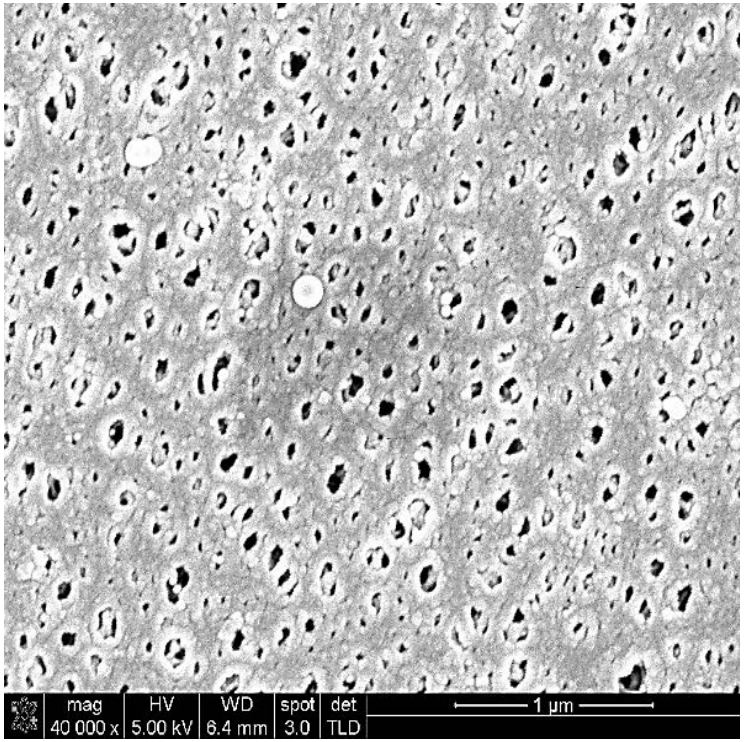
# Successful Continuous Roll-to-Roll Fabrication of Affordable PES Support

