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

DE-FE0026919

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The Ohio State University

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NETL, Pittsburgh, PA, April 4, 2016

Outline

- Project Objective
- Process
- Membrane
- Project Scope – 3 Budget Periods
- Success Criteria
- Tasks – 3-BP Gantt Charts
- Project Team and Outlook

Project Objective

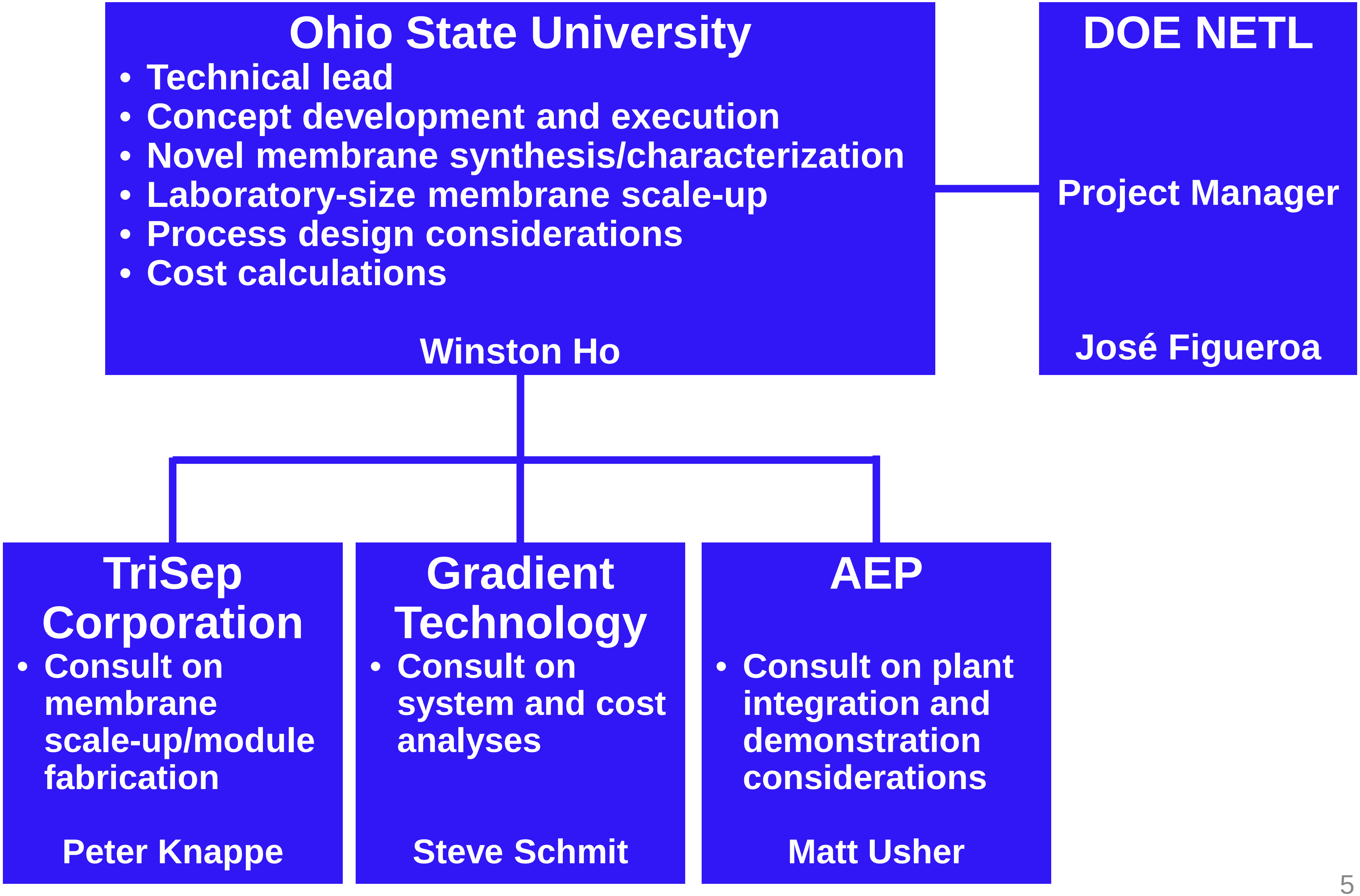
- Develop a novel cost-effective membrane and design of membrane modules that capture CO_2 from <1% CO_2 sources
  - 90% CO_2 Capture
  - 95% CO_2 Purity

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 lab size membrane (~ 6” by 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 laboratory membrane modules
  - 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
- Laboratory-size 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

