Transformational Membranes for Pre-combustion Carbon Capture

DE-FE0031635

PI: Winston Ho, Professor

William G. Lowrie Department of Chemical & Biomolecular Engineering
Department of Materials Science and Engineering
The Ohio State University

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NETL, Pittsburgh, PA, November 16, 2018

Outline

- Project Objective
- Project Organization and Roles
- Technical Background
- Technical Approach
- Funding and Performance Dates
- Project Schedule/Milestones
- Success Criteria
- Risk Management
- Outlook

Project Objective

- **Develop a cost-effective design and fabrication process for a novel transformational membrane and its membrane modules that capture CO_2 from coal-derived syngas**
  - **95% CO_2 Purity**
  - **>99% H_2 Recovery**
  - **COE 30% Less than Baseline Approaches**

Project Organization and Roles

Ohio State University

- Technical lead
- New membrane synthesis/characterization
- Prototype membrane & module fabrication
- Testing of the membrane modules
- Cost calculations

Winston Ho

DOE NETL

Project Officer

David Lang

AEP

- Consult on plant integration and demonstration considerations

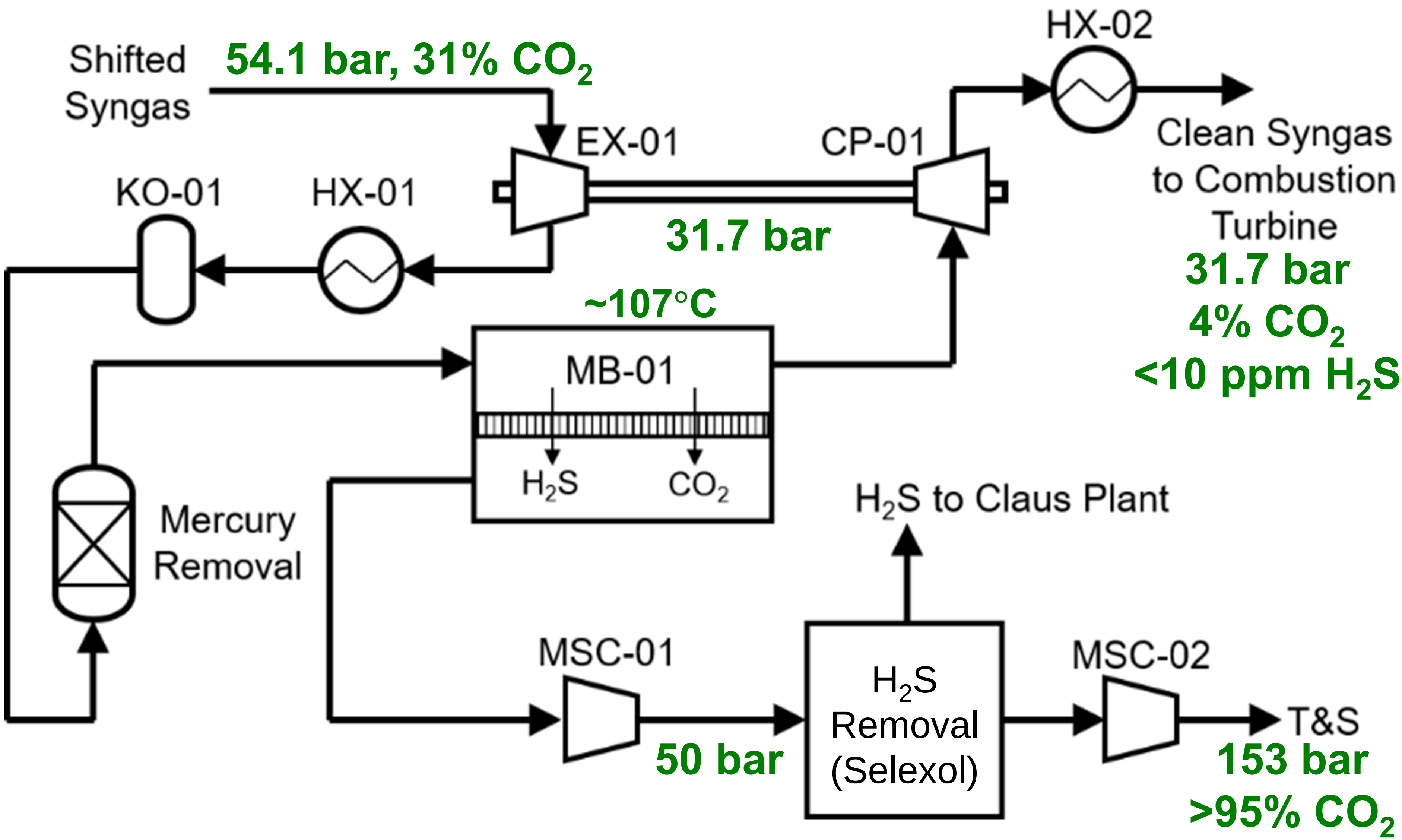
Matt Usher

Microdyn-Nadir US Inc.