**Casting Machine**



**14-inch PES Support**

**SEM – Top View**

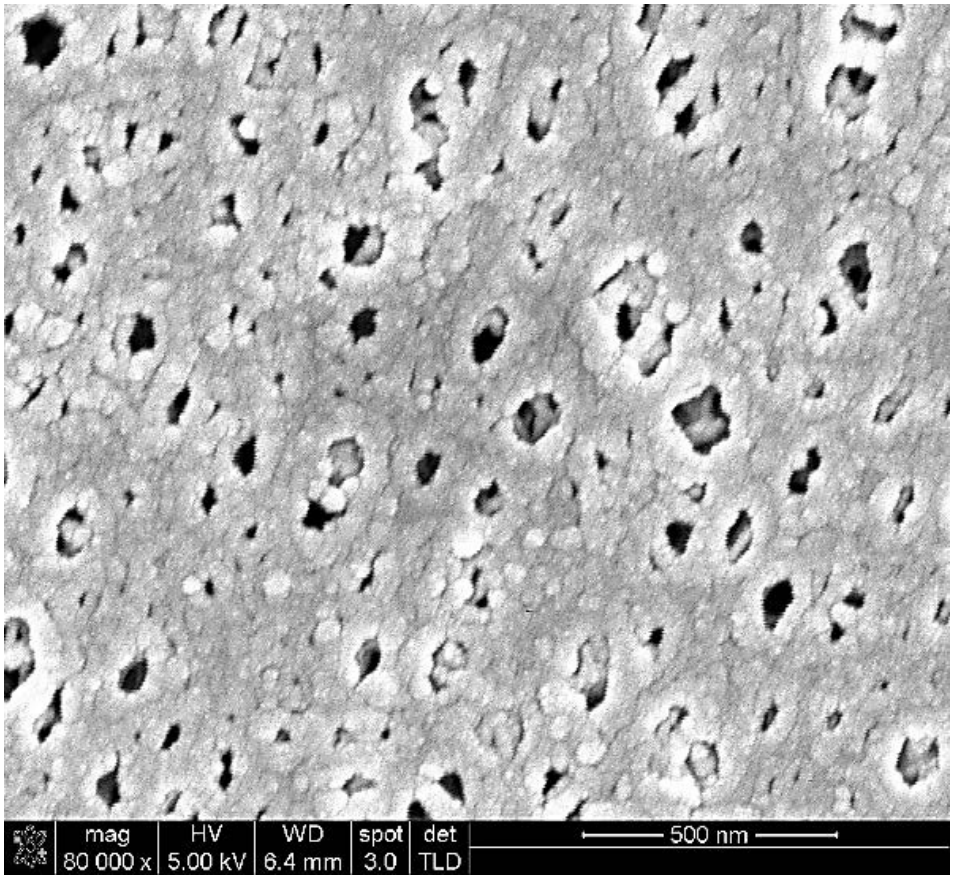



**1500 feet fabricated**

- **PES support synthesized and developed at OSU**
- **PES technology being transferred to a membrane company**

