Novel Transformational Membranes and Process for CO_2 Capture from Flue Gas

DE-FE0031731

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Carbon Management and Natural Gas & Oil Research Project Review Meeting
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Outline

- Project Overview
- Technical Background
- Accomplishments
- Summary/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 flue gas**
  - **95% CO_2 Purity**
  - **60 – 90% CO_2 Recovery**

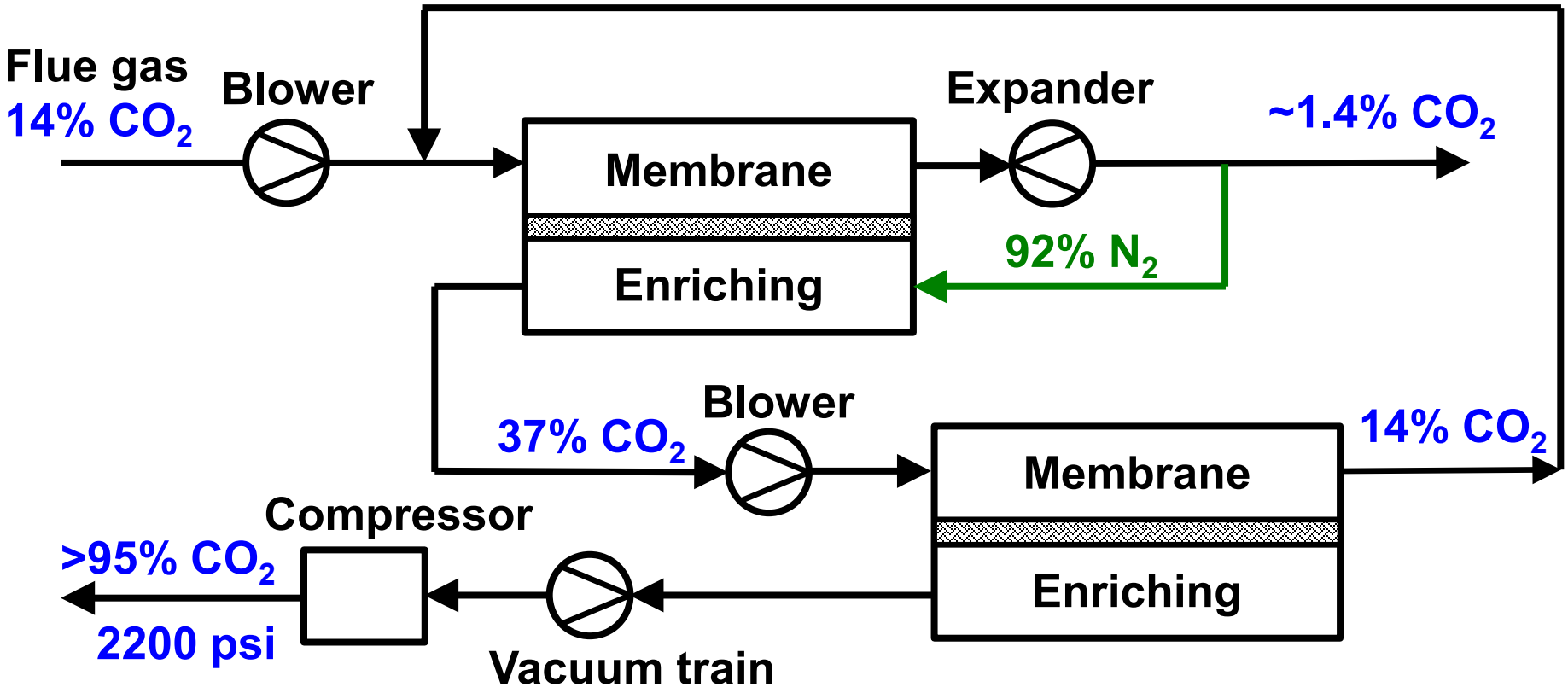
Funding and Performance Dates

- **Total Budget: 07/01/2019 – 06/30/2022**
  DOE: $2,999,988; OSU: $740,000; GTI: $10,000
  (20% cost share)

  - **BP1: 07/01/2019 – 12/31/2020**
    DOE: $1,395,100; OSU: $348,778

  - **BP2: 01/01/2021 – 06/30/2022**
    DOE: $1,604,888; OSU: $391,222; GTI: $10,000

Technical Background: Proposed Process



- Partial retentate recycle enables efficient separation
- Proposed membrane process does not require flue gas cooling and cryogenic distillation

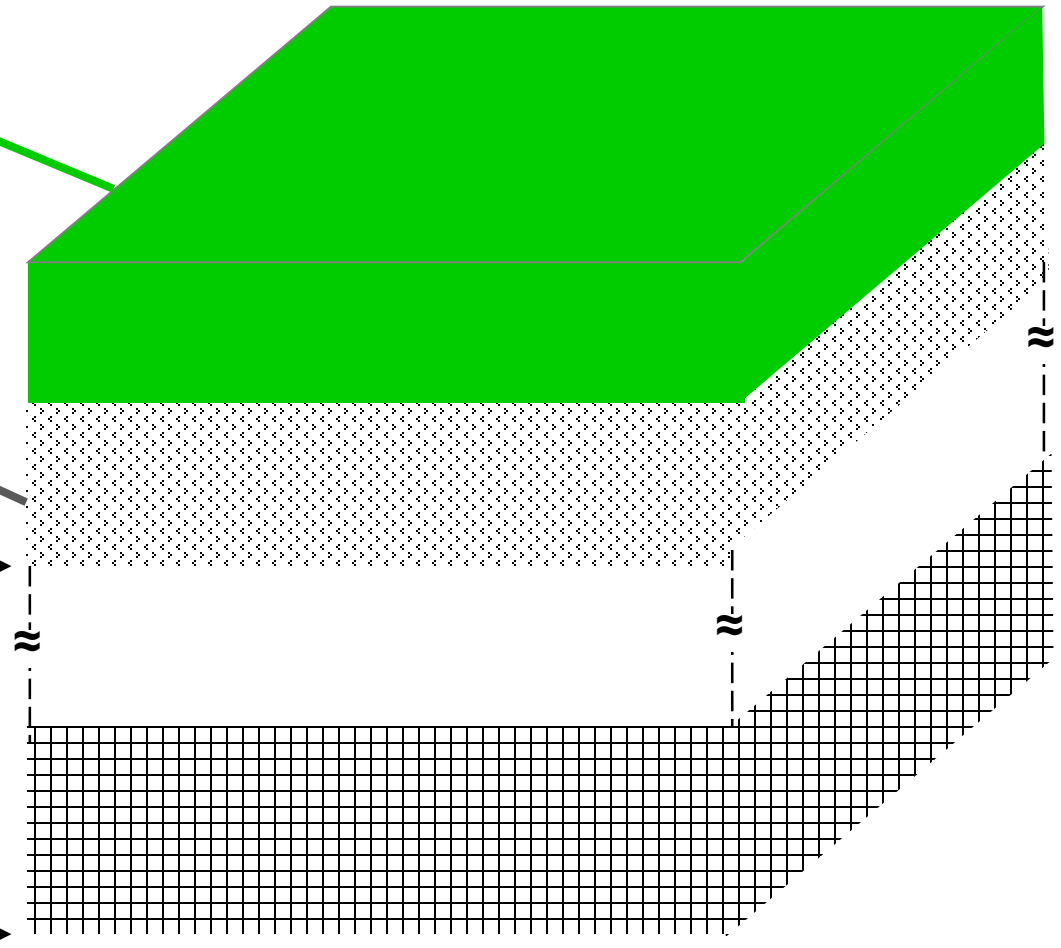
Selective Amine Polymer Layer / Polymer Support