- Consult on membrane scale-up and module fabrication

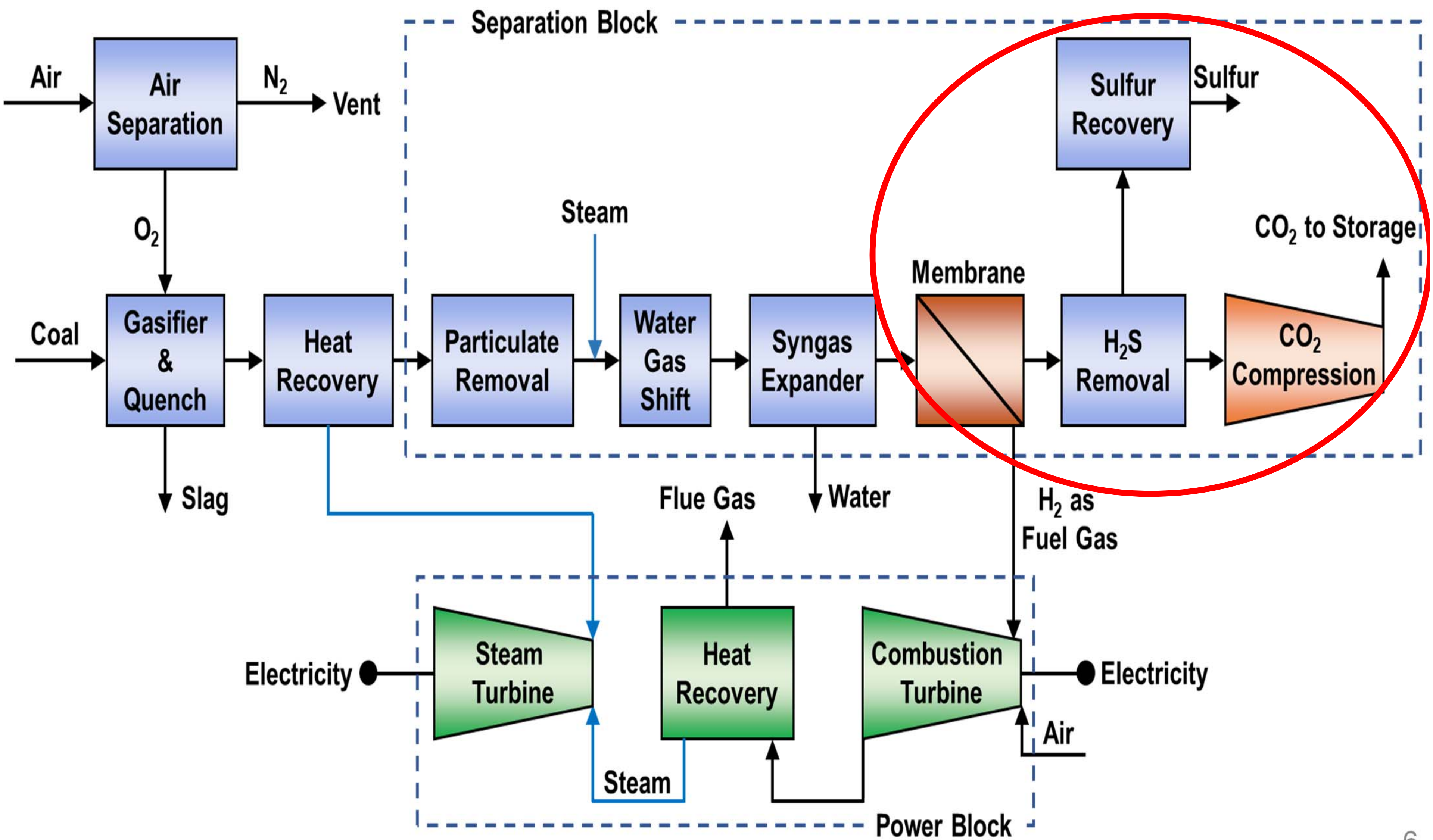
Peter Knappe

Technical Background: Proposed Process



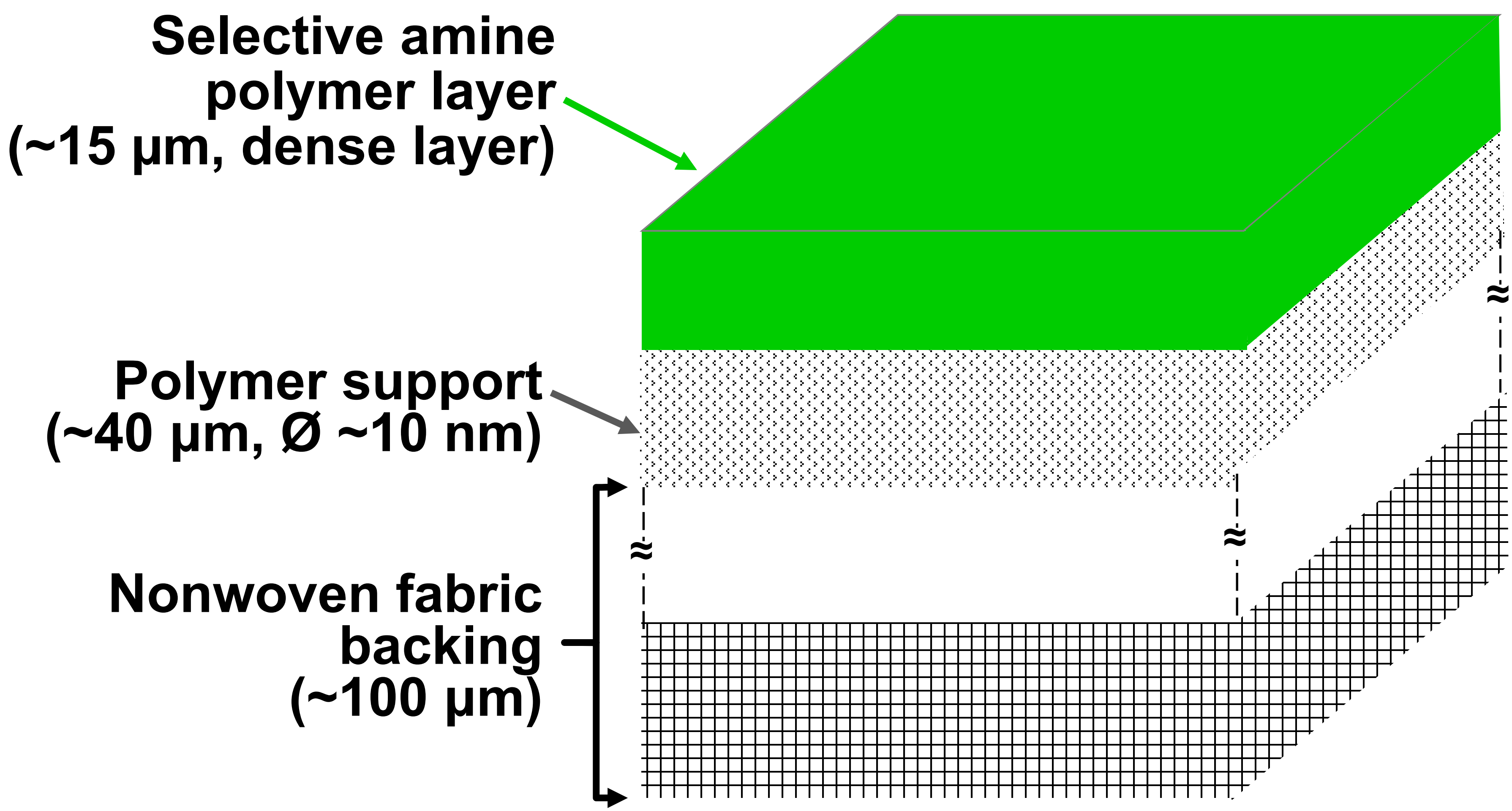
- **Proposed membrane process does not require significant syngas cooling (compared to competition)**

Location of Proposed Technology in IGCC Plant



Selective Amine Polymer Layer / Polymer Support

Simplicity of Membrane for Low Cost



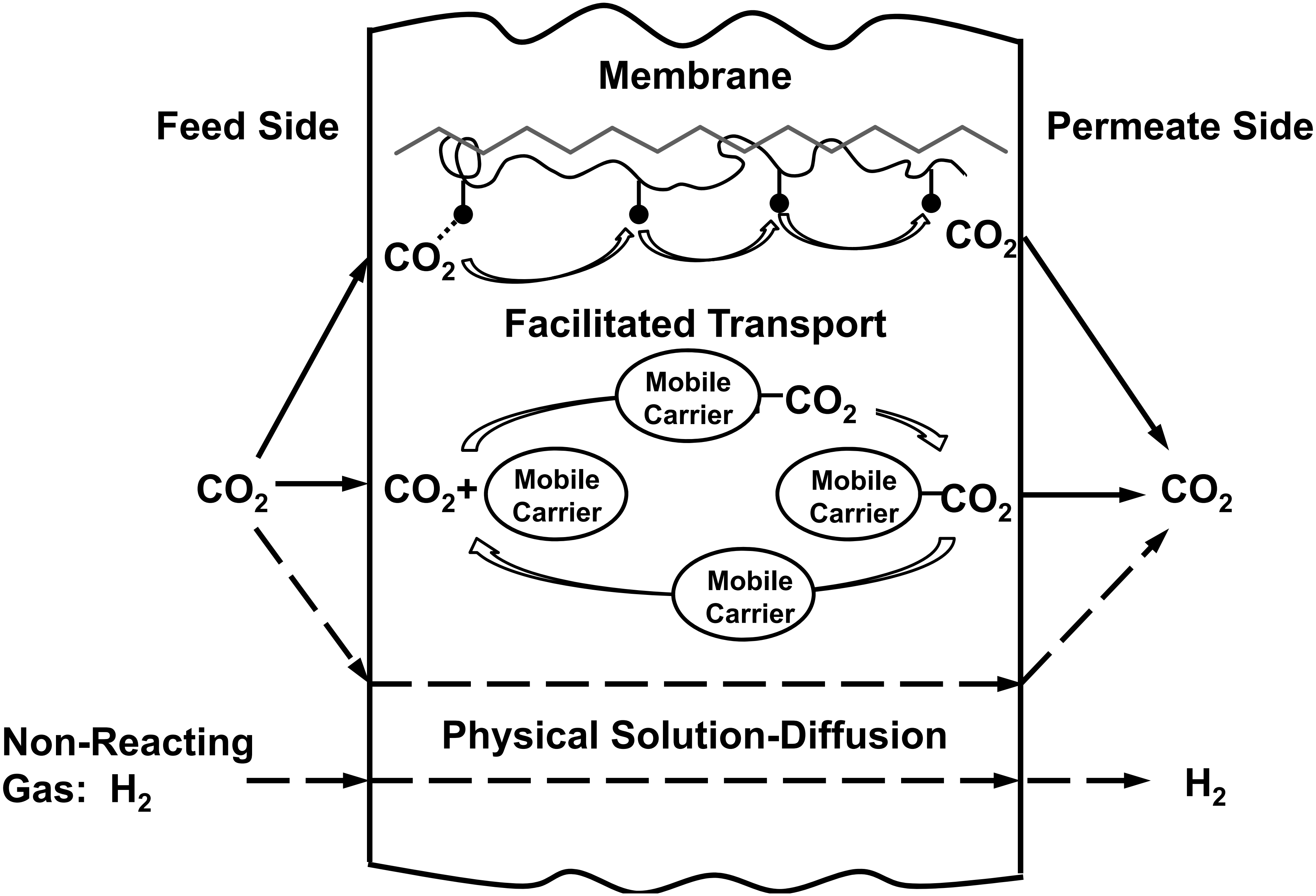
Selective Amine Polymer Layer / Polymer Support

