Development of Self-Assembly Isoporous Supports Enabling Transformational Membrane Performance for Cost Effective Carbon Capture (DE-FE0031596)

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Project Kick Off Meeting

WebEx

September 24, 2018

Outline

- Project overview slides
- Technology background
  - Composite Membranes
  - Support Membranes
  - Selective Materials
- Project tasks, timeline

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Project Overview

- **Award Name:** Development of Self-Assembly Isoporous Supports Enabling Transformational Membrane Performance for Cost Effective Carbon Capture (DE-FE0031596)
- **Project Period:** June 1, 2018 – May 31, 2021
- **Funding:** $2,905,620 DOE; $726,805 cost share (MTR and University of Buffalo)
- **DOE Project Manager:** José Figueroa, Bruce Lani
- **Participants:** Membrane Technology and Research, Inc., University of Buffalo
- **Project Objectives:**
  - Develop supports for composite membranes with highly regular surface pore structures that eliminate the restriction on diffusion in the selective layer that is present with current generation supports
  - Develop improved selective materials with higher permeance and/or higher selectivity compared to the current generation Polaris material
- **Project Plan:**
  - **BP1:** Lab-scale support development, screening of novel selective materials
  - **BP2:** Commercial-scale support development, scale up of 5 selective materials, composite membrane optimization
  - **BP3:** Commercial-scale composite membrane development, lab-scale module testing at MTR, bench-scale module test at NCCC

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