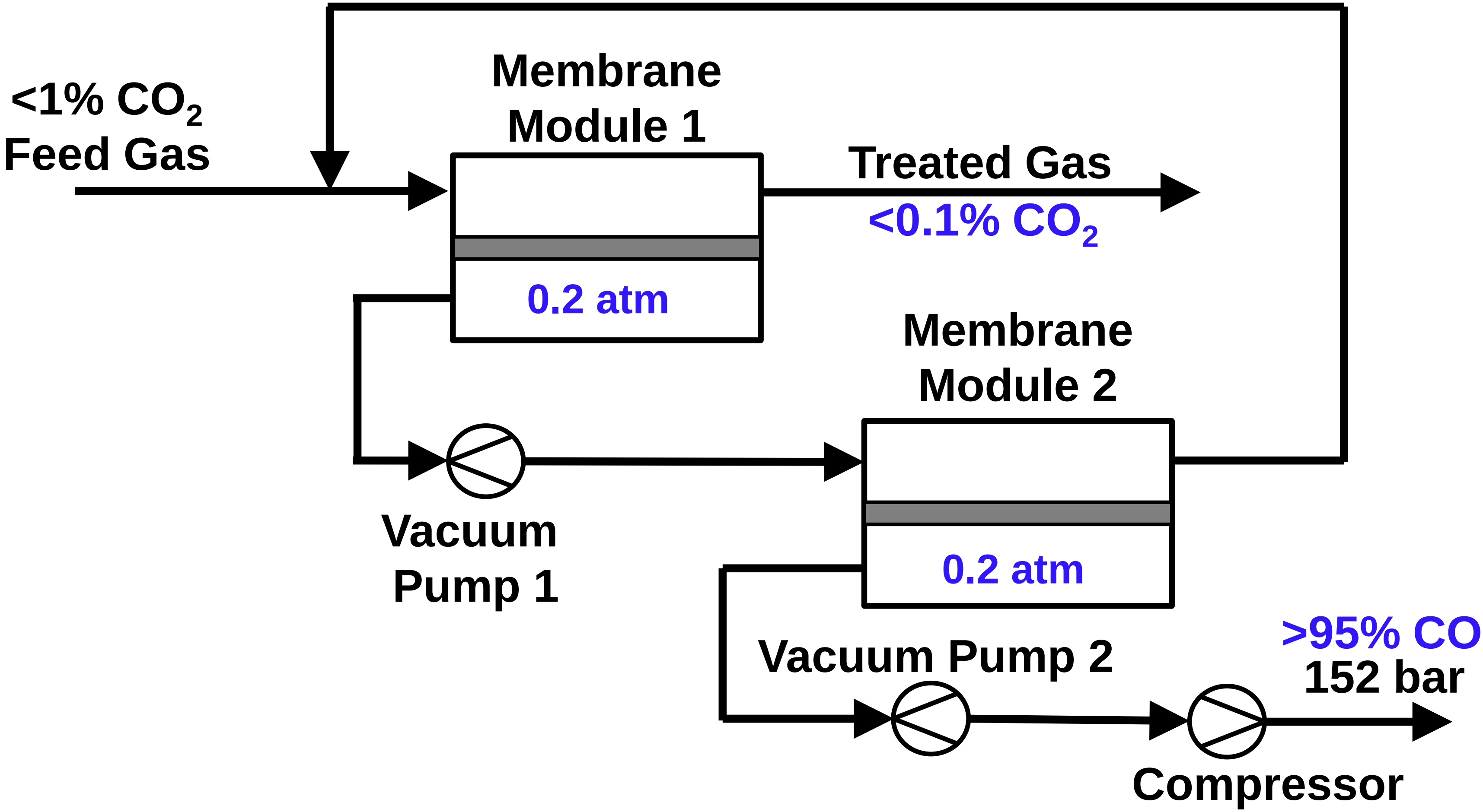
Steve Schmit

AEP

- Consult on plant integration and demonstration considerations

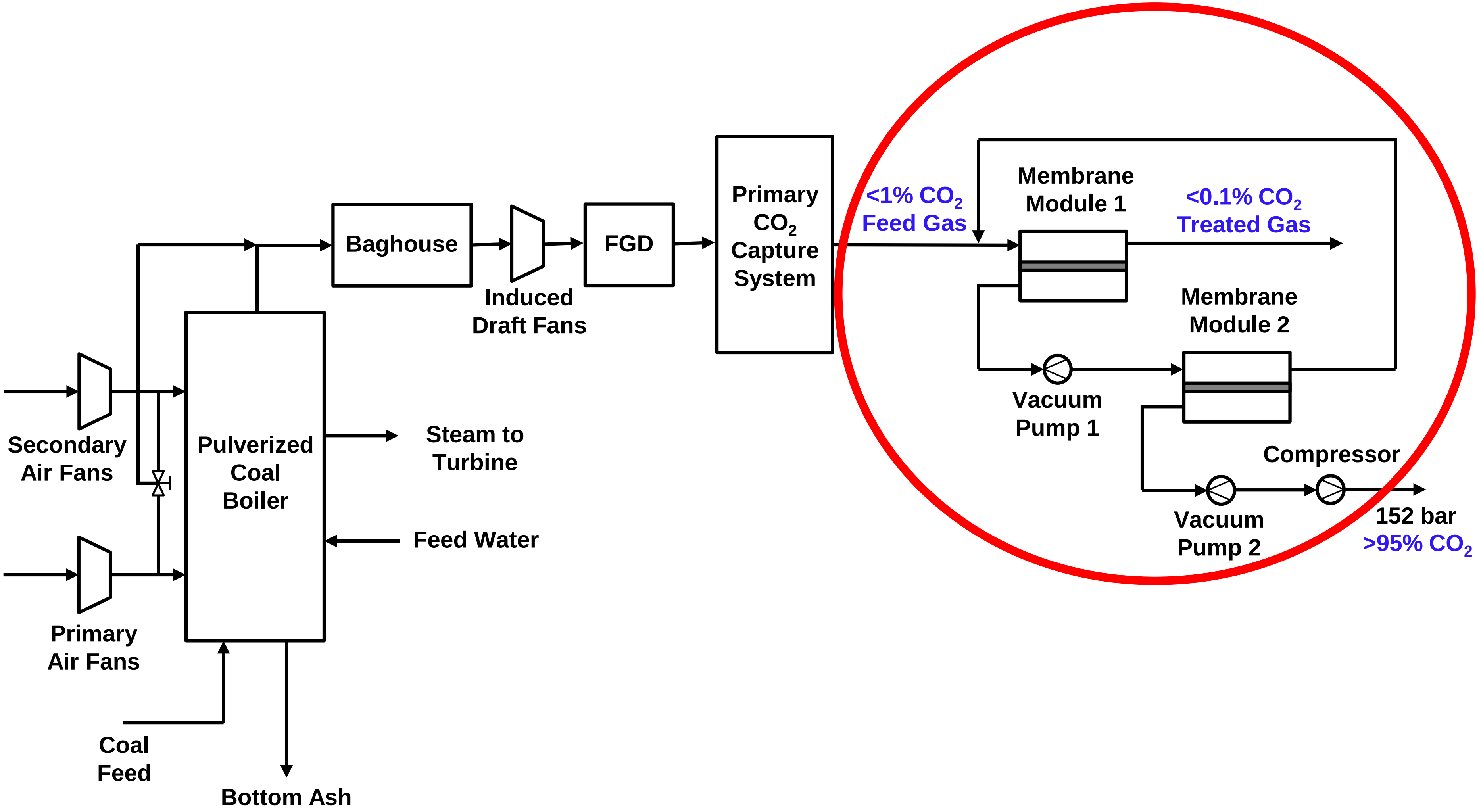
Matt Usher

Process Proposed for CO_2 Capture from <1% CO_2 Sources



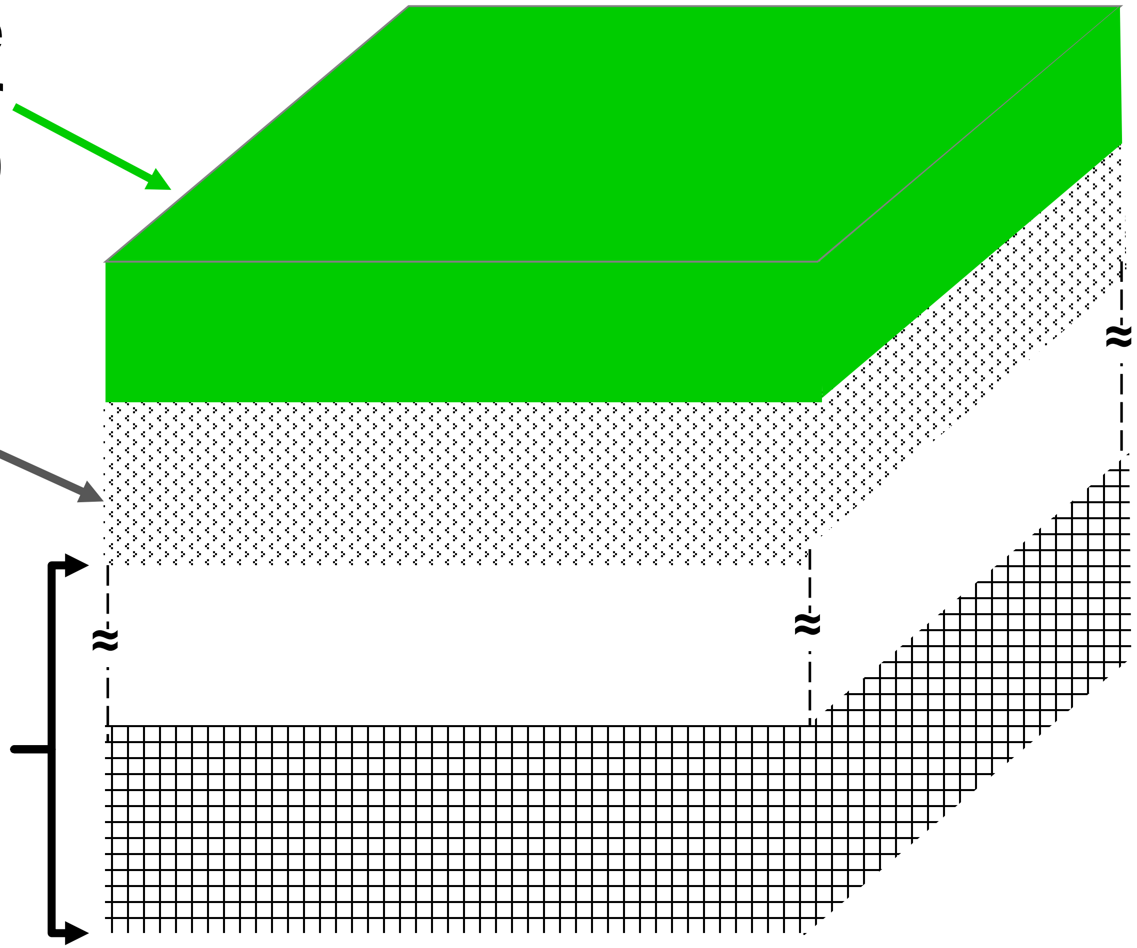
- **Proposed membrane process does not require cryogenic distillation (compared to competition)**

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 (180 nm, dense layer)

Polymer support (~30 µm, Ø ~70 nm)

Nonwoven fabric backing (~120 µm)