- **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/H_2 selectivity**

Amine Polymer Layer Contains Mobile and Fixed Carriers: Facilitated Transport



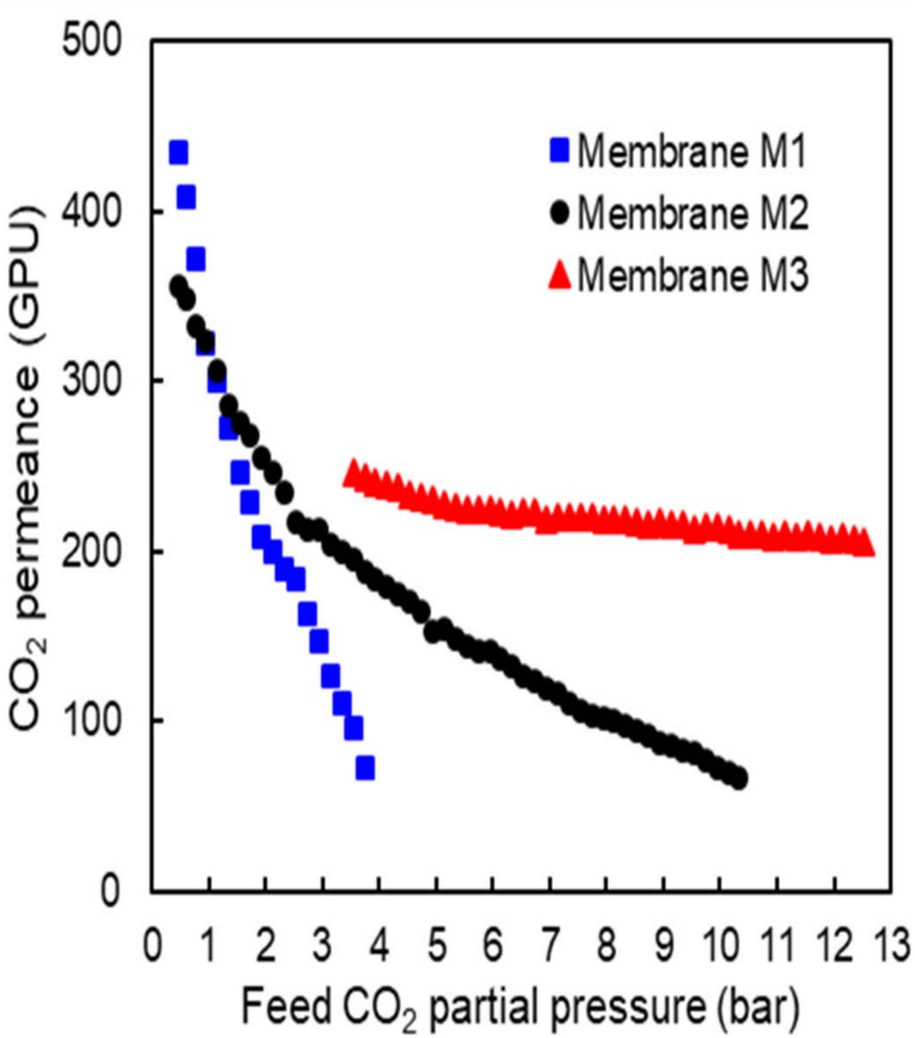
Facilitated Transport vs. Solution-Diffusion Mechanism

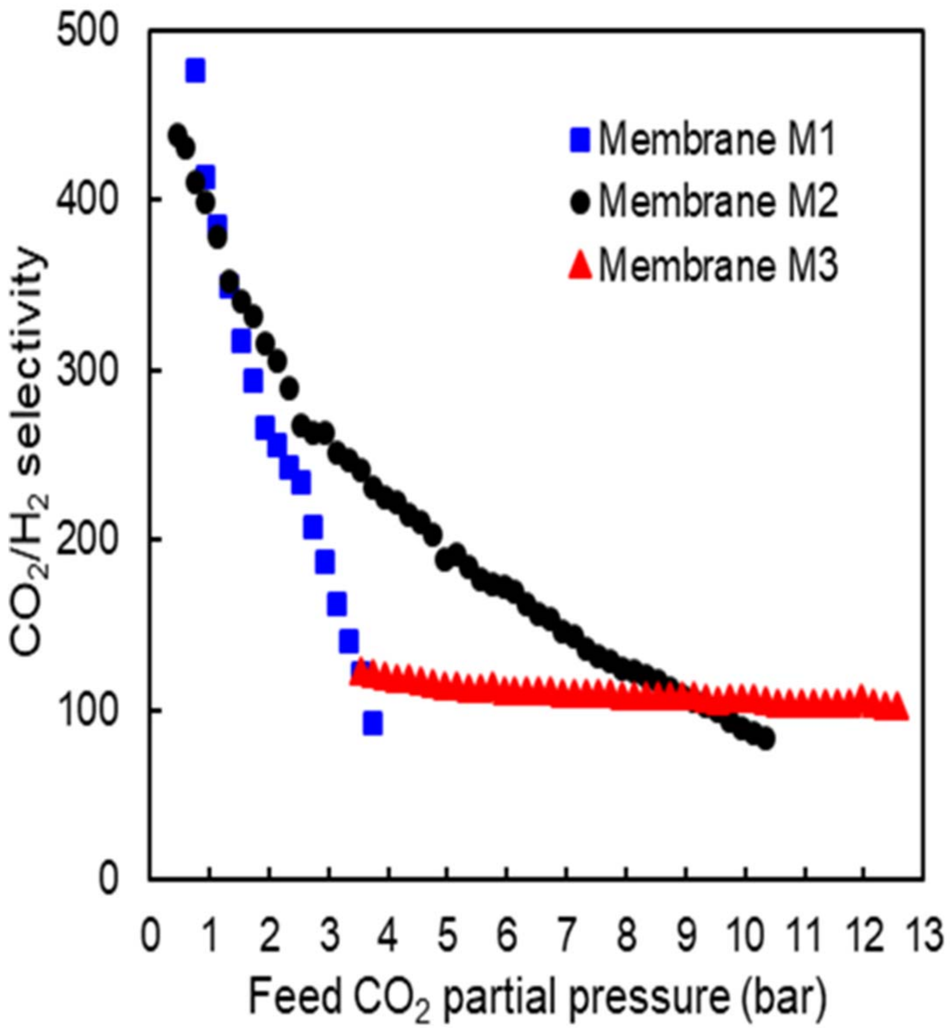
- **CO_2 Facilitated Transport Flux: Very High**
  - **CO_2-amine reaction enhances CO_2 flux**

- **H_2 Flux: Very Low**
  - **H_2 does not react with amine**
  - **H_2 transport follows conventional physical solution-diffusion mechanism, which is very slow**