Efficient and Scalable Membrane for Low Cost

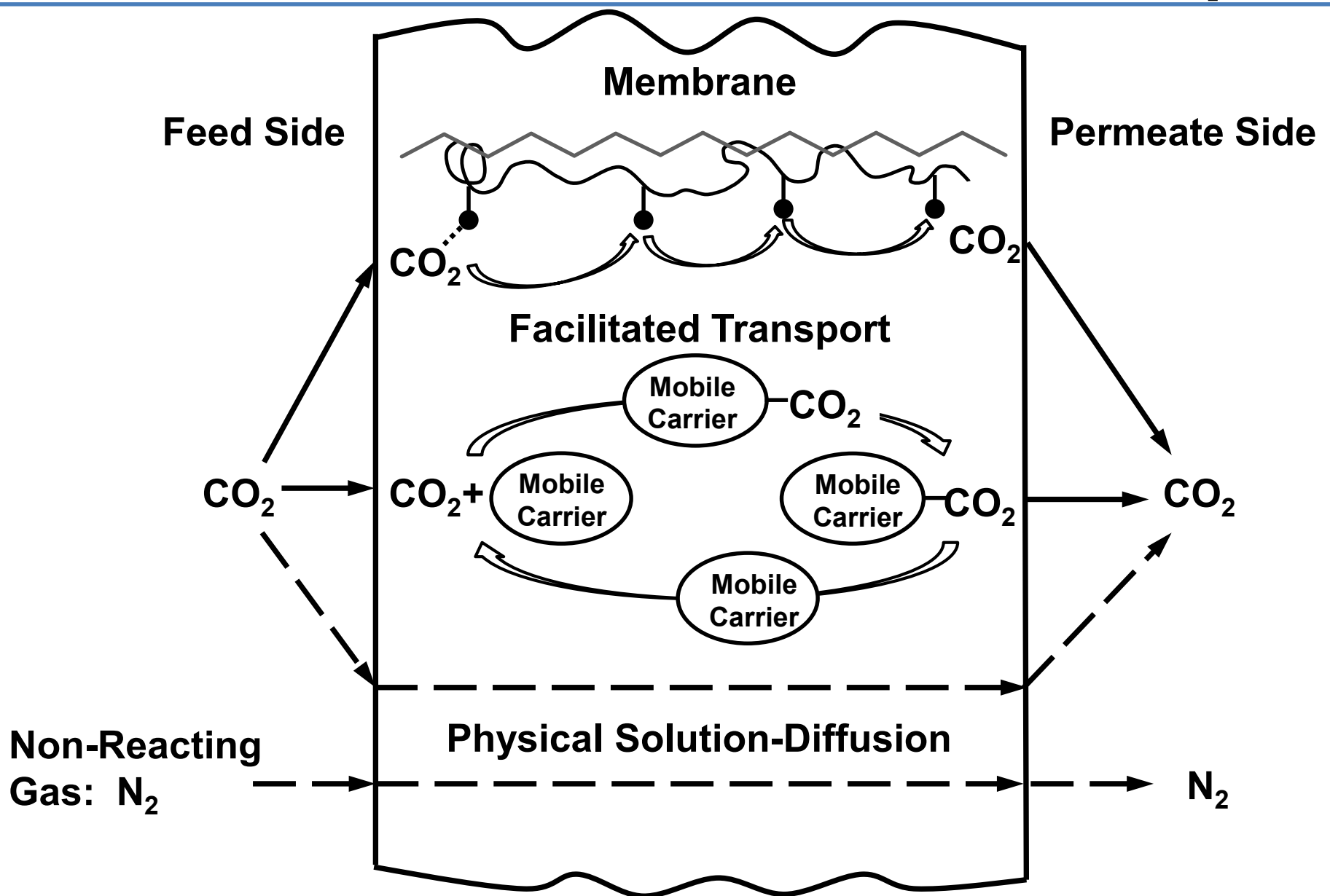
Highly selective amine polymer layer (170 nm, dense layer)
>140 CO_2/N_2 selectivity

Ultra-permeable polymer support (~20 µm, Ø ~40 nm)
>22,000 GPU CO_2 permeance

Nonwoven fabric backing (~100 µm)



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**

Technical Approach

- **BP1: 07/01/2019 – 12/31/2020**
  - Computation-aided material design
  - Lab-scale membrane synthesis, characterization and transport performance studies
  - Design of integrated membrane skid
  - High-level techno-economic analysis
- **BP2: 01/01/2021 – 06/30/2022**
  - Laboratory-scale membrane synthesis to continue
  - Fabrication and characterization of scale-up membrane (21″ wide)
  - Fabrication and evaluation of spiral-wound membrane modules (8″ diameter, 20″ length)
  - Fabrication and field test of integrated membrane skid
  - Update techno-economic analysis by Gas Technology Inst.

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

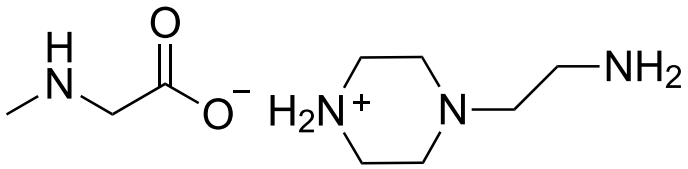
Computational Study

Novel Carrier 1 Favors HCO_3^- & Higher CO_2 Capacity

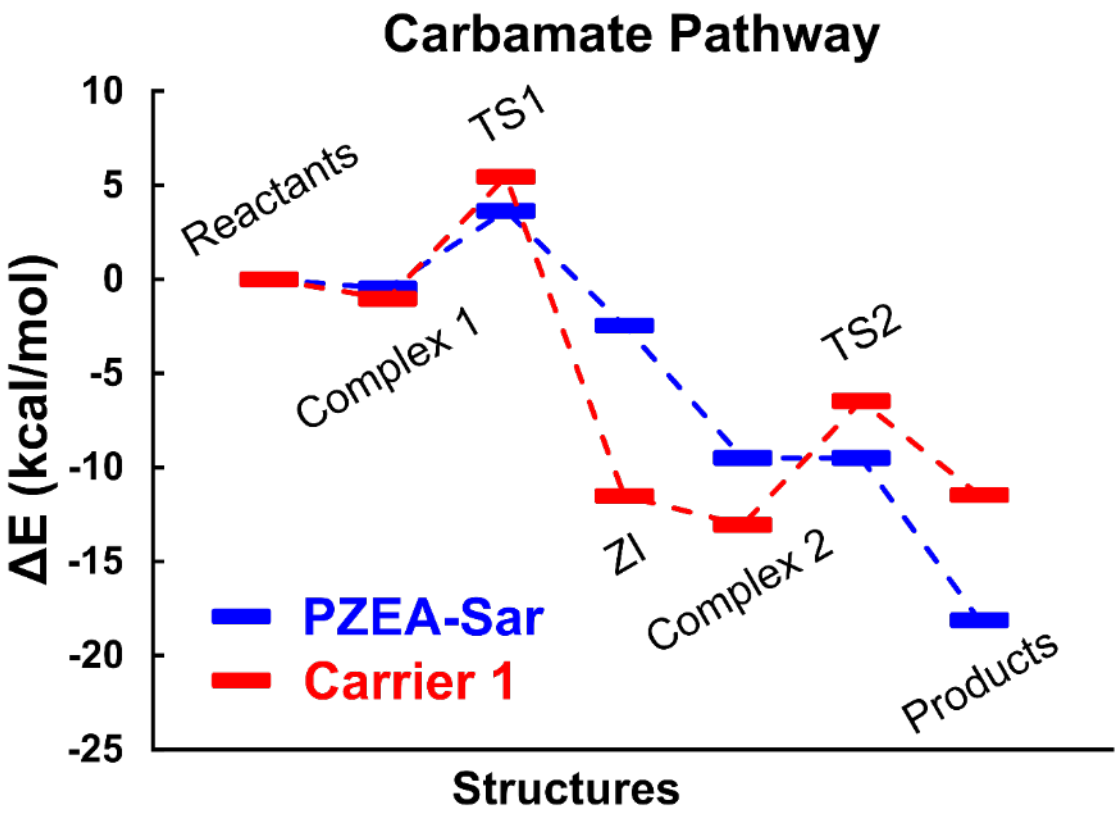
Carbamate: 2 Carrier + CO_2 ⇌ Carrier–COO^- + Carrier$^+$

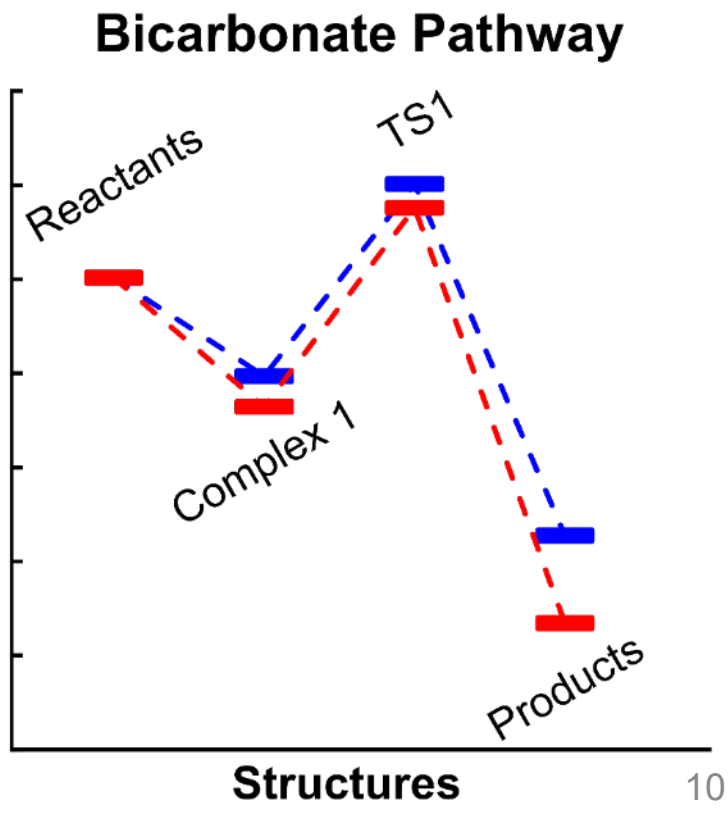
✓ **Bicarbonate:** Carrier + CO_2 + H_2O ⇌ Carrier$^+$ + HCO_3^-

PZEA-Sar
(DE-FE0026919)