Selective Amine Polymer Layer / Polymer Support

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

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

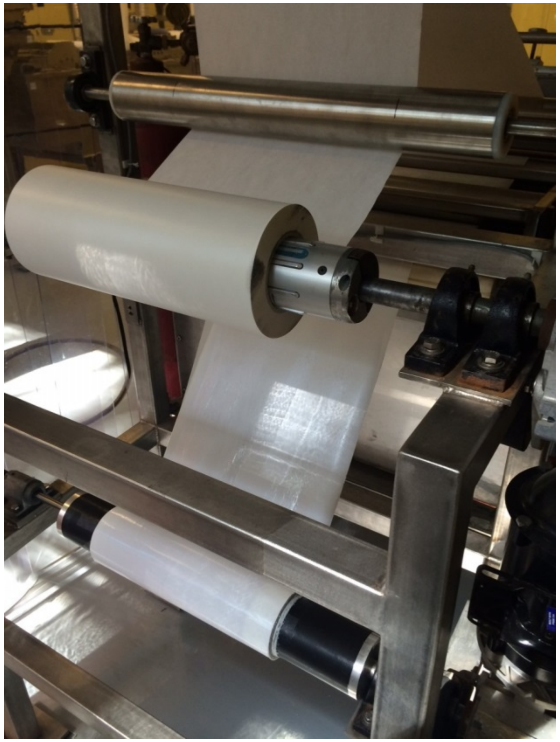
  - Facilitated transport = flux augmentation via reaction
  - High CO_2 permeance and CO_2/N_2 selectivity

Scale-up for PES Support

Continuous Membrane Fabrication Machine at OSU

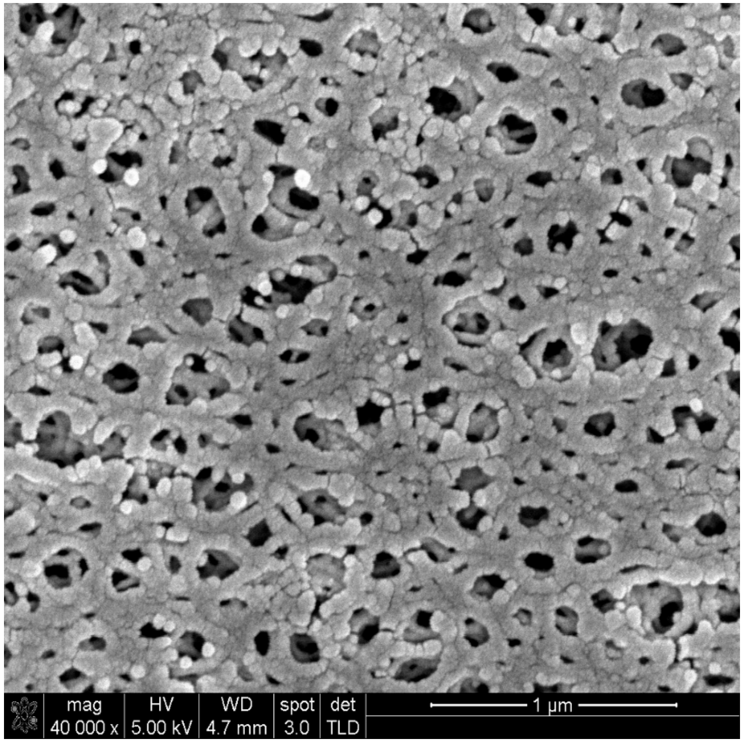
Successful Continuous Fabrication of Affordable PES Support Demonstrated in DE-FE0007632