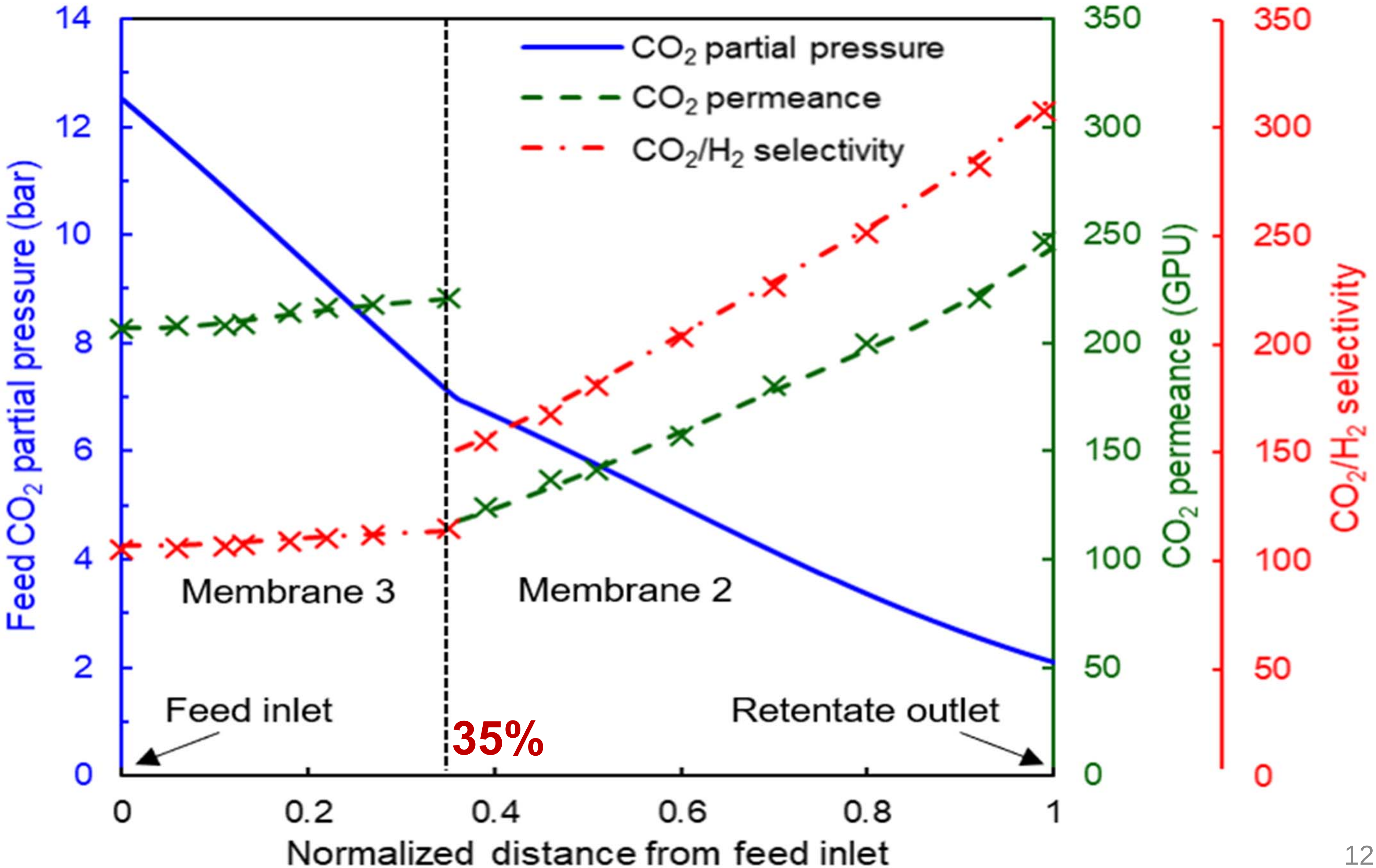
Membrane Performances

Simulated Syngas at 107°C and 31.7 bar

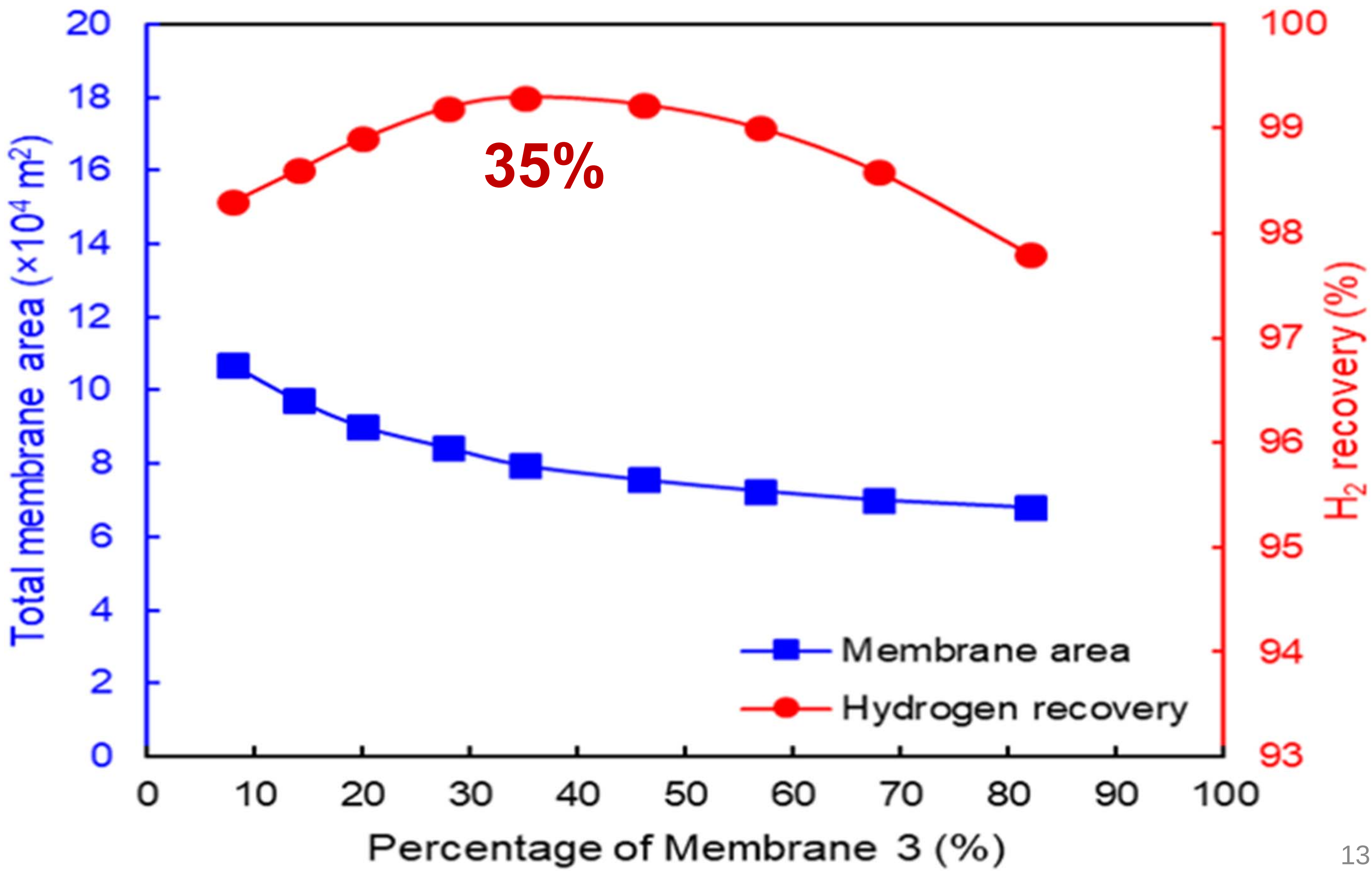




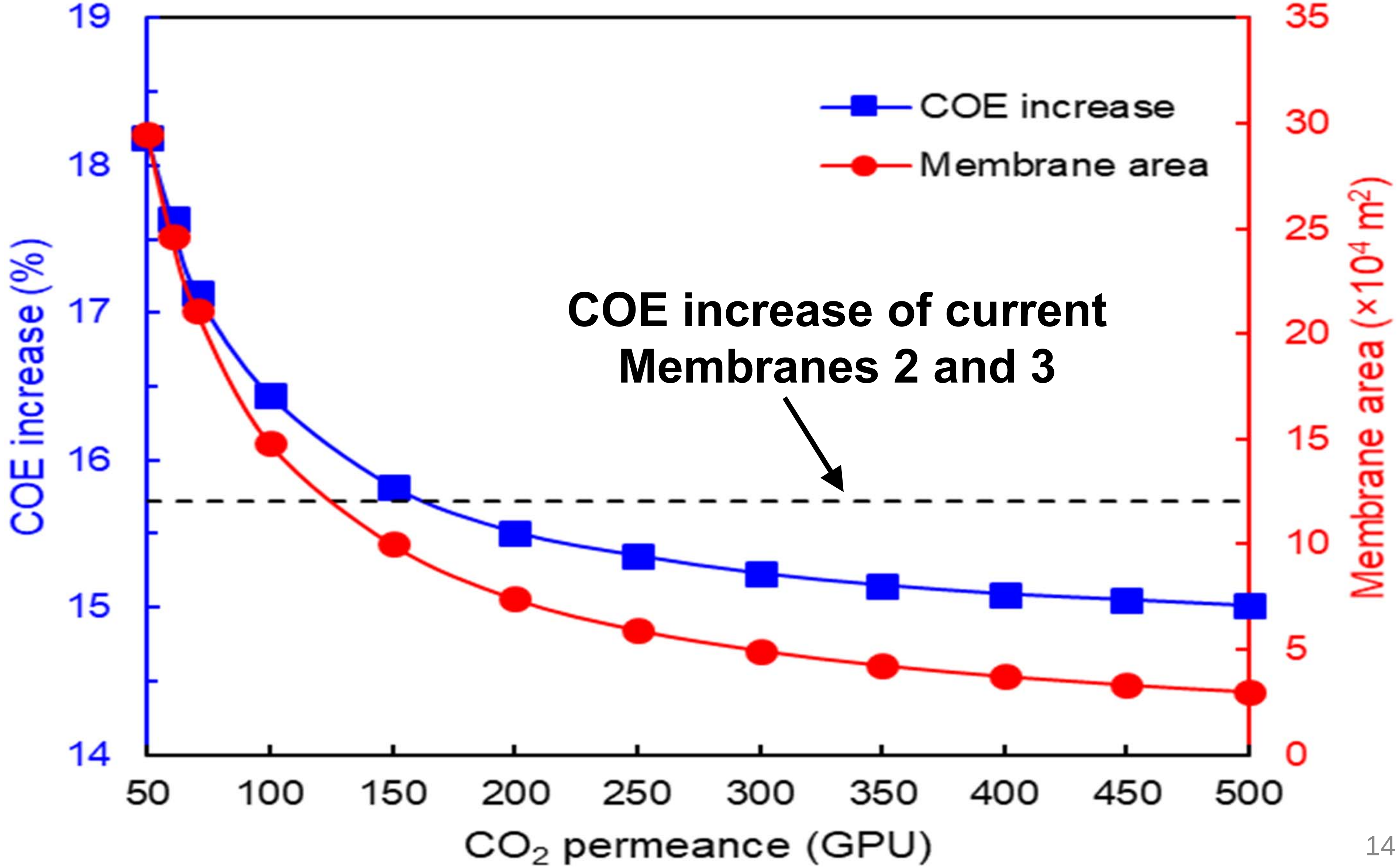