# Successful Continuous Fabrication of Affordable PES Support

## SEM Analysis of 14-inch PES Support

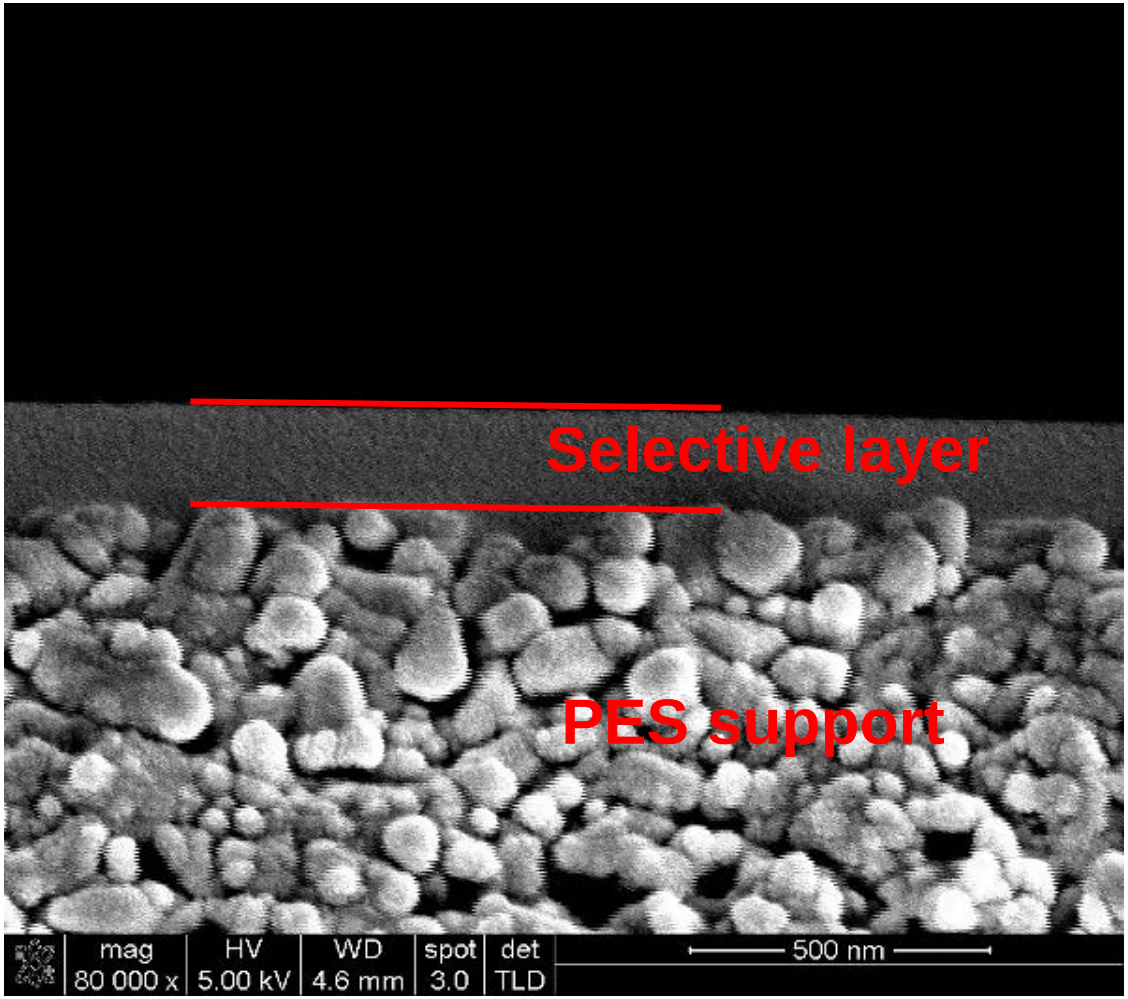



**Ave. pore size = 32.5 nm, Porosity = 12.5%**