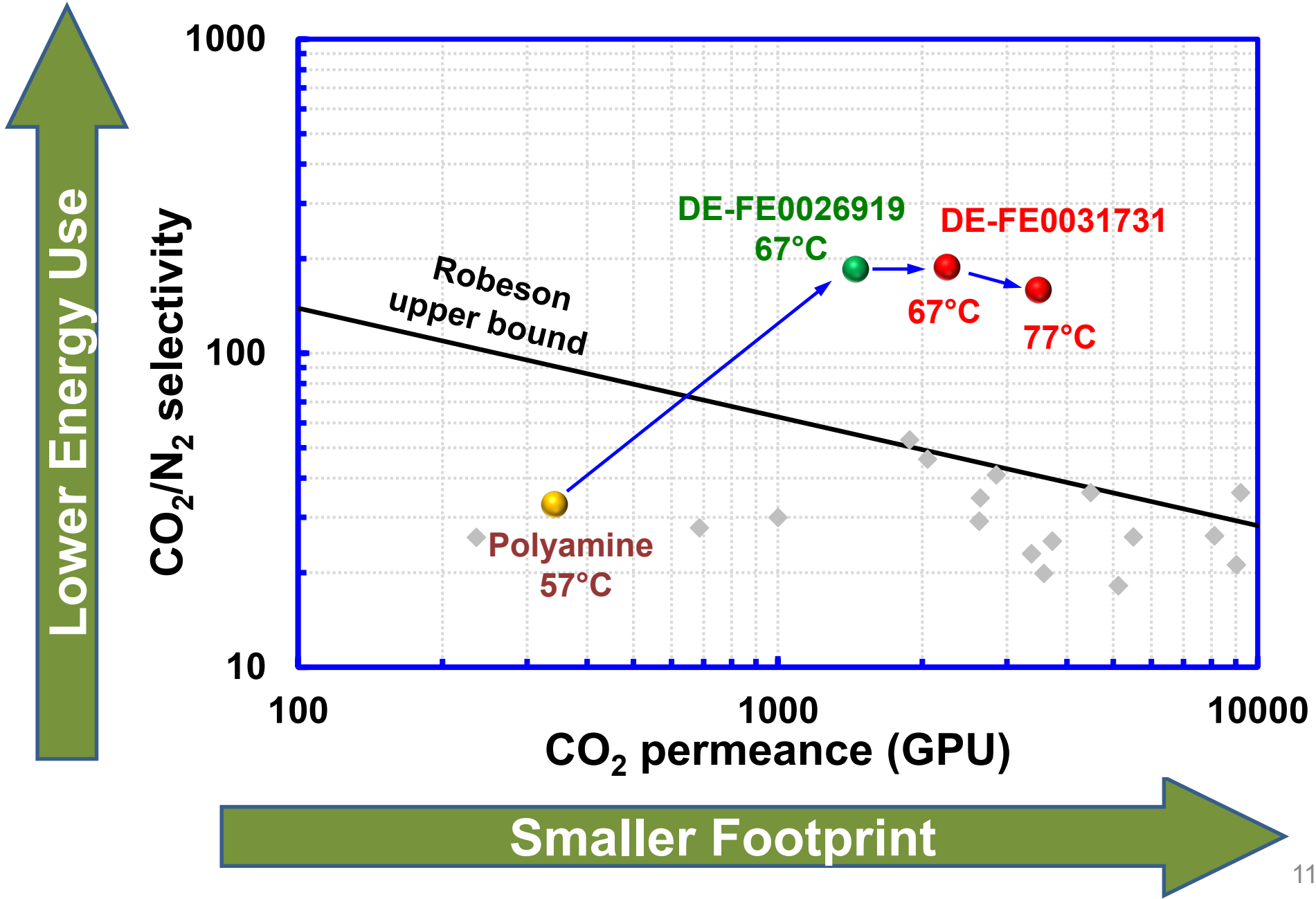


Carrier 1
(DE-FE0031731)





Developed Membrane Outperforms Others

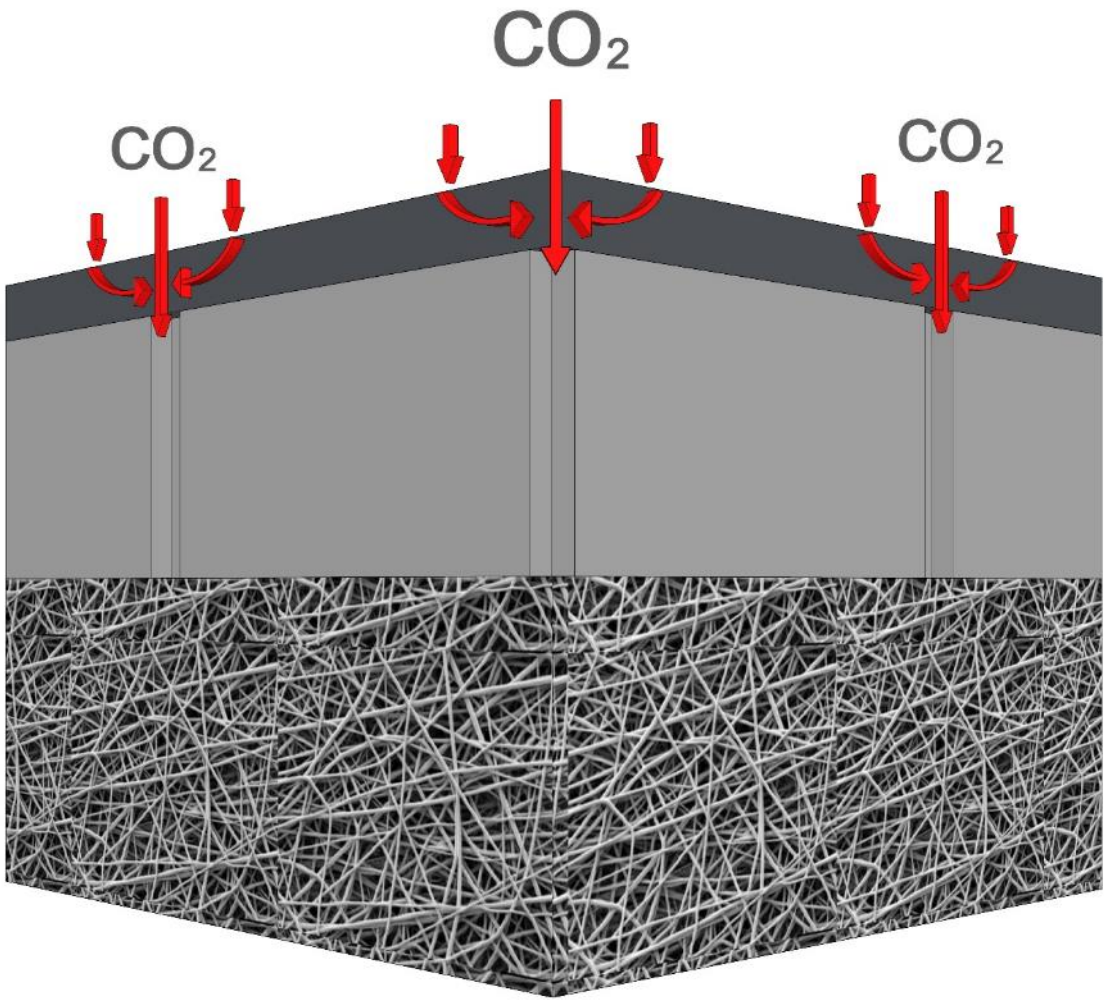


Improved Polymer Support

Dense selective layer
(Lateral diffusion)

Porous substrate layer
(Knudsen diffusion)

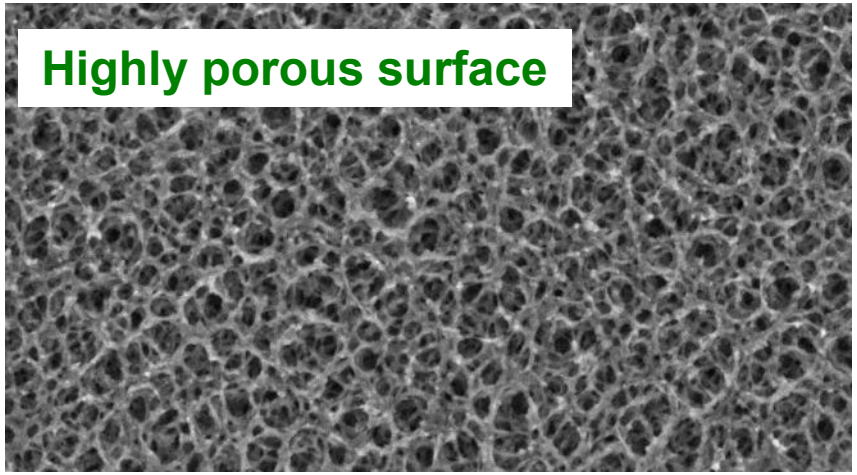
Nonwoven fabric backing
(Viscous flow)

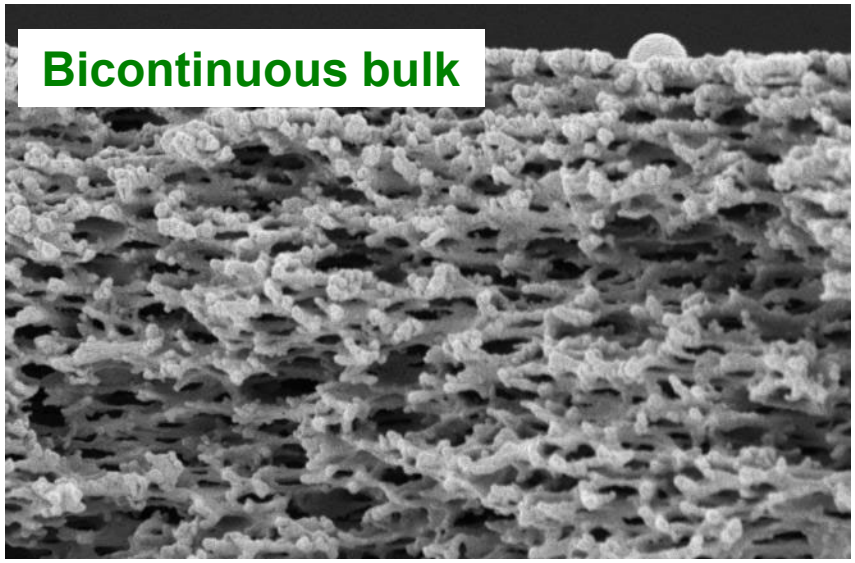


- **Substrate morphology has significant effect on CO_2 transport performance of composite membrane**