Effect of Carrier Saturation Phenomenon on Performance



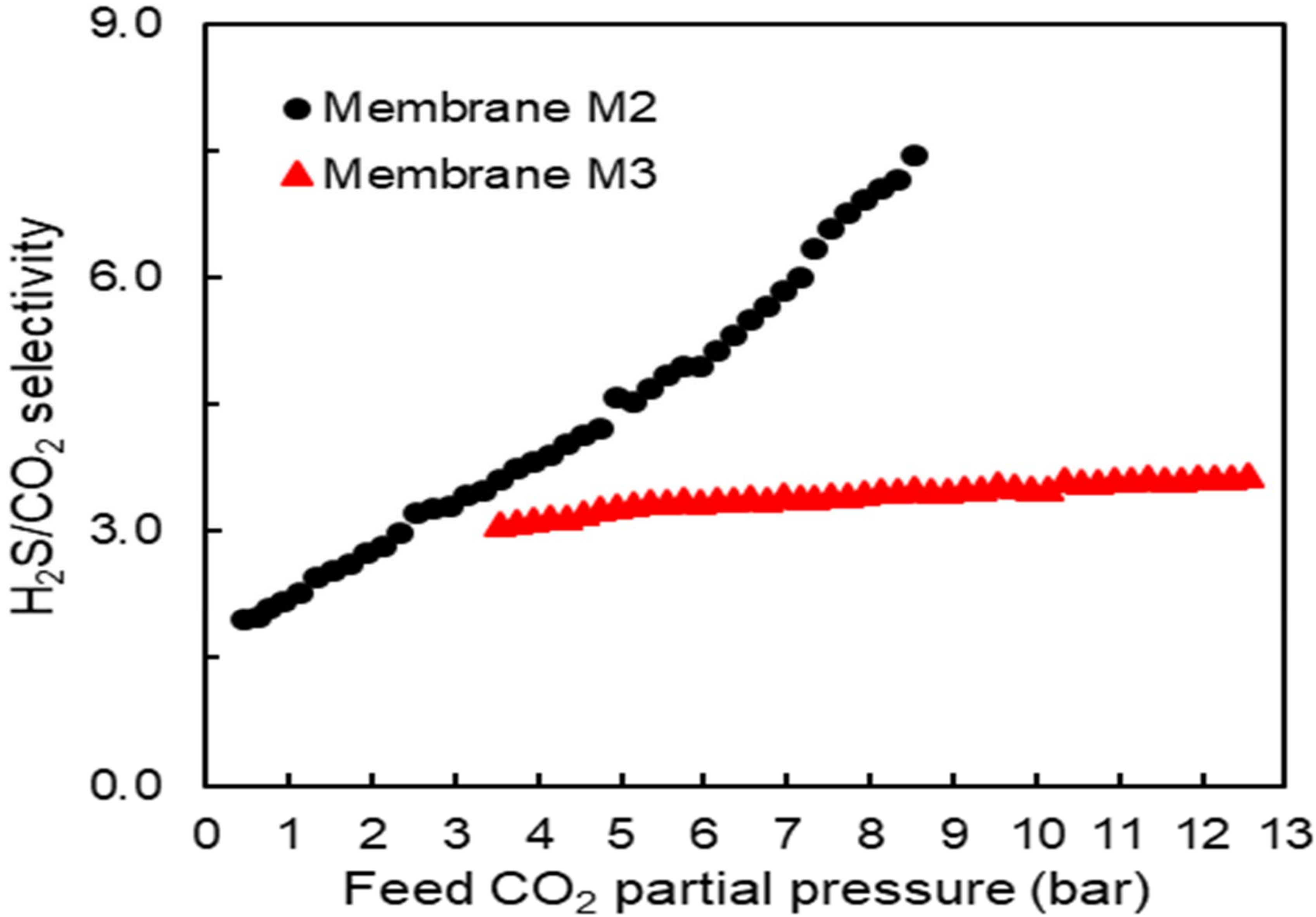
Effects of Membrane Allocation on Membrane Area and H_2 Recovery