Casting Machine



14-inch PES Support

SEM – Top View

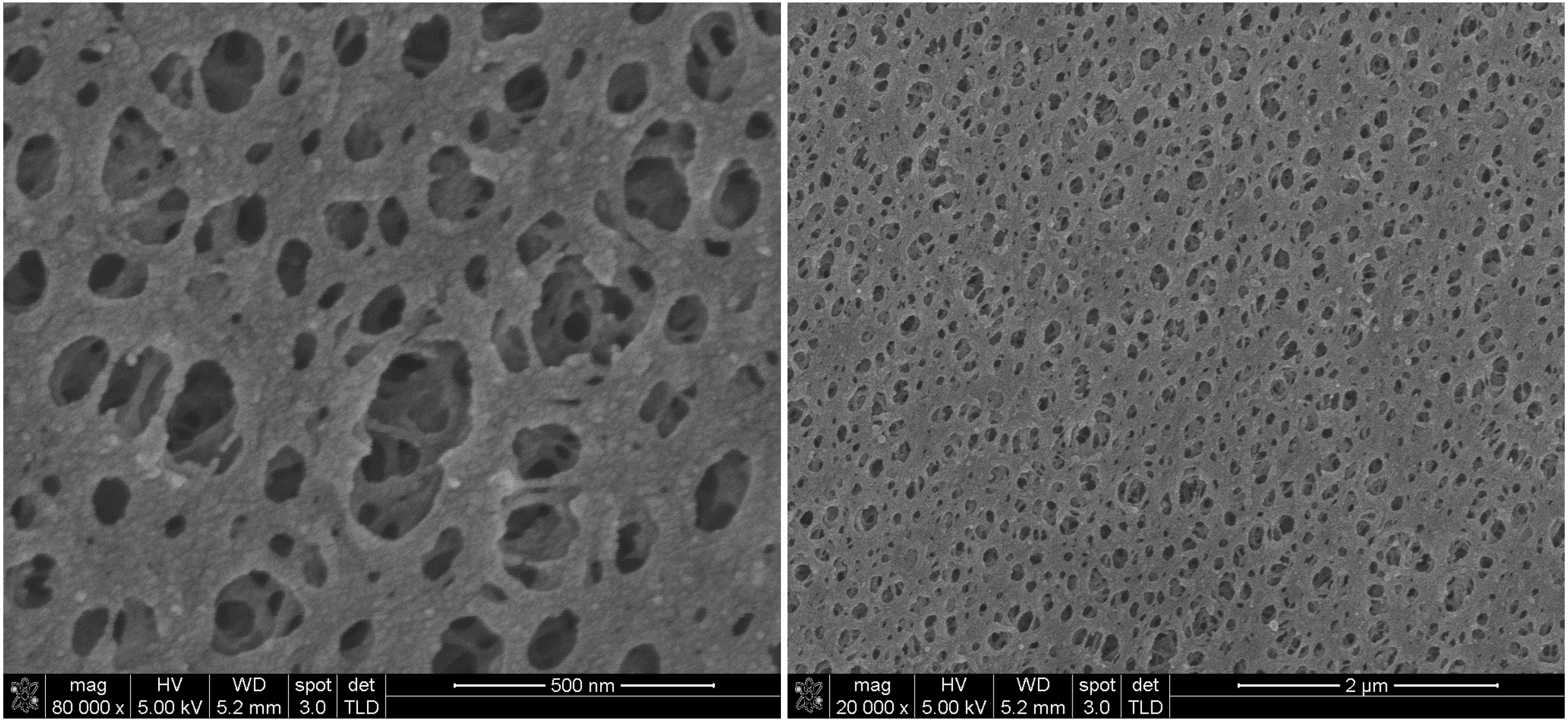


2500 feet fabricated

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

Successful Continuous Fabrication of Affordable PES Support

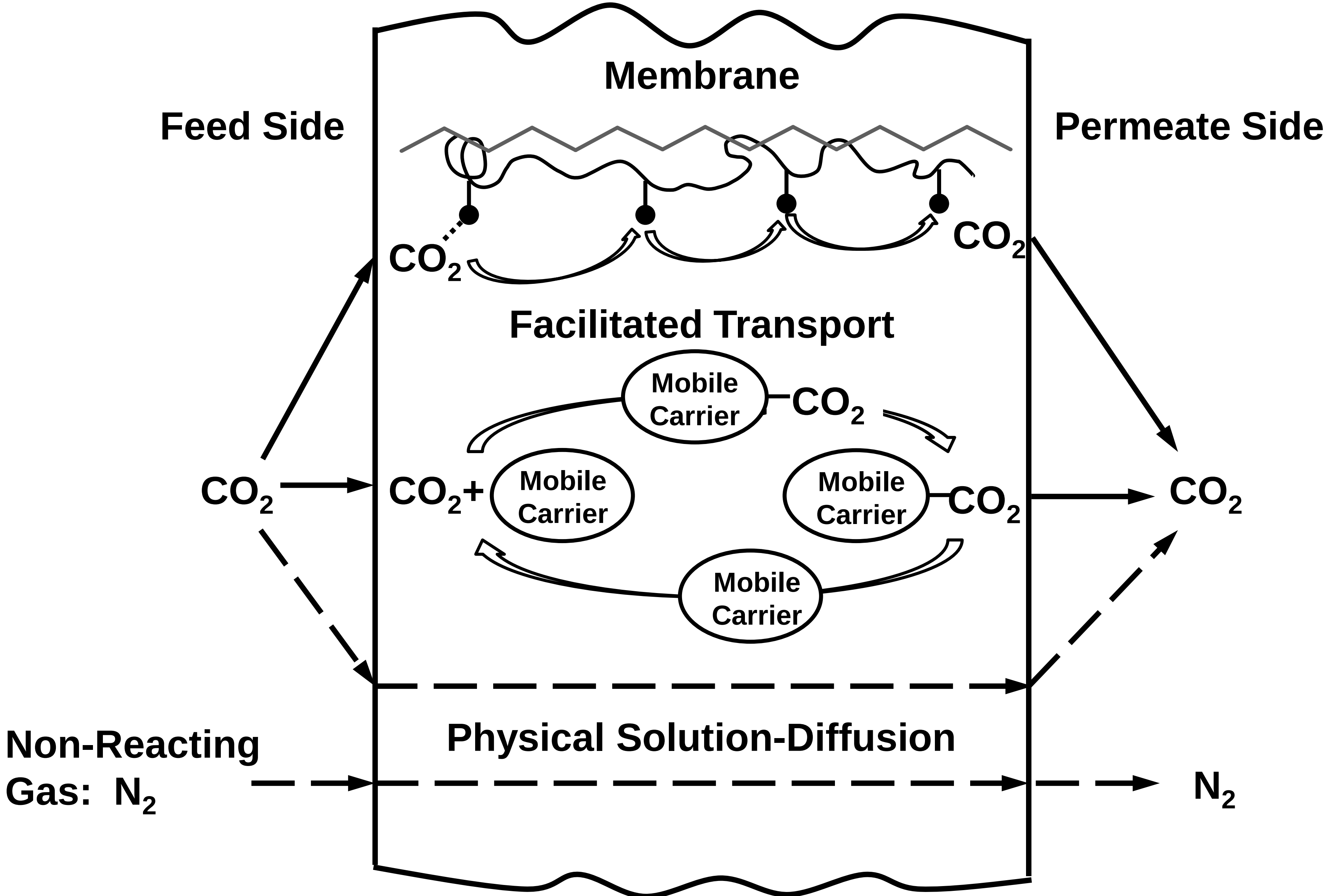
SEM Analysis of 14-inch PES Support



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

Will Improve Polymer Support for Higher Membrane Performance