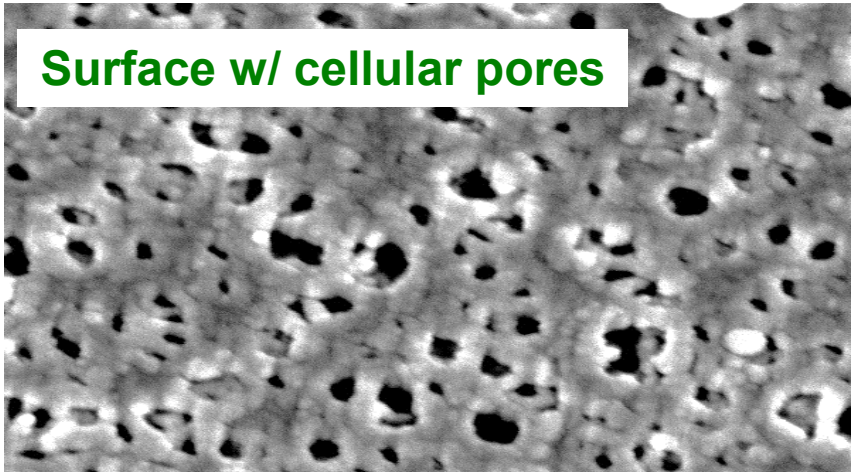
Improved vs. Benchmark Supports

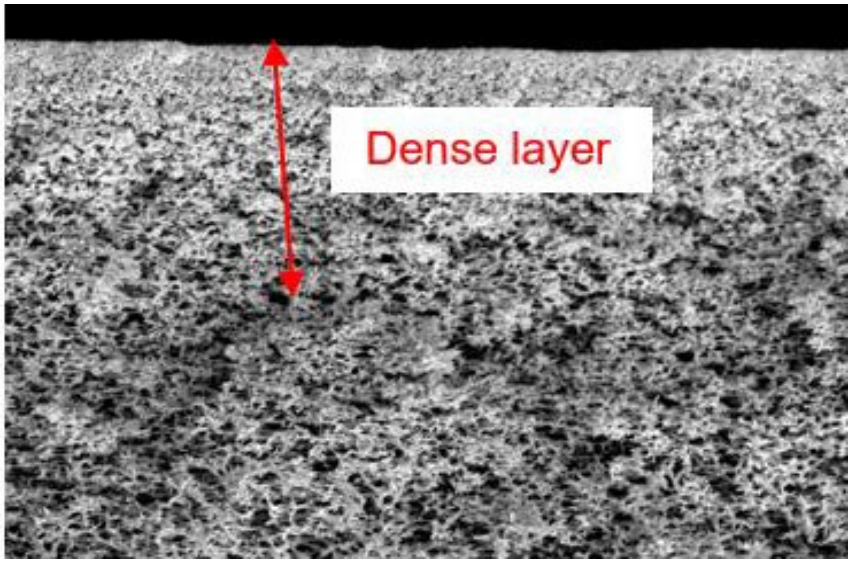
Improved



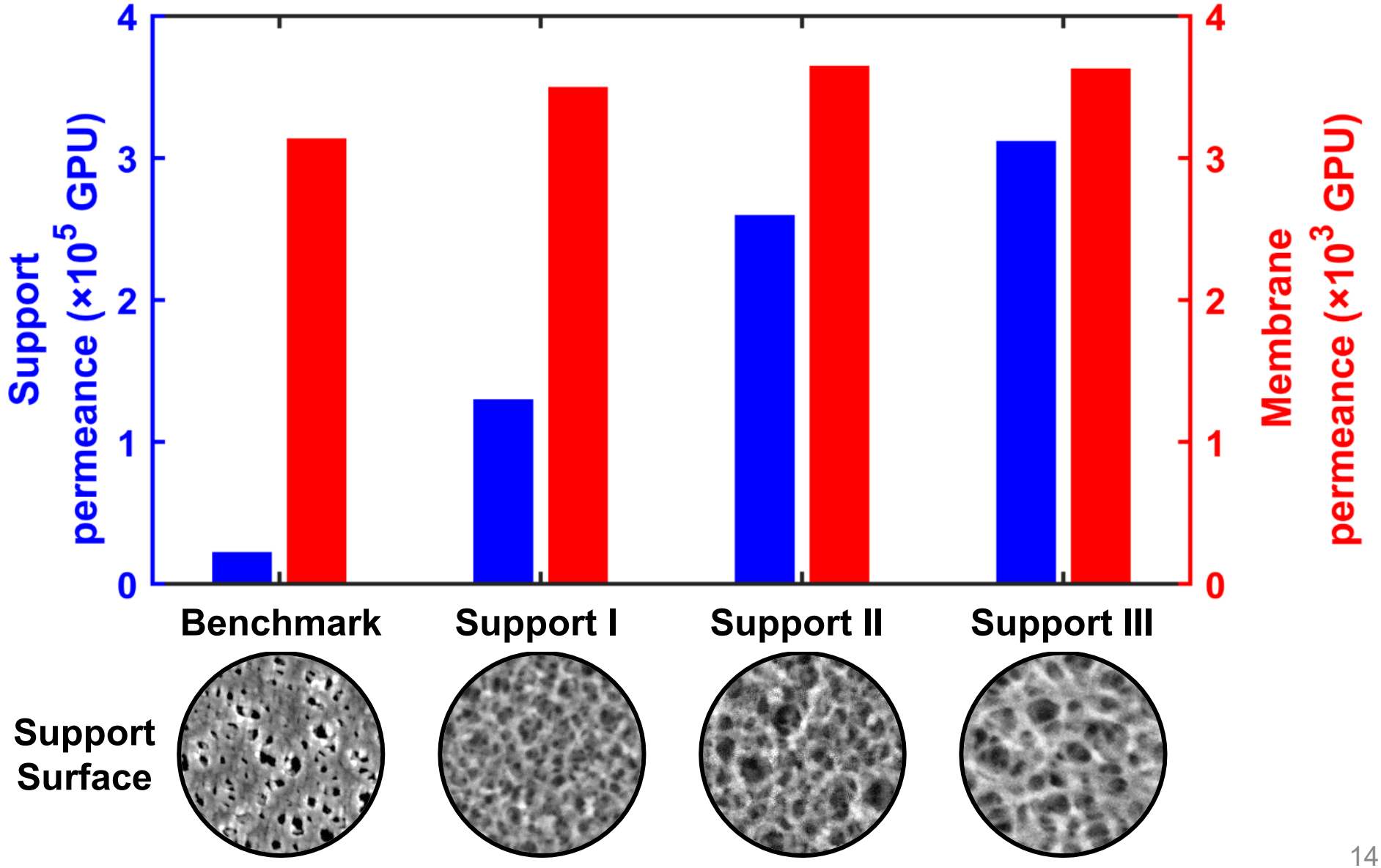


Benchmark

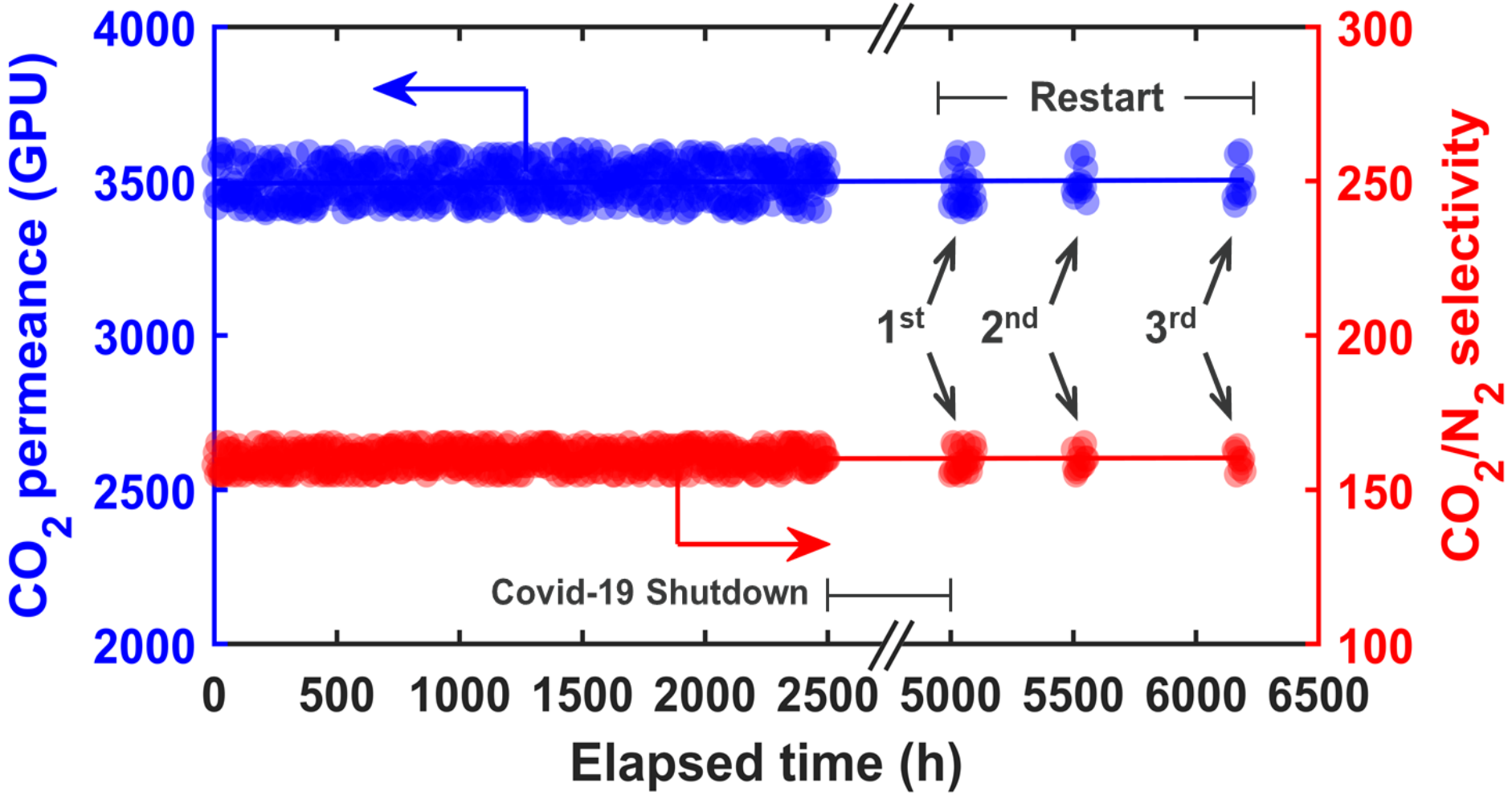




Better Membranes by Improved Polymer Supports

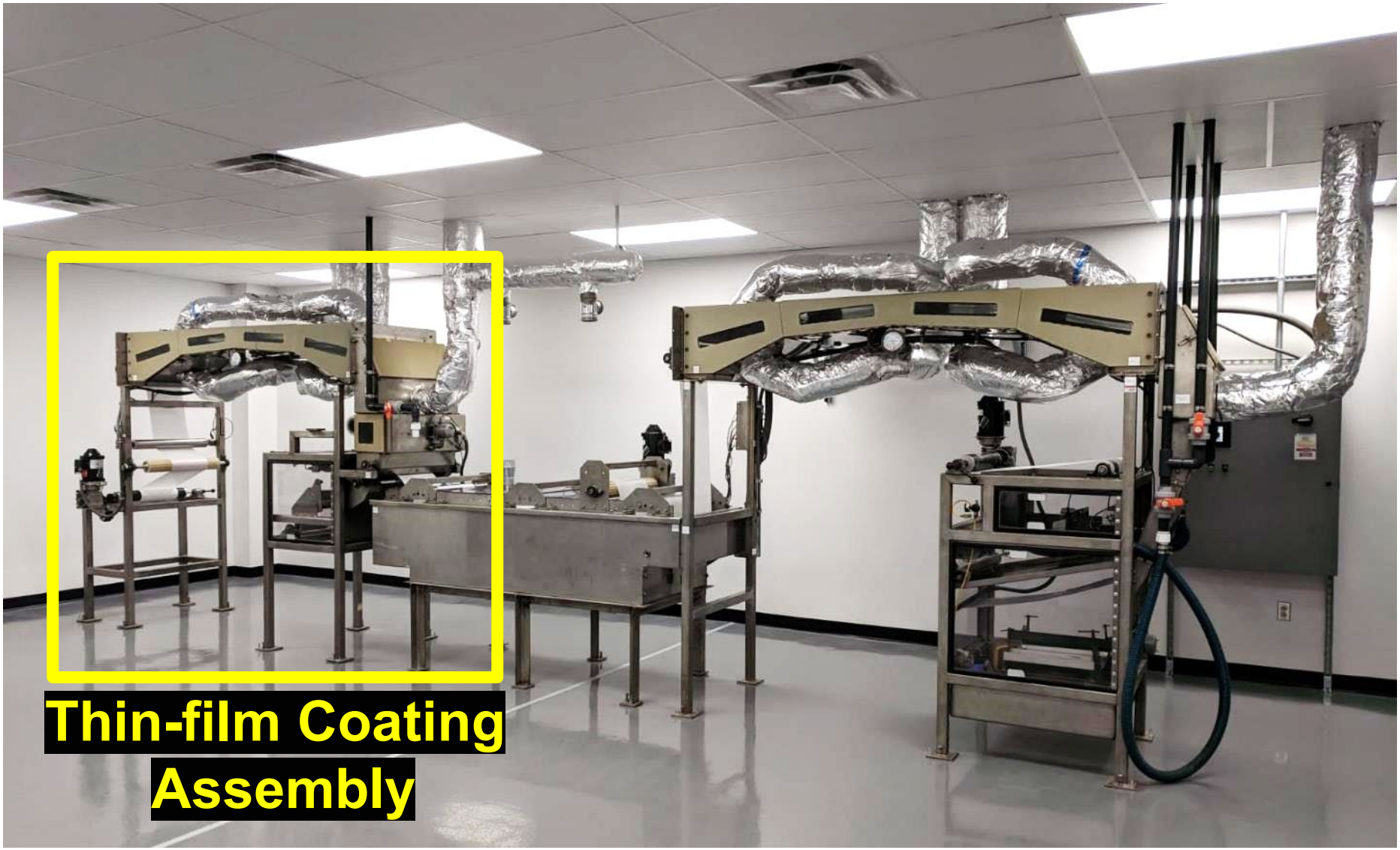