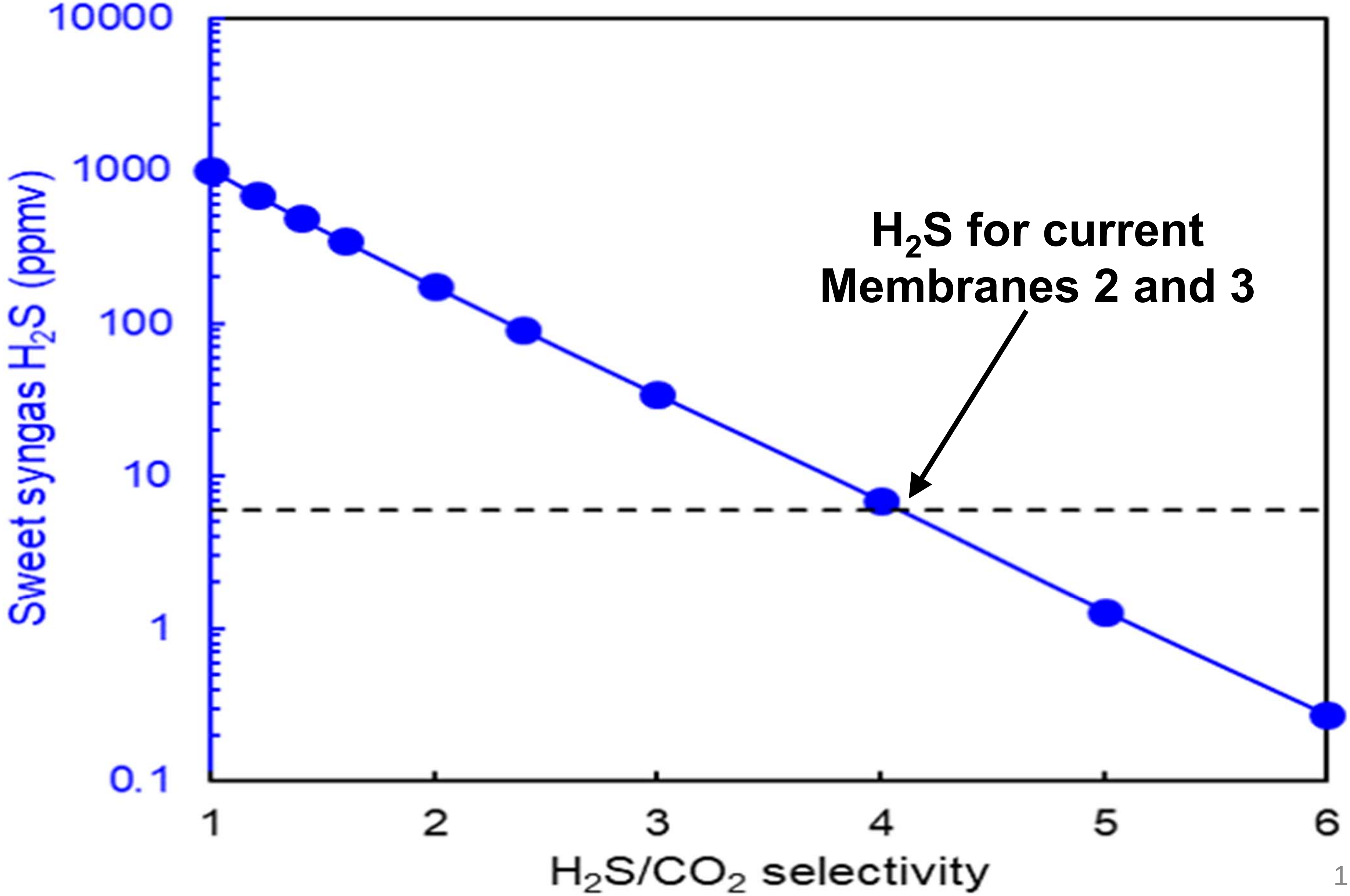
Effect of CO_2 Permeance on Cost of Electricity Increase



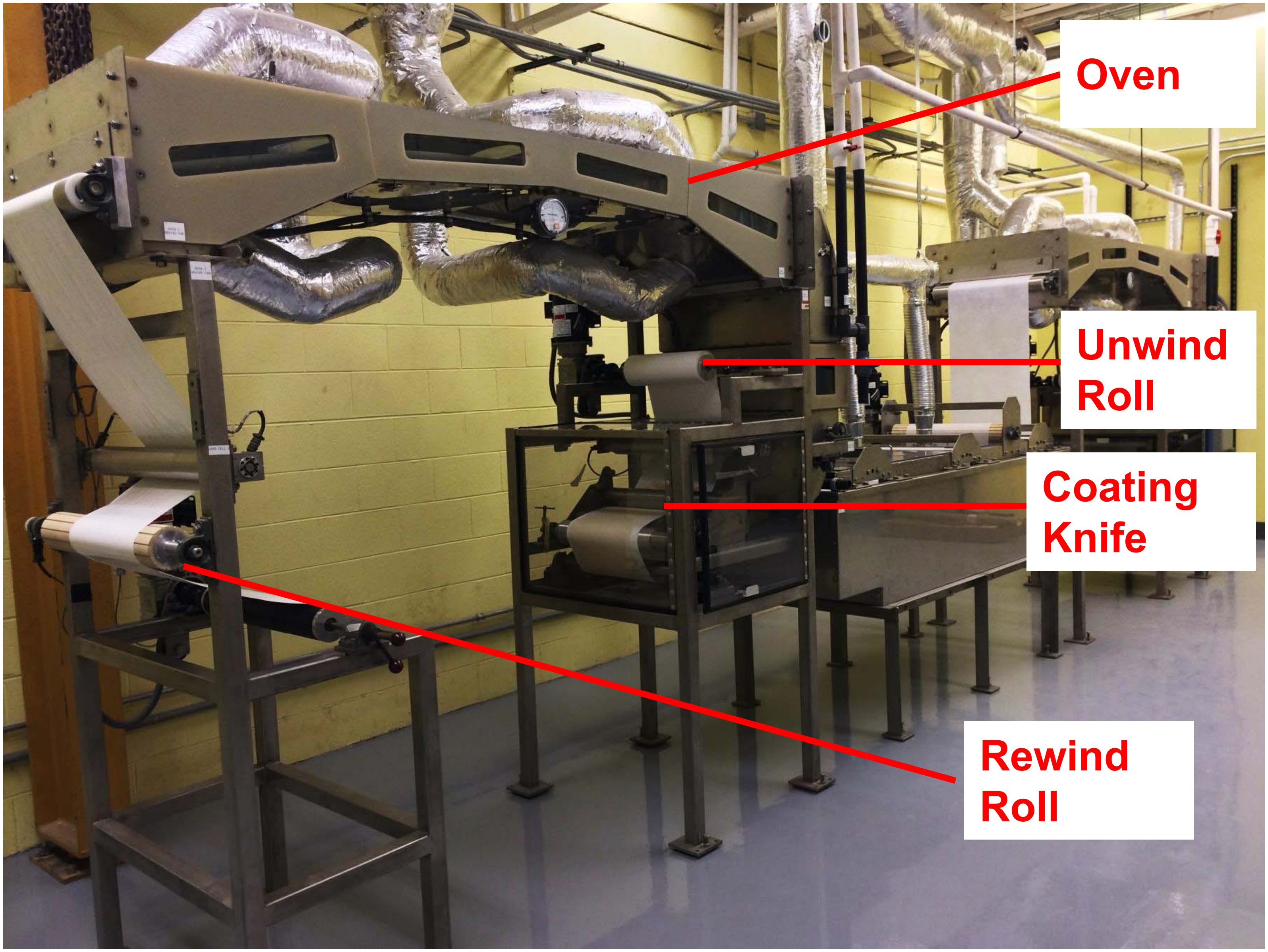
Membranes Synthesized with Tuned H_2S/CO_2 Selectivities