Amine Polymer Layer Contains Mobile and Fixed Carriers: Facilitated Transport



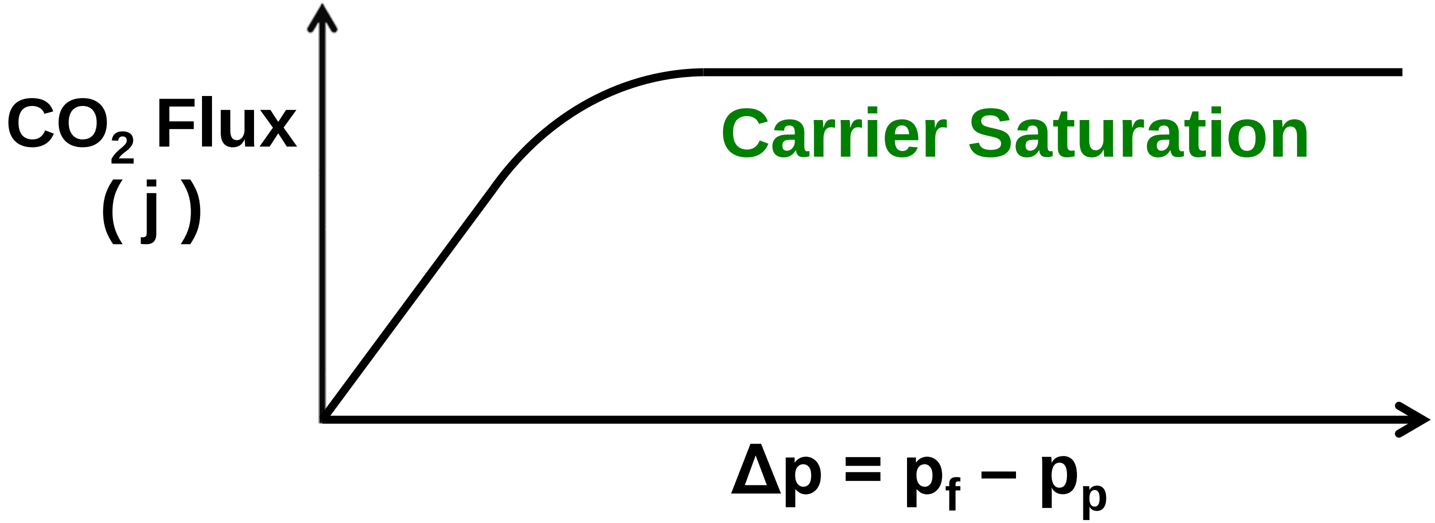
Facilitated Transport vs. Solution-Diffusion Mechanism

- **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

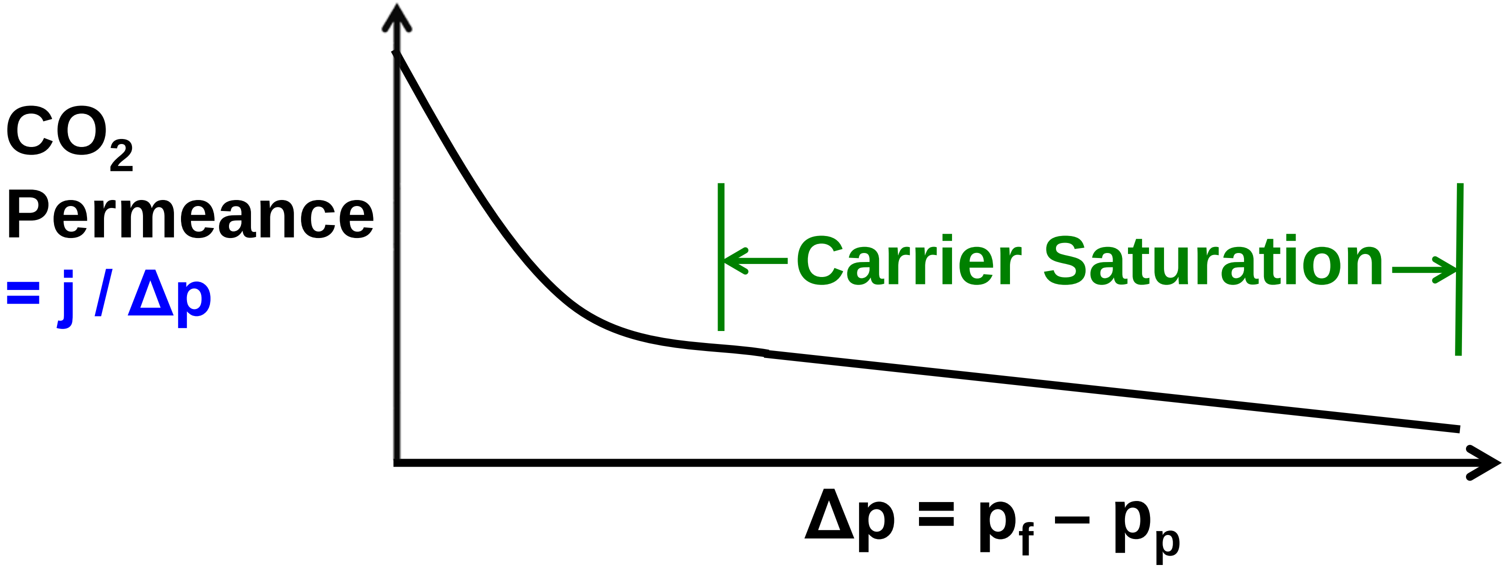
- **CO_2 Flux Increases as Pressure Increases until Carrier Saturation Occurs**



- **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)