Excellent Stability with Simulated Flue Gas

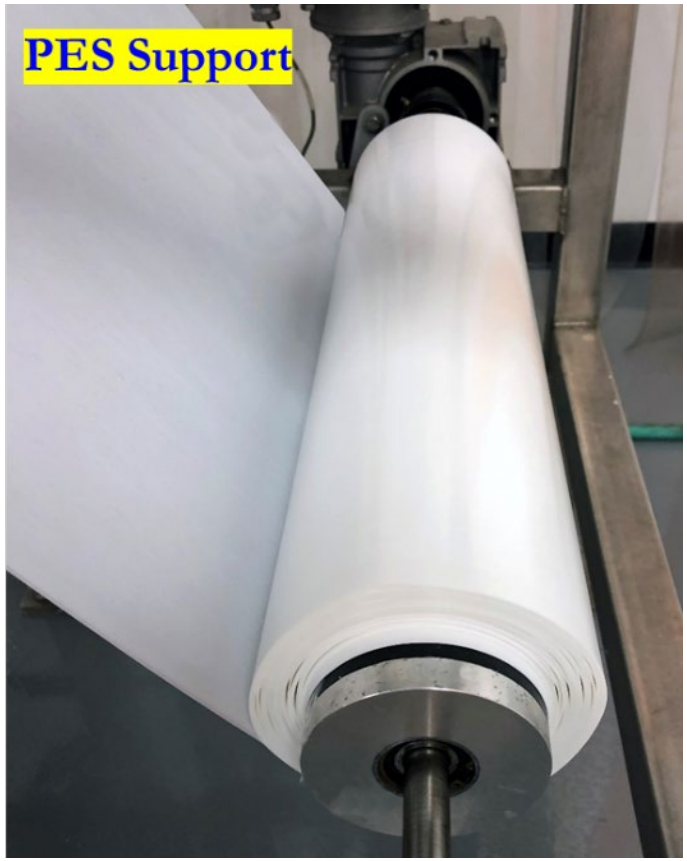


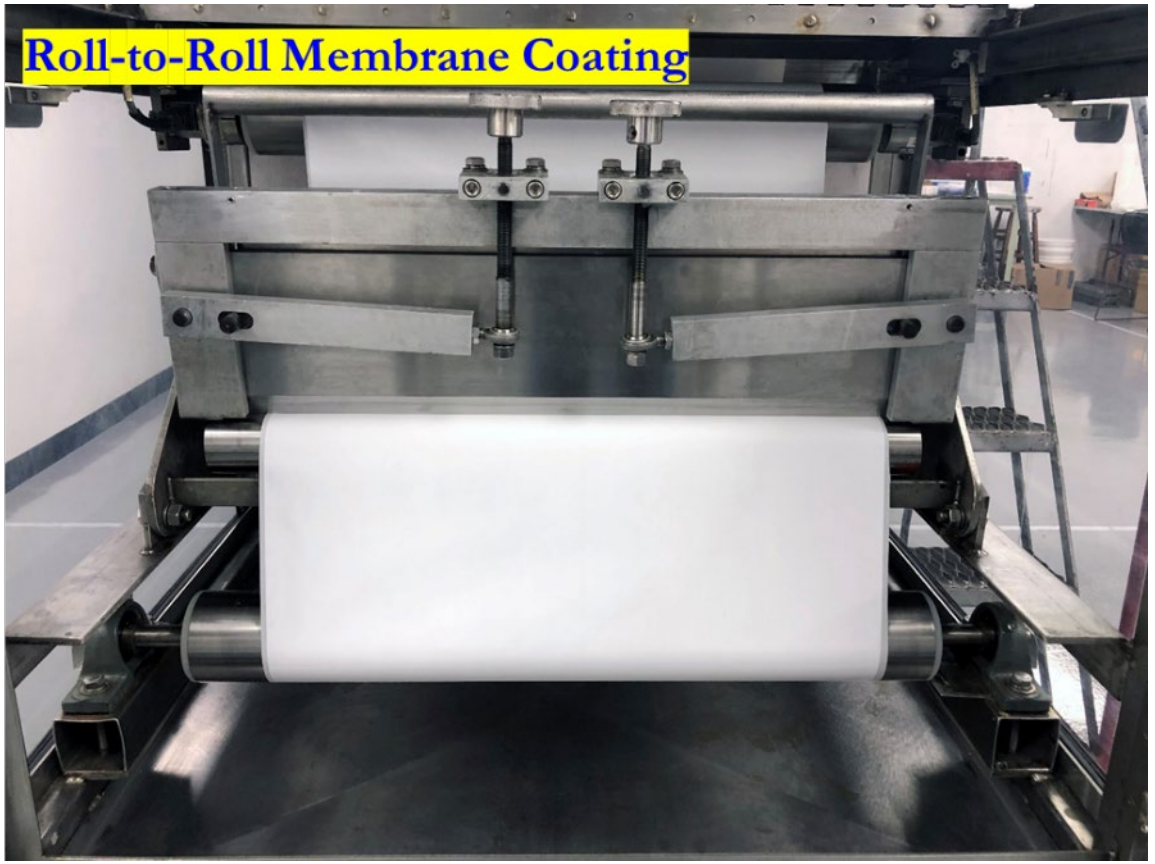
- Feed gas contained 3 ppm SO_2 and 7% O_2 at 77°C
- Stability test resumed after 3-month shutdown due to COVID-19
  - It remained stable with 3 restarts