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

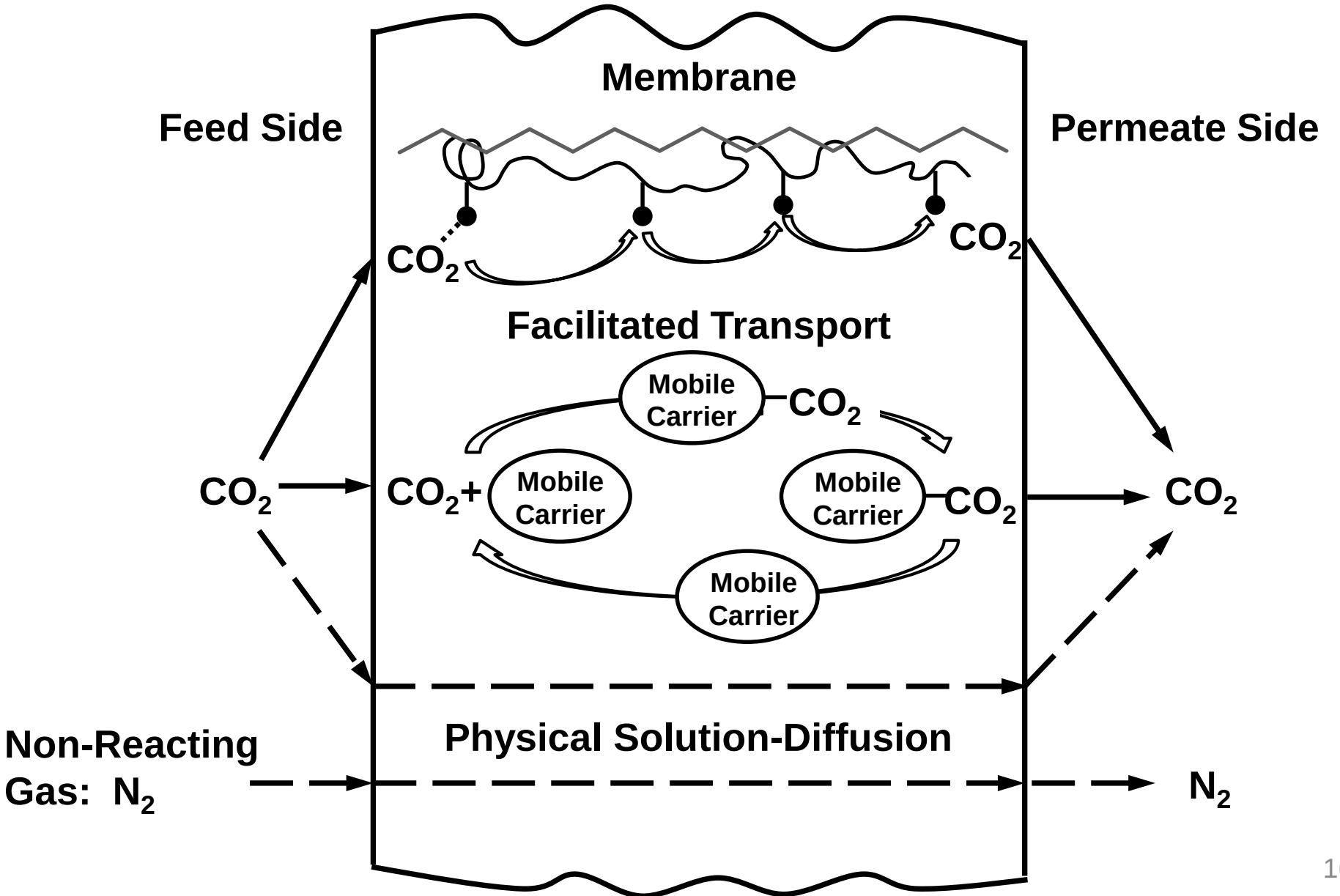
# Composite Membrane Synthesized

## 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**

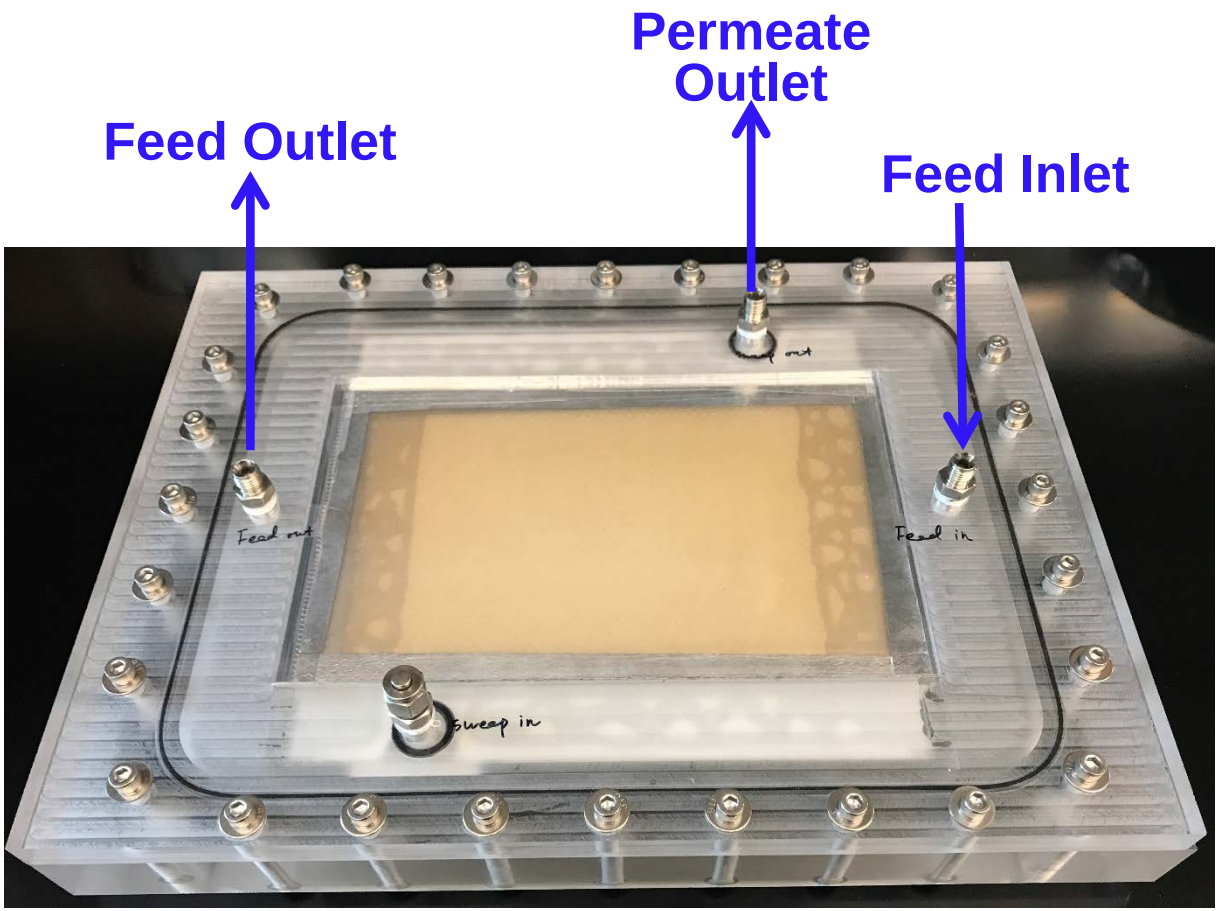
- **$N_2$ Flux: Very Low**
  - **$N_2$ does not react with amine**
  - **$N_2$ transport follows conventional physical solution-diffusion mechanism, which is very slow**