Effect of H_2S/CO_2 Selectivity on H_2S Concentration in H_2 Product

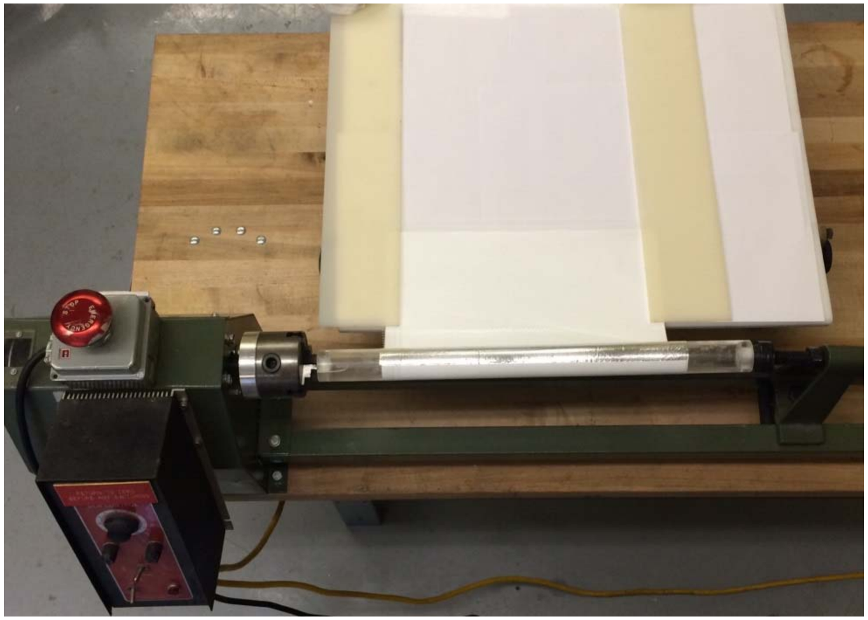


Membrane Scale-up: Continuous Roll-to-Roll Fabrication Machine at OSU

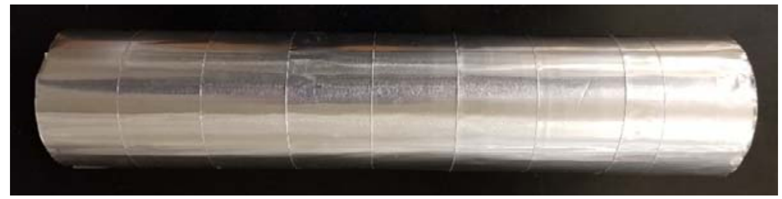


Spiral-Wound Membrane Module Fabrication

Element Rolling Machine



Spiral-Wound Membrane Element



Membrane Module

Feed Outlet

Vacuum Permeate

Feed Inlet

Technical Approach

- **BP1: 10/01/2018 – 03/31/2020**
  - Laboratory-scale membrane synthesis, characterization and transport performance studies
  - High-level preliminary techno-economic analysis

- **BP2: 04/01/2020 – 09/30/2021**
  - Laboratory-scale membrane synthesis, characterization and transport performance studies to continue
  - Fabrication, characterization and transport performance studies of scale-up membrane (14″ wide by 20′ long)
  - Fabrication, evaluation and stability testing of spiral-wound membrane modules
  - Update techno-economic analysis performed in BP1

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

BP1 – Lab-Scale Membrane Synthesis

- **Increase CO_2 Sorption at High Pressure**
  - Use sterically hindered amines as CO_2 carriers
  - Incorporate ethylene oxide moieties to enhance CO_2 capacity at high pressure
  - Study effects of polyethylene glycol and its derivatives
  - Synthesize higher MW polyvinylalcohol and polyamines
- **Enhance Membrane Mechanical Properties**
  - Incorporate 2-D nanofillers
  - Optimize filler geometry and surface properties
  - Study permeants-polymer-filler interactions
- **Preliminary Techno-Economic Analysis**
  - Research guideline for membrane performance
  - Demonstrate feasibility for high CO_2 purity and H_2 recovery
  - Show pathway for a 15.3% COE increase

BP1 Approach – Sterically Hindered Amine

- **Reaction of CO_2 with Unhindered Amines**

$$CO_2 + R\text{–}NH_2 \rightleftharpoons R\text{–}NH_2^+\text{–}COO^-$$

$$R\text{–}NH_2^+\text{–}COO^- + R\text{–}NH_2 \rightleftharpoons R\text{–}NH\text{–}COO^- + R\text{–}NH_3^+$$

Overall:

$$CO_2 + 2\ R\text{–}NH_2 \rightleftharpoons R\text{–}NH\text{–}COO^- + R\text{–}NH_3^+$$

- **Reaction of CO_2 with Hindered Amines**

$$CO_2 + R_1\text{–}NH\text{–}R_2 \rightleftharpoons R_1R_2\text{–}NH^+\text{–}COO^-$$

$$R_1R_2\text{–}NH^+\text{–}COO^- + H_2O \rightleftharpoons R_1R_2\text{–}NH_2^+ + HCO_3^-$$

Overall: **Can double the CO_2 capacity**

$$CO_2 + R_1\text{–}NH\text{–}R_2 + H_2O \rightleftharpoons R_1R_2\text{–}NH_2^+ + HCO_3^-$$

BP2 – Membrane Scale-up and Prototype Module Fabrication

- **Membrane Scale-up and Characterization**
  - Lab-scale membrane synthesis, characterization and transport performance studies to continue
  - Continuous roll-to-roll fabrication (14″ wide by 20′ long)
  - Characterize performance with simulated syngas
  - Demonstrate facile and reproducible fabrication in pilot scale

- **Prototype SW Module Fabrication**
  - Fabricate 9 prototype SW modules (800 cm^2 each)
  - Characterize separation performance and pressure drop
  - Test modules in series with hybrid membrane allocation
  - 200-h stability test with simulated syngas

- **Final Techno-Economic Analysis**
  - Update techno-economic analysis with module performance
  - Environmental Health and Safety (EH&S) evaluation

Funding and Performance Dates

- **Total Budget: 10/01/2018 – 09/30/2021**
  DOE: $799,988; OSU: $199,998 (20% cost share)

  - **BP1: 10/01/2018 – 03/31/2020**
    DOE: $386,694; OSU: $96,674

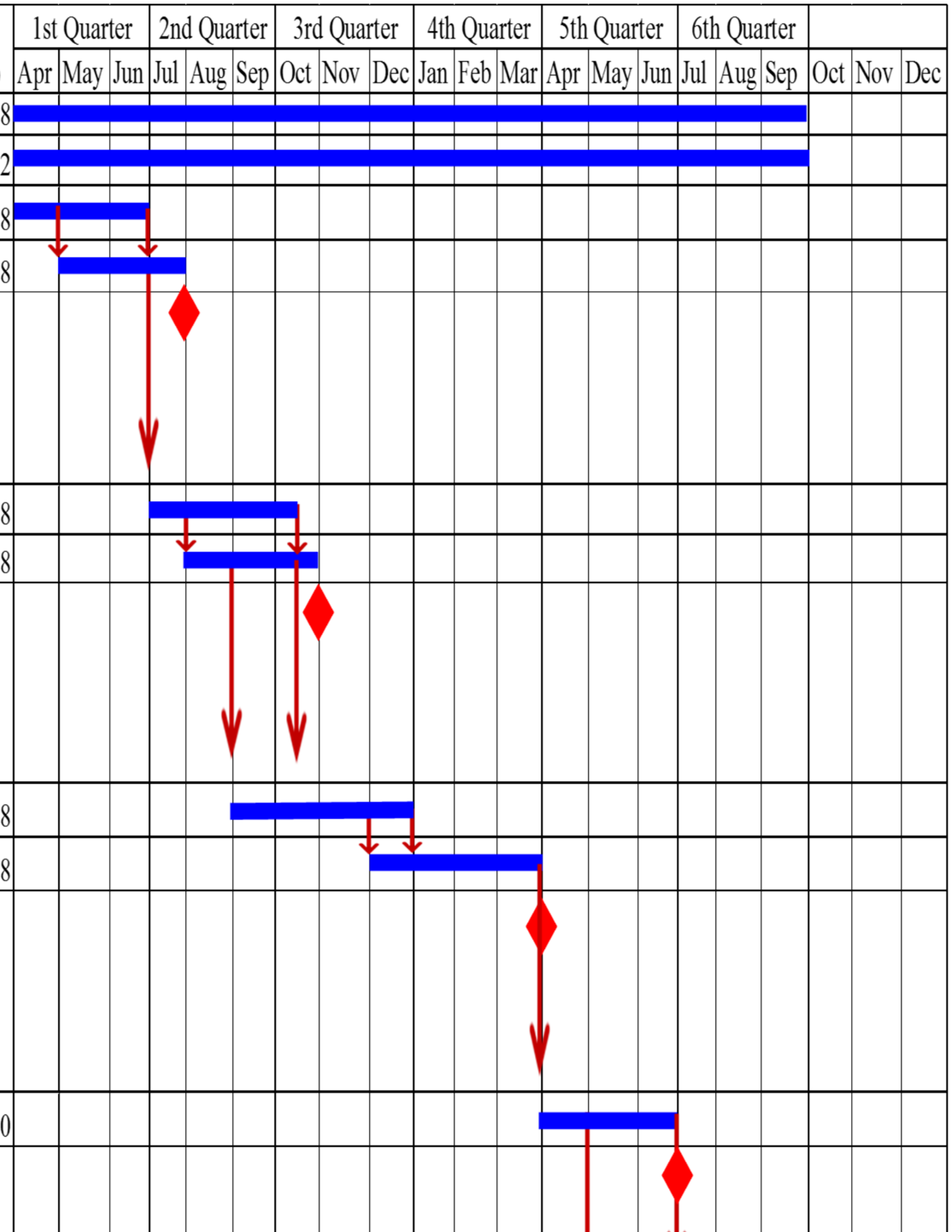
  - **BP2: 04/01/2020 – 09/30/2021**
    DOE: $413,294; OSU: $103,324