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



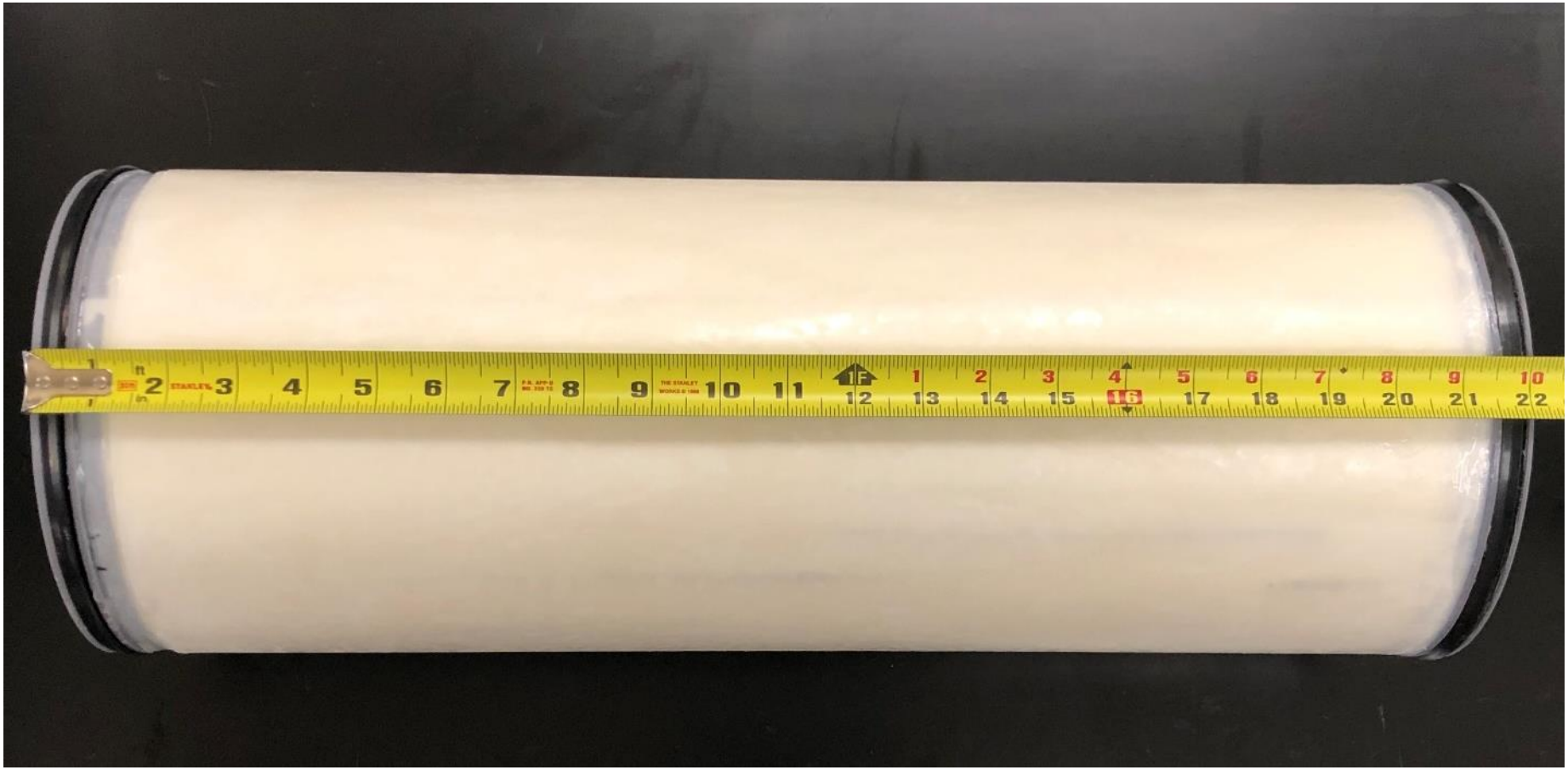
Prototype Membrane Fabricated by Roll-to-Roll Casting and Coating





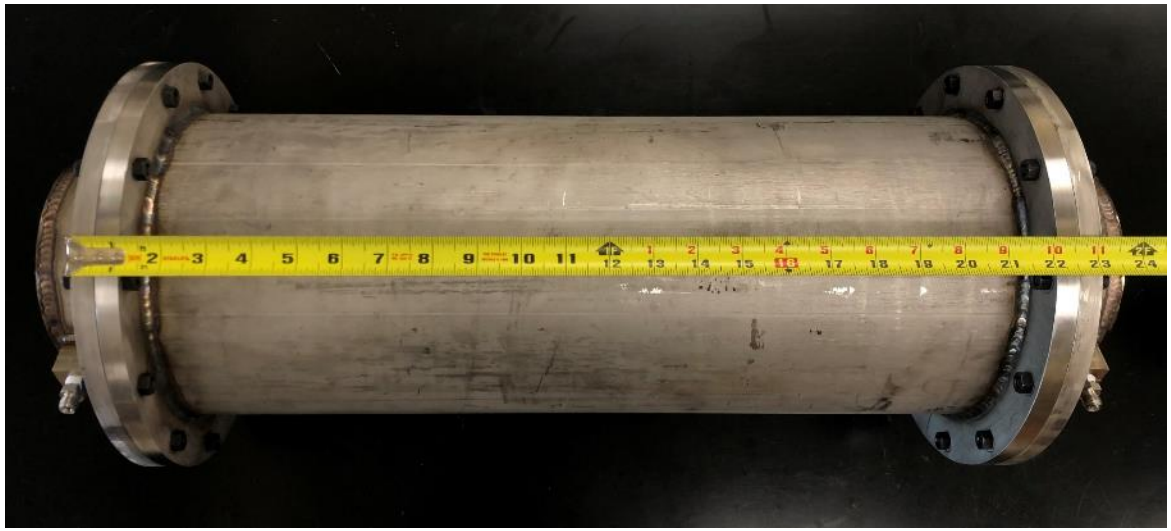
- **21″ wide PES support fabricated for > 200 ft in length**
- **Thin selective layer coated on fabricated PES support**

Prototype Spiral-Wound (SW) Membrane Element Fabricated



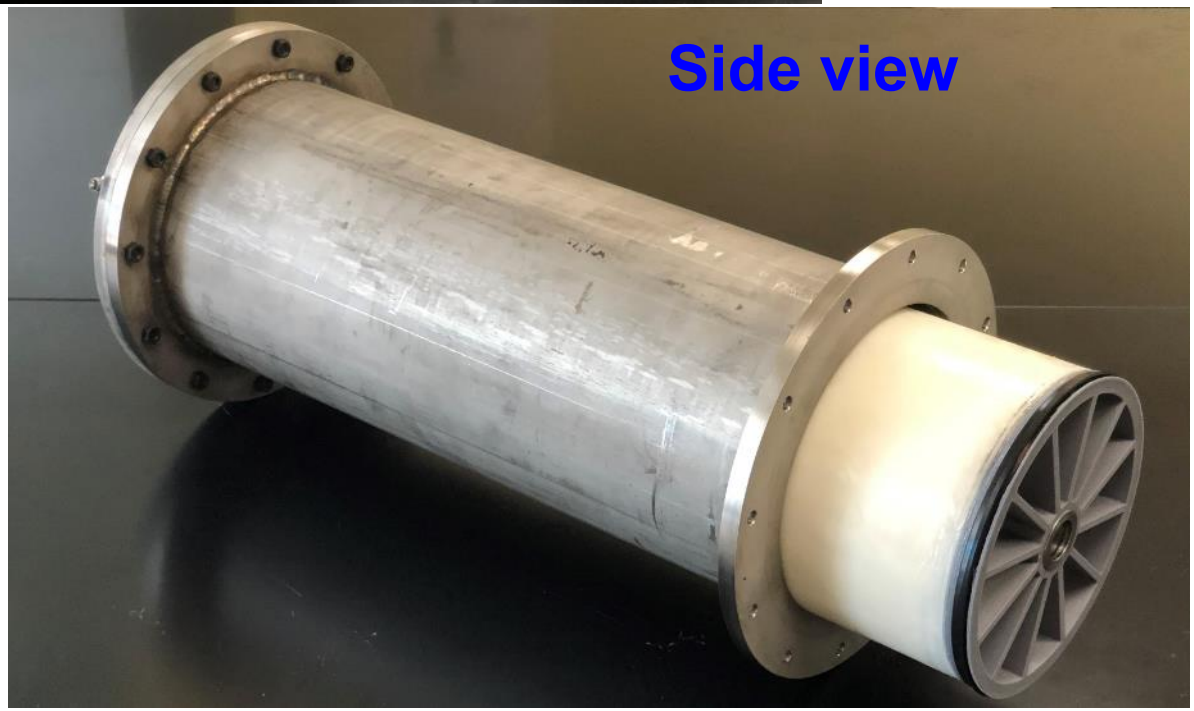
- 8″-diameter SW element fabricated using scale-up membrane
- Element contained 41 membrane leaves for 35 m^2 area