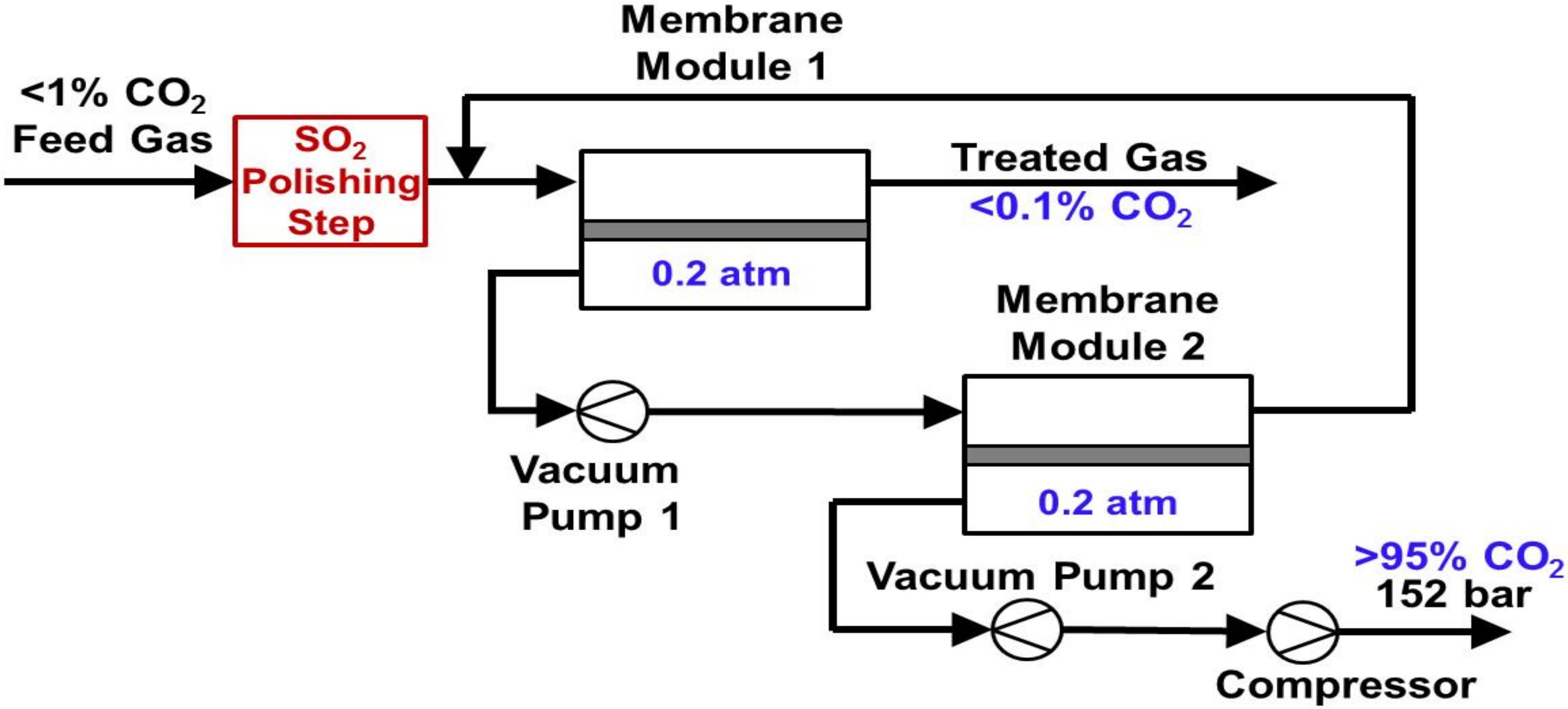
- **At Carrier Saturation (High CO_2 Pressure), i.e., Maximum, But Constant CO_2 Flux (j)**
  - CO_2 permeance reduces as pressure increases
  - That is: CO_2 permeance increases as pressure reduces



- **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

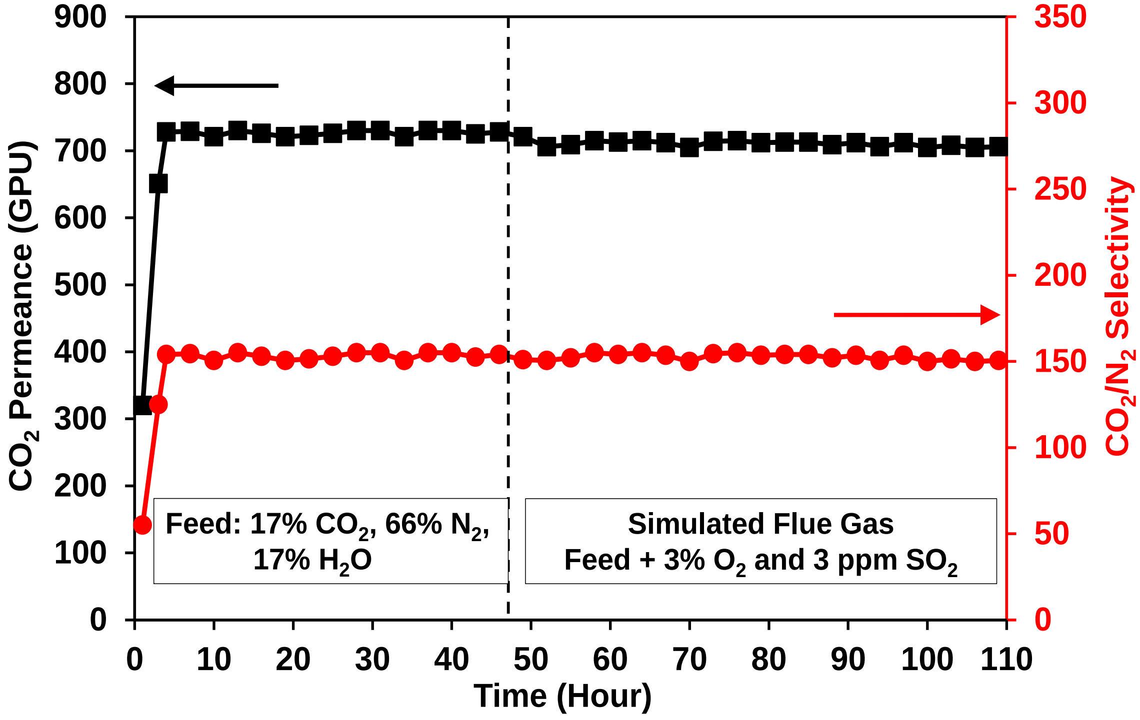
SO_2 Membrane Mitigation

- **Absorption into 20 wt% NaOH Solution**
  - **Polishing step based on NETL baseline document**
    - **Estimated to be about \$4.3/tonne CO_2 (in 2007 dollar, 6.5% COE increase)**
  - **Non-plugging, low-differential-pressure, spray baffle scrubber**
  - **High efficiencies (>95%)**



SO_2 Effects on Amine-containing Membranes

- **SO_2 Effects**
  - SO_2 permeated with CO_2
  - SO_2 at 1 – 3 ppm did not affect stability of membrane with amine cover layer



- **Propose SO_2 Polishing Step before membrane**
  - 1 – 3 ppm SO_2 in flue gas
  - Used in NCCC testing in 2015