# Plate-and-Frame Membrane Module Fabricated

## Membrane Leaf

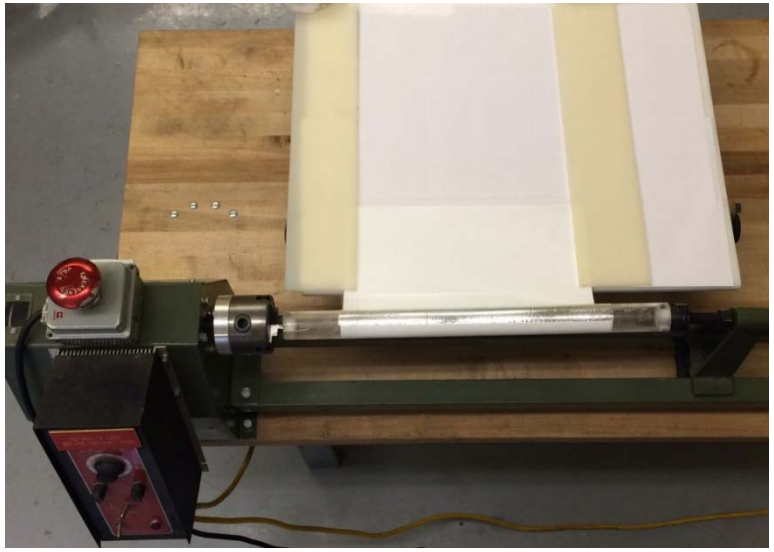
## Membrane Element

## Membrane Module



# Spiral-Wound Membrane Module Fabricated

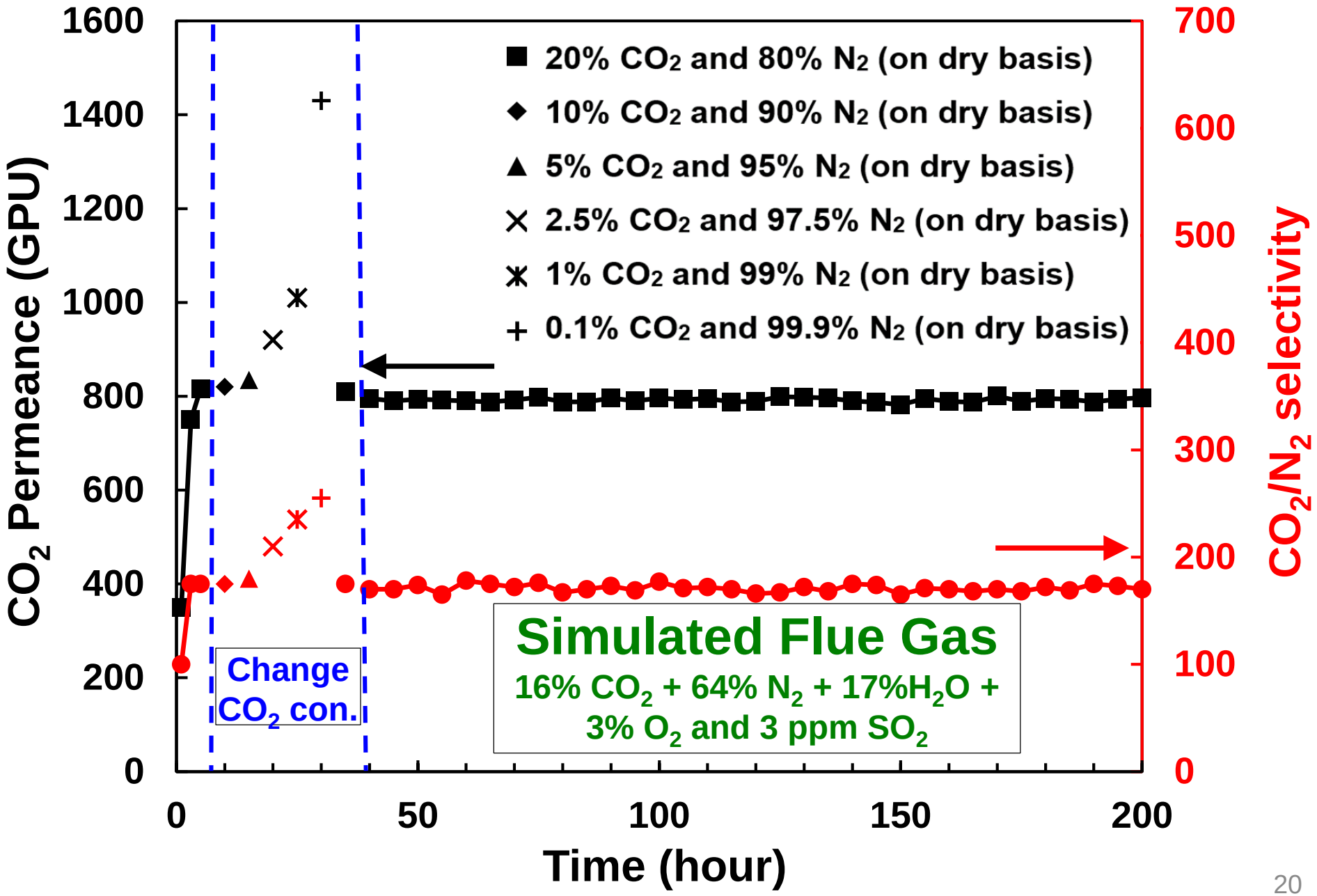
## Element Rolling Machine



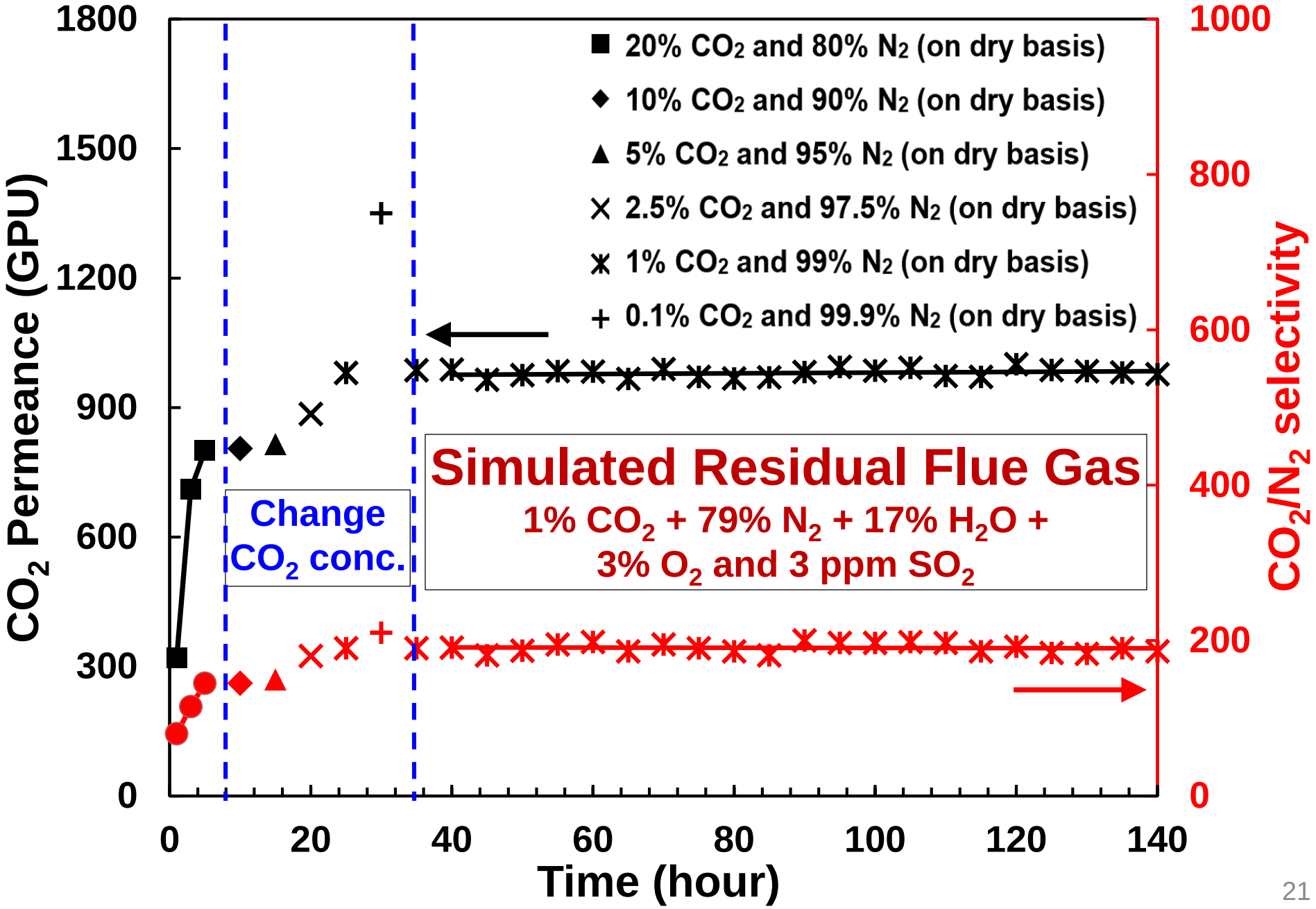
## Spiral-Wound Membrane Element

## Membrane Module

# Good Membrane Module Stability Obtained



# Good Membrane Module Stability Obtained



# High-Level Techno-Economic Calculations

- **Basis: Membrane Results at 57ºC**
  - **1400 GPU & 220 Selectivity for 1% $CO_2$ concentration feed gas**
  - **940 GPU & 160 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**
  - **31.9 tonne/h of $CO_2$ captured from 1% $CO_2$ source**
  - **$97 million bare equipment cost**
    - ➢ Membrane 27%, blowers and vacuum pumps 56%, others 18%
  - **1.63 ¢/kWh (1.17 ¢/kWh capital cost, 0.21 ¢/kWh fixed cost, 0.22 ¢/kWh variable cost, and 0.03 ¢/kWh T&S cost)**
    - ➢ COE = 8.09 ¢/kWh for 550 MW supercritical pulverized coal power plant
  - **$281/tonne capture cost ($16.3/MWh × 550 MW/(31.9 tonne/h))**
  - **20.1% Increase in COE (1.63/8.09 = 20.1%)**

# Plans for Future Testing/Development

- **Remaining BP2**
  - Continue laboratory-scale membrane synthesis and characterization for performance improvement
  - Fabricate pilot-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**
  - Fabricate 3 pilot membrane modules
  - Test modules with <1% $CO_2$ simulated gas mixture
  - Update techno-economic analysis

# Acknowledgments

**José Figueroa**
**Great efforts and strong inputs**

**DOE/NETL**
**Financial support**