SW Membrane Element in Housing



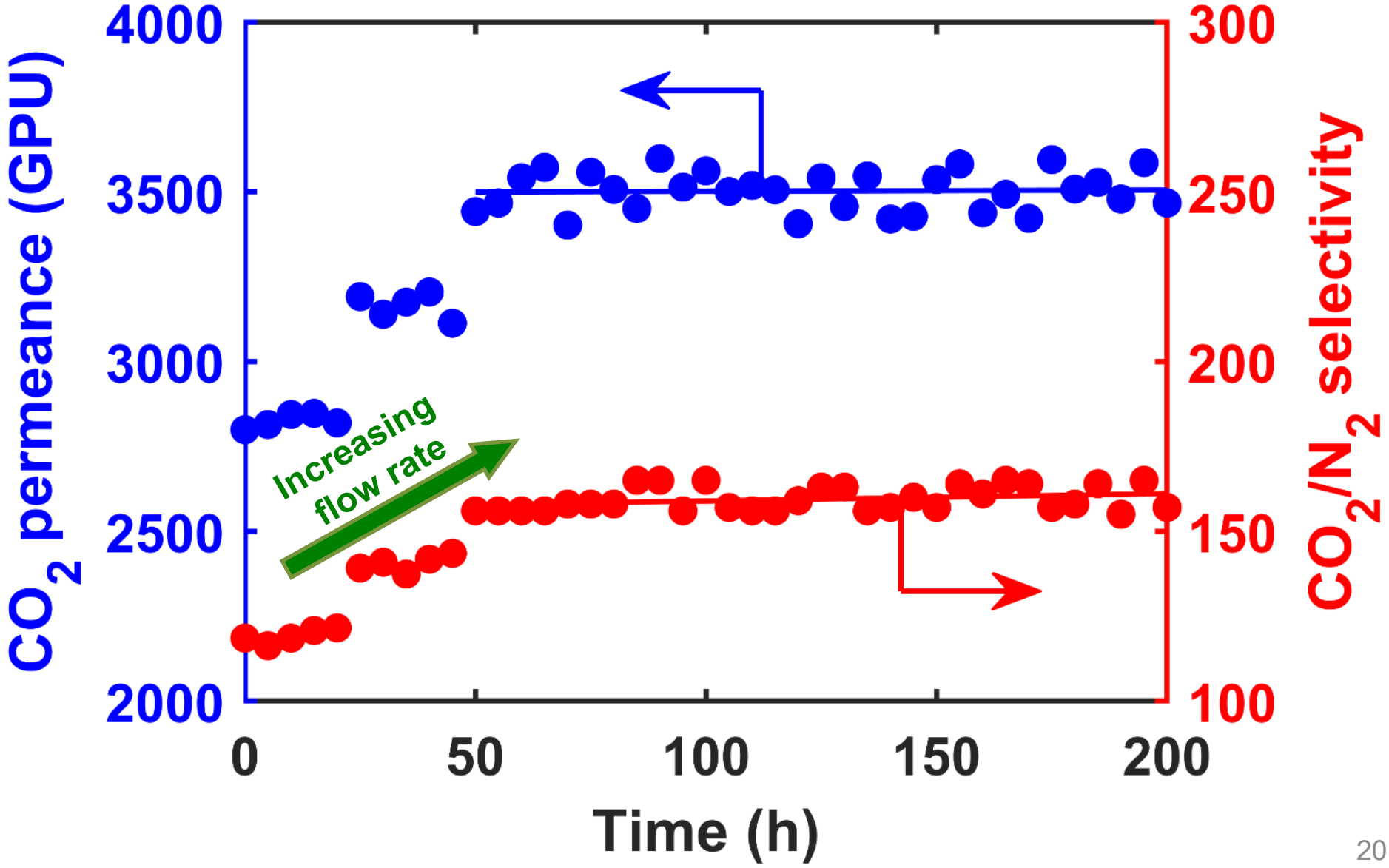
End view

Side view



- ⌀8″ SW element fitted tightly into SS module housing

Initial Module Test with Simulated Flue Gas



Summary/Outlook

- **Achieved milestones/success criteria**
  - Support CO_2 permeance = 23000 – 30000 GPU (>310000)
  - Membrane CO_2 permeance = 3000 – 3800 GPU (>3600)
  - CO_2/N_2 selectivity = 80 – 140 (~160)
  - TEA: $40.0 – 41.5/tonne capture cost ($39.60/tonne)
  - Scale-up membranes fabricated (21″ wide)
  - Prototype SW modules fabricated (Ø8″ & 35 m^2)

- **Remaining tasks**
  - Construction of bench skid
  - Skid testing with simulated flue gas at OSU
  - 500-h skid stability with actual flue gas at NCCC
  - Environmental Health and Safety (EH&S) assessment

Acknowledgments

Krista Hill and Andy Aurelio, DOE/NETL

– Great efforts and strong inputs

Financial Support

DOE/NETL: DE-FE0031731

Appendix

- **Project Organization**
- **Gantt Chart**

Project Organization and Roles

Ohio State University

- Technical lead
- New membrane synthesis/characterization
- Computation-aided material design
- Prototype membrane & module fabrication
- Integrated membrane skid fabrication
- Testing of integrated membrane skid