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

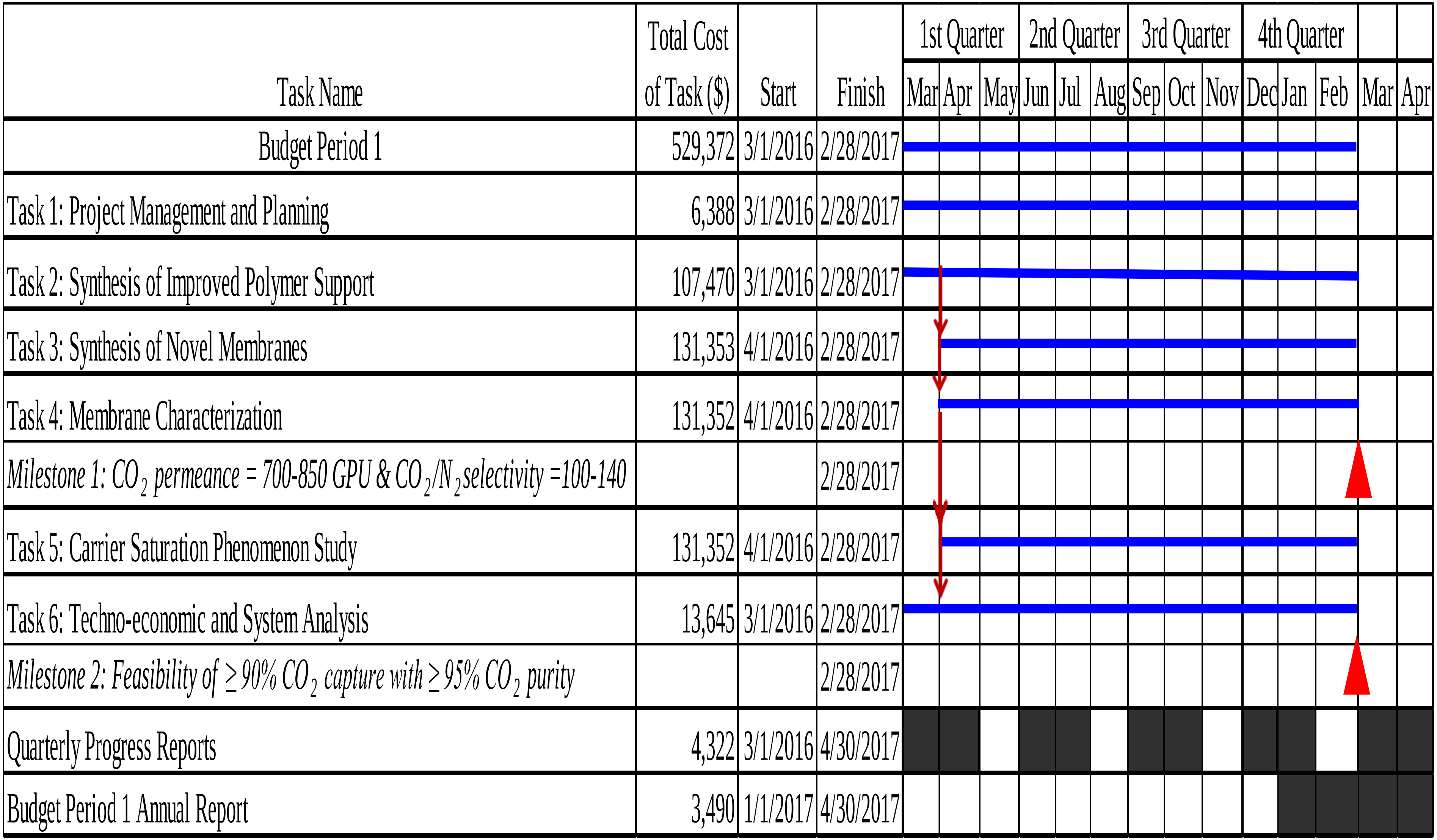
Success Criteria

- **BP1: 03/01/2016 – 02/28/2017**
  - **CO_2 permeance = 700 – 850 GPU**
  - **CO_2/N_2 selectivity = 100 – 140**

- **BP2: 03/01/2017 – 02/28/2018**
  - **CO_2 permeance = 850 – 1000 GPU**
  - **CO_2/N_2 selectivity = 100 – 140**

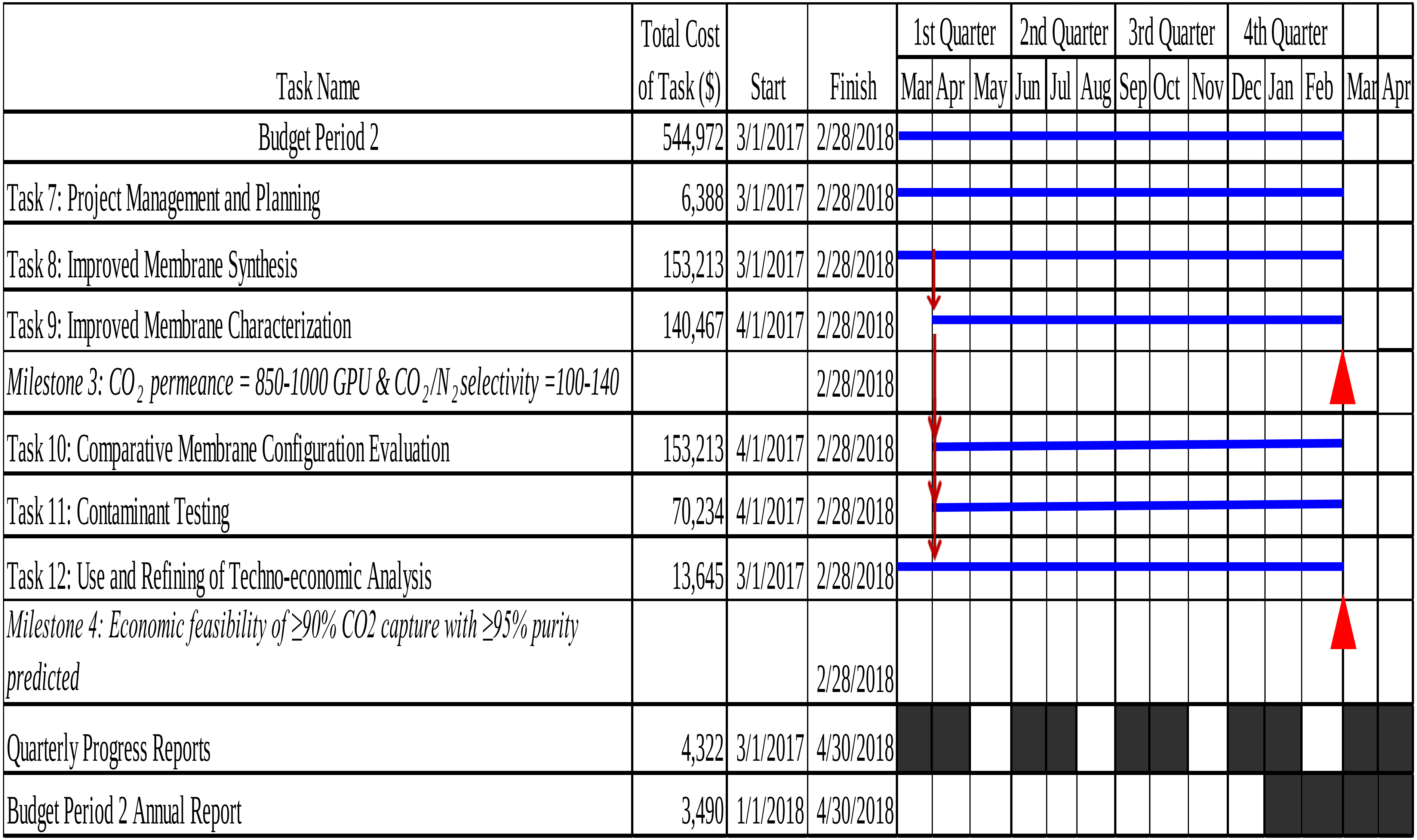
- **BP3: 03/01/2018 – 02/28/2019**
  - **CO_2 permeance = 1000 – 1800 GPU**
  - **CO_2/N_2 selectivity = 140 – 200**