Schedule/Milestones - BP1

Task Name	Start Date	End Date	Cost ($)	1st Quarter			2nd Quarter			3rd Quarter			4th Quarter			5th Quarter			6th Quarter					
				Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Budget Period 1	10/1/2018	3/31/2020	483,368																					
Task 1: Project Management and Planning	10/1/2018	3/31/2020	48,339																					
Updated PMP submitted		10/30/2018																						
Task 2: Synthesis of Transformational Membranes	10/1/2018	3/31/2020	193,402																					
Complete investigation of 5 of the 7 proposed membrane synthesis approaches		12/31/2019																						
Task 3: Membrane Characterization	11/1/2018	3/31/2020	193,402																					
Complete membrane characterization and demonstrate CO_2 permeance = 200 – 275 GPU and CO_2/H_2 selectivity = 100 – 120 at ~110°C and 31.7 bar feed inlet (12.5 bar CO_2)		3/31/2020																						
Task 4: Preliminary Techno-economic Analysis	10/1/2018	3/31/2020	48,225																					
Complete preliminary techno-economic analysis showing the feasibility of a COE increase of 15.3%		3/31/2020																						
Quarterly Progress Reports	1/1/2019	4/30/2020																						
Budget Period 1 Annual Report	4/1/2020	6/30/2020																						

Schedule/Milestones - BP2

Task Name	Start Date	End Date	Cost ($)
Budget Period 2	4/1/2020	9/30/2021	516,618
Task 1: Project Management and Planning	4/1/2020	9/30/2021	51,662
Task 5: Optimized Membrane Synthesis	4/1/2020	6/30/2020	53,268
Task 6: Optimized Membrane Characterization	5/1/2020	7/31/2020	53,268
Complete optimized membrane characterization and demonstrate CO_2 permeance = 275 – 350 GPU and CO_2/H_2 selectivity = 120 – 140 at ~110° C and 31.7 bar feed inlet (12.5 bar CO_2)		7/31/2020	
Task 7: Optimized Membrane Scale-up Fabrication	7/1/2020	10/15/2020	63,868
Task 8: Optimized Scale-up Membrane Characterization	8/1/2020	10/31/2020	43,658
Complete optimized scale-up membrane characterization and demonstrate CO_2 permeance = 275 – 350 GPU & CO_2/H_2 selectivity = 120 – 140 at ~110° C and 31.7 bar feed inlet (12.5 bar CO_2)		10/31/2020	
Task 9: Prototype Membrane Module Fabrication	9/1/2020	12/31/2020	58,338
Task 10: Prototype Membrane Module Testing	12/1/2020	3/31/2021	53,328
Complete prototype membrane module testing and demonstrate CO_2 permeance = 275 – 350 GPU & CO_2/H_2 selectivity = 120 – 140 at ~110° C and 31.7 bar feed inlet (12.5 bar CO_2)		3/31/2021	
Task 11: Parametric Testing with Prototype Modules in Series	4/1/2021	6/30/2021	50,210
Complete parametric testing with prototype modules in series and conditions for steady state operation identified		6/30/2021	



Schedule/Milestones - BP2 (cont'd)

Task Name	Start Date	End Date	Cost ($)	1st Quarter			2nd Quarter			3rd Quarter			4th Quarter			5th Quarter			6th Quarter					
				Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Budget Period 2	4/1/2020	9/30/2021	516,618																					
Task 12: Continuous Steady Operation with Modules in Series	7/1/2021	9/30/2021	50,210																					
Complete steady state operation with modules in series and demonstrate feasibility on capture of the CO_2 with >95% CO_2 purity with simulated syngas for 200 hours		9/30/2021																						
Task 13: Final Updated Techno-economic Analysis	5/1/2021	9/30/2021	38,808																					
Complete final techno-economic analysis showing the feasibility of a COE increase of 15.0%		9/30/2021																						
Task 14: State Point Data Table	9/1/2021	9/30/2021	0																					
State point data table submitted		9/30/2021																						
Task 15: Final Technology Maturation Plan	9/1/2021	9/30/2021	0																					
Final technology maturation plan submitted		9/30/2021																						
Task 16: Environmental Health & Safety Risk Assessment	9/1/2021	9/30/2021	0																					
EH&S risk assessment submitted		9/30/2021																						
Quarterly Progress Reports	7/1/2020	10/30/2021																						
Final Project Report	10/1/2021	12/30/2021																						

Success Criteria

- **BP1: 10/01/2018 – 03/31/2020**
  - CO_2 permeance = 200 – 275 GPU
  - CO_2/H_2 selectivity = 100 – 120
  - TEA: 15.3% COE increase
- **BP2: 04/01/2020 – 09/30/2021**
  - CO_2 permeance = 275 – 350 GPU
  - CO_2/H_2 selectivity = 120 – 140
  - 200-h module stability with simulated syngas
  - TEA: 15% COE increase

Risk Management

Perceived Risk	Probability	Impact
Insufficient membrane selectivity	Low	Medium
Insufficient membrane permeance	Medium	Medium
Pretreatment not working properly	Low	High
Insufficient compression resistance of polymer support	Low	Medium
Polymer support layer too resistive	Low	Low
Thermal processing stability of polymer support insufficient	Low	Low
Project complexity	Medium	Medium
Academic culture	Medium	Medium
Subcontracts/consultants not in place in a timely manner	Low	Low

- **Mitigation approaches identified and available**

Past Work Facilitates Success of Current Project

- **Amine Polymer Cover Layer can be Used as Highly CO_2-Selective Membrane**
- **Polyamine and Membrane Syntheses / Characterization Ready for Improvement**
  - Good foundation and knowledge base for novel membranes
  - Experimental set-ups in place for current project
- **Trained Qualified Researchers Available**
  - In place and making impacts
- **Membrane Module Fabrication Experience**
  - Good for module fabrication of current project
- **Techno-economic Analysis Conducted**
  - Beneficial for high-level TEA of current project

Summary/Outlook

- **Exciting Project**
- **Qualified Researchers are in Place**
- **Project Team is Ready for Significant Progress**

Acknowledgments

David Lang, Project Officer, DOE/NETL

DOE/NETL, Financial Support