Winston Ho, Yang Han & Li-Chiang Lin

DOE NETL

Project Officer

Krista Hill

AEP

- Consult on plant integration and demonstration considerations

Randy Keefer

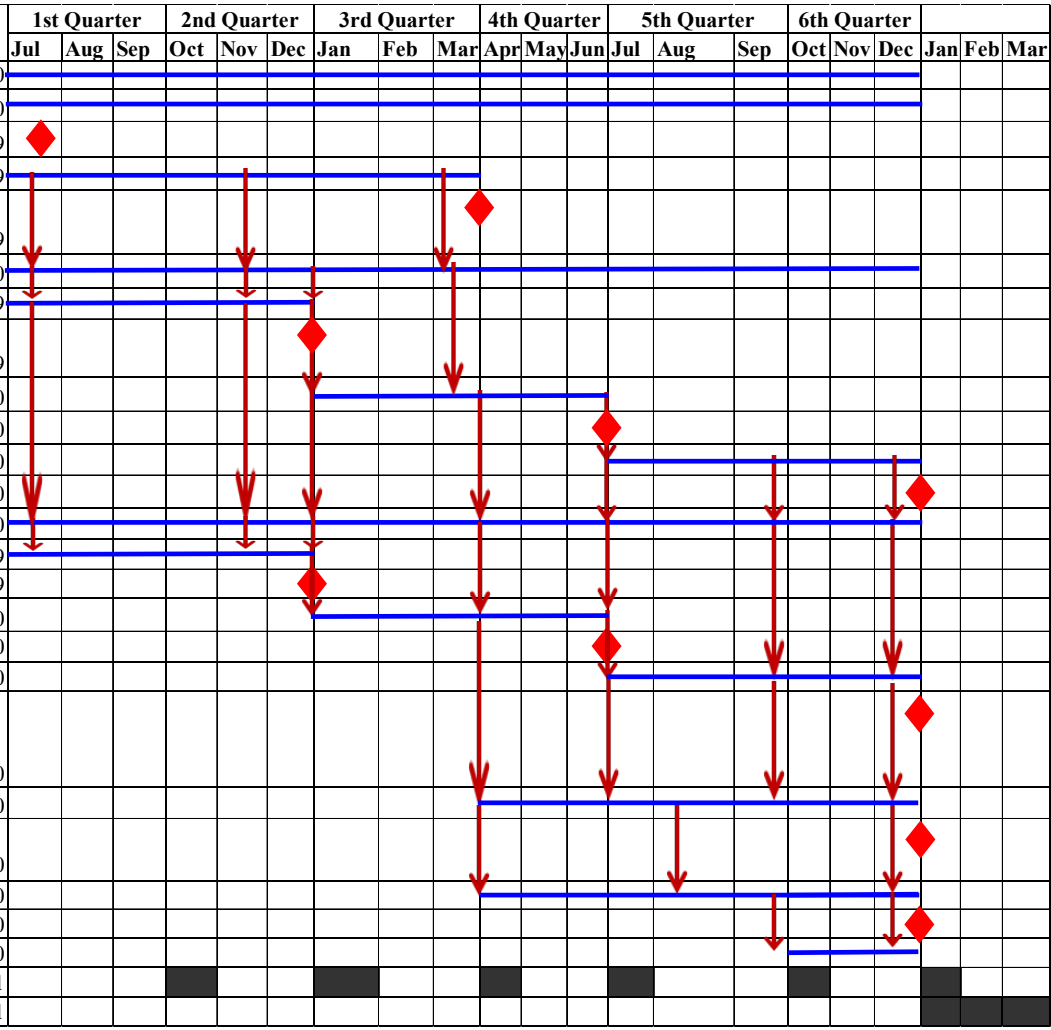
GTI

- Techno-economic analysis and cost calculations

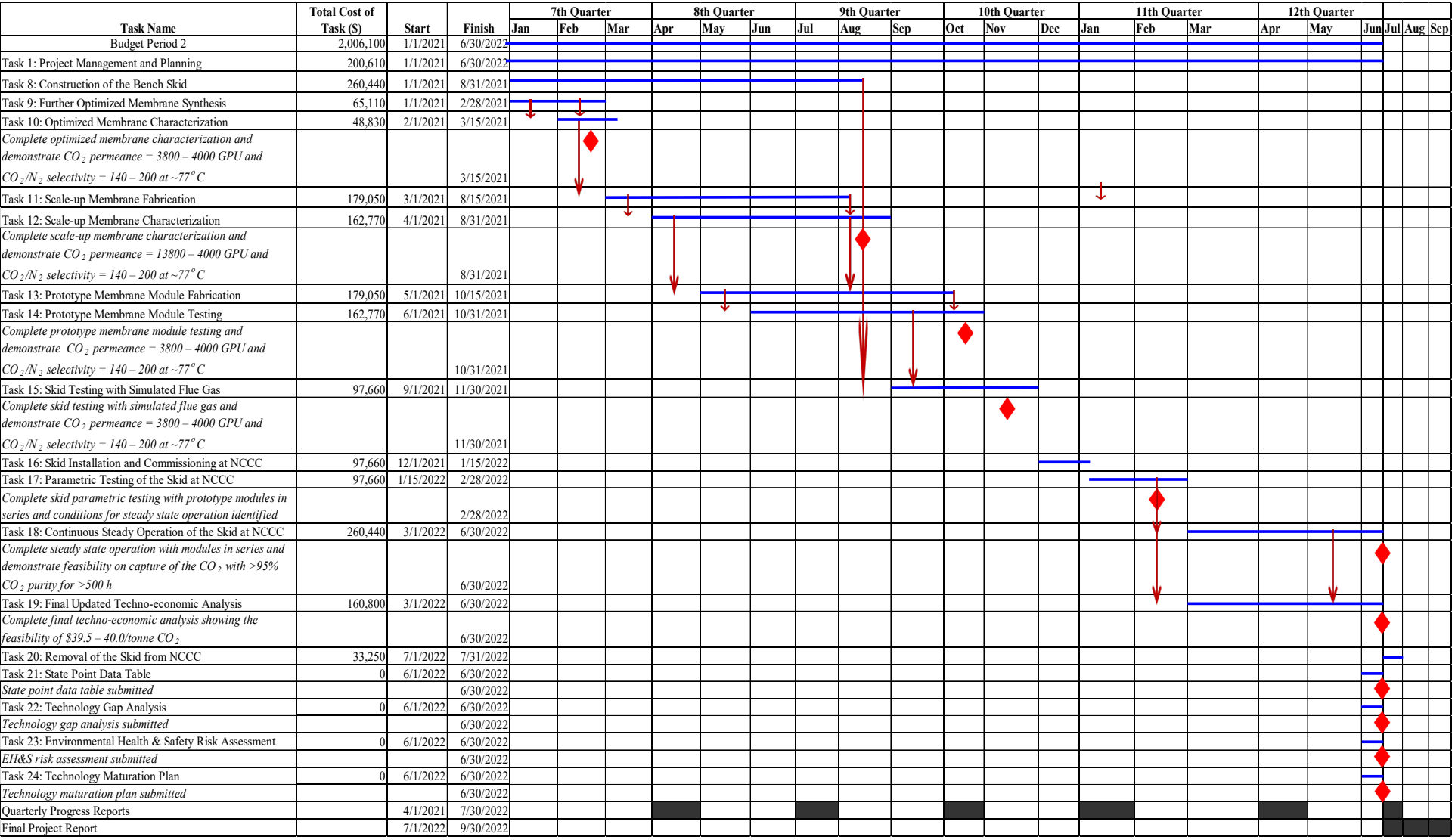
Shiguang Li

Gantt Chart

Task Name	Total Cost of Task ($)	Start	Finish
Budget Period 1	1,743,878	7/1/2019	12/31/2020
Task 1: Project Management and Planning	174,388	7/1/2019	12/31/2020
Updated PMP submitted			7/30/2019
Task 2: Synthesis of Improved Polymer Support	227,610	7/1/2019	3/31/2019
Complete polymer support synthesis and demonstrate CO_2 permeance of the support = 23000 – 30000 GPU at ~77° C			3/31/2019
Task 3: Optimized Synthesis of Transformational Membrane	455,222	7/1/2019	12/31/2020
Subtask 3.1: Investigation of CO_2 Carrier Structures	151,742	7/1/2019	12/31/2019
Complete density functional theory calculations to identify the structures for synthesis			12/31/2019
Subtask 3.2: Incorporation of Nano-fillers	151,740	1/1/2020	6/30/2020
Nano-fillers incorporated in the membrane			6/30/2020
Subtask 3.3: Synthesis of Higher MW Polyamine	151,740	7/1/2020	12/31/2020
Complete synthesis of 3 – 5 million MW polyamine			12/31/2020
Task 4: Membrane Characterization	455,222	7/1/2019	12/31/2020
Subtask 4.1: Morphology of Membranes	151,742	7/1/2019	12/31/2019
Obtain SEMs showing membrane morphologies			12/31/2019
Subtask 4.2: Transport Properties	151,740	1/1/2020	6/30/2020
Determine CO_2 permeance and CO_2/N_2 selectivity			6/30/2020
Subtask 4.3: Membrane Stability	151,740	7/1/2020	12/31/2020
Complete membrane stability testing and demonstrate CO_2 permeance = 3000 – 3800 GPU and CO_2/N_2 selectivity = 80 – 140 at ~77° C			12/31/2020
Task 5: Preliminary Techno-economic Analysis	158,886	4/1/2020	12/31/2020
Complete preliminary techno-economic analysis showing the feasibility of $40.0 – 41.5/tonne CO_2 for 90% recovery			12/31/2020
Task 6: Design of an Integrated Skid	227,610	4/1/2020	12/31/2020
Complete the design of the integrated skid			12/31/2020
Task 7: NCCC Site Preparation	44,940	10/1/2020	12/31/2020
Quarterly Progress Reports		10/1/2019	1/30/2021
Budget Period 1 Annual Report		1/1/2021	3/30/2021



Gantt Chart



Task Name	Total Cost of Task ($)	Start	Finish
Budget Period 2	2,006,100	1/1/2021	6/30/2022
Task 1: Project Management and Planning	200,610	1/1/2021	6/30/2022
Task 8: Construction of the Bench Skid	260,440	1/1/2021	8/31/2021
Task 9: Further Optimized Membrane Synthesis	65,110	1/1/2021	2/28/2021
Task 10: Optimized Membrane Characterization	48,830	2/1/2021	3/15/2021
Complete optimized membrane characterization and demonstrate CO_2 permeance = 3800 – 4000 GPU and CO_2/N_2 selectivity = 140 – 200 at ~77° C			3/15/2021
Task 11: Scale-up Membrane Fabrication	179,050	3/1/2021	8/15/2021
Task 12: Scale-up Membrane Characterization	162,770	4/1/2021	8/31/2021
Complete scale-up membrane characterization and demonstrate CO_2 permeance = 13800 – 4000 GPU and CO_2/N_2 selectivity = 140 – 200 at ~77° C			8/31/2021
Task 13: Prototype Membrane Module Fabrication	179,050	5/1/2021	10/15/2021
Task 14: Prototype Membrane Module Testing	162,770	6/1/2021	10/31/2021
Complete prototype membrane module testing and demonstrate CO_2 permeance = 3800 – 4000 GPU and CO_2/N_2 selectivity = 140 – 200 at ~77° C			10/31/2021
Task 15: Skid Testing with Simulated Flue Gas	97,660	9/1/2021	11/30/2021
Complete skid testing with simulated flue gas and demonstrate CO_2 permeance = 3800 – 4000 GPU and CO_2/N_2 selectivity = 140 – 200 at ~77° C			11/30/2021
Task 16: Skid Installation and Commissioning at NCCC	97,660	12/1/2021	1/15/2022
Task 17: Parametric Testing of the Skid at NCCC	97,660	1/15/2022	2/28/2022
Complete skid parametric testing with prototype modules in series and conditions for steady state operation identified			2/28/2022
Task 18: Continuous Steady Operation of the Skid at NCCC	260,440	3/1/2022	6/30/2022
Complete steady state operation with modules in series and demonstrate feasibility on capture of the CO_2 with >95% CO_2 purity for >500 h			6/30/2022
Task 19: Final Updated Techno-economic Analysis	160,800	3/1/2022	6/30/2022
Complete final techno-economic analysis showing the feasibility of $39.5 – 40.0/tonne CO_2			6/30/2022
Task 20: Removal of the Skid from NCCC	33,250	7/1/2022	7/31/2022
Task 21: State Point Data Table	0	6/1/2022	6/30/2022
State point data table submitted			6/30/2022
Task 22: Technology Gap Analysis	0	6/1/2022	6/30/2022
Technology gap analysis submitted			6/30/2022
Task 23: Environmental Health & Safety Risk Assessment	0	6/1/2022	6/30/2022
EH&S risk assessment submitted			6/30/2022
Task 24: Technology Maturation Plan	0	6/1/2022	6/30/2022
Technology maturation plan submitted			6/30/2022
Quarterly Progress Reports		4/1/2021	7/30/2022
Final Project Report		7/1/2022	9/30/2022