Budget Period 1



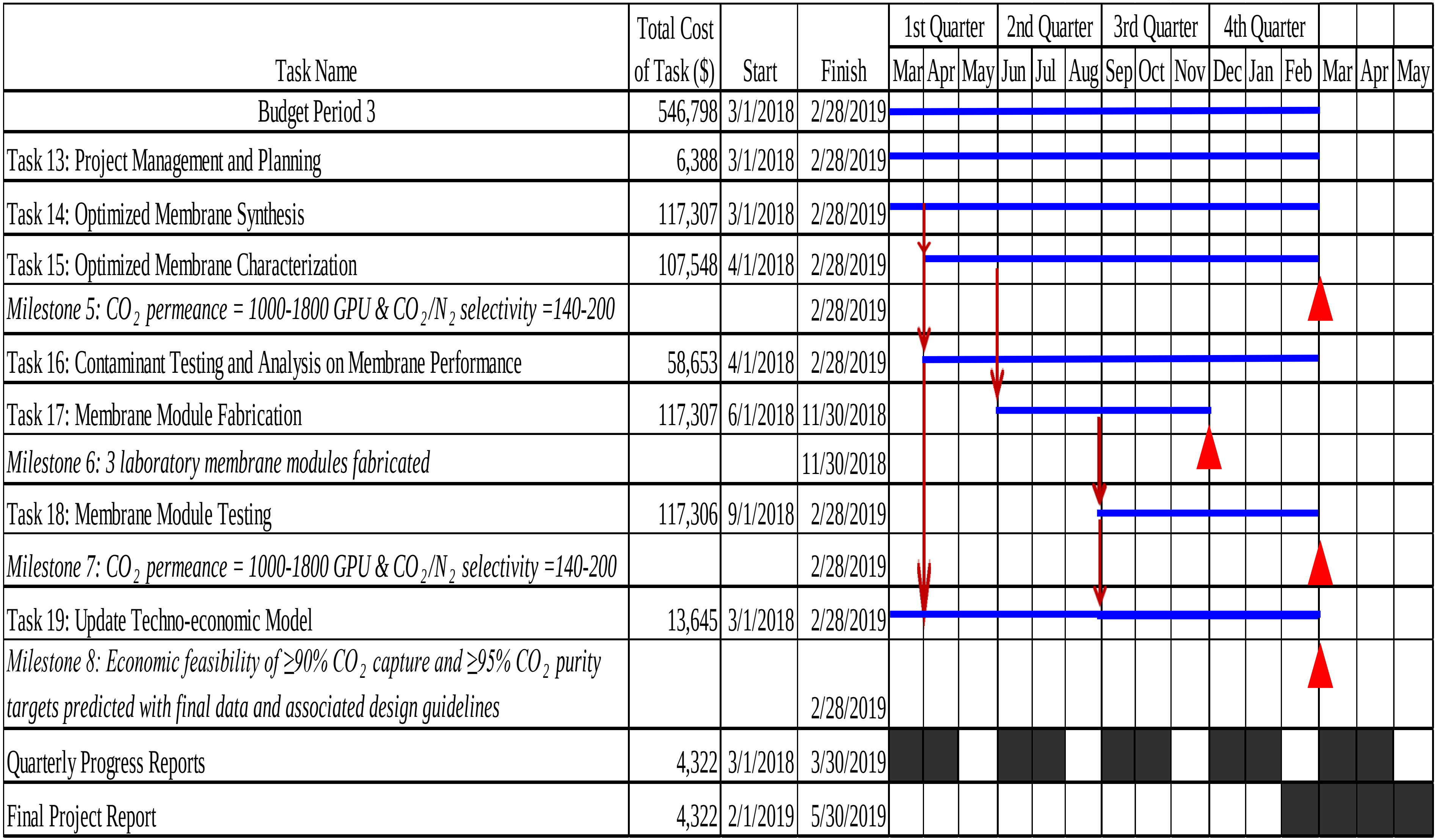
Task Name	Total Cost of Task ($)	Start	Finish	1st Quarter			2nd Quarter			3rd Quarter			4th Quarter				
				Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Budget Period 1	529,372	3/1/2016	2/28/2017	━	━	━	━	━	━	━	━	━	━	━	━		
Task 1: Project Management and Planning	6,388	3/1/2016	2/28/2017	━	━	━	━	━	━	━	━	━	━	━	━		
Task 2: Synthesis of Improved Polymer Support	107,470	3/1/2016	2/28/2017	━	━	━	━	━	━	━	━	━	━	━	━		
Task 3: Synthesis of Novel Membranes	131,353	4/1/2016	2/28/2017		━	━	━	━	━	━	━	━	━	━	━		
Task 4: Membrane Characterization	131,352	4/1/2016	2/28/2017		━	━	━	━	━	━	━	━	━	━	━		
Milestone 1: CO_2 permeance = 700-850 GPU & CO_2/N_2 selectivity =100-140			2/28/2017												▲		
Task 5: Carrier Saturation Phenomenon Study	131,352	4/1/2016	2/28/2017		━	━	━	━	━	━	━	━	━	━	━		
Task 6: Techno-economic and System Analysis	13,645	3/1/2016	2/28/2017	━	━	━	━	━	━	━	━	━	━	━	━		
Milestone 2: Feasibility of ≥90% CO_2 capture with ≥95% CO_2 purity			2/28/2017												▲		
Quarterly Progress Reports	4,322	3/1/2016	4/30/2017	■	■		■	■		■	■		■	■		■	■
Budget Period 1 Annual Report	3,490	1/1/2017	4/30/2017											■	■	■	■

Budget Period 2



Task Name	Total Cost of Task ($)	Start	Finish	1st Quarter			2nd Quarter			3rd Quarter			4th Quarter				
				Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
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	1st Quarter			2nd Quarter			3rd Quarter			4th Quarter					
				Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
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 laboratory 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												■	■	■	■

Past Work Facilitates Success of Current Project

- **PES Support Ready for Use/Improvement**
  - **Scale-up demonstrated in DE-FE0007632**
- **Amine Polymer Cover Layer can be Used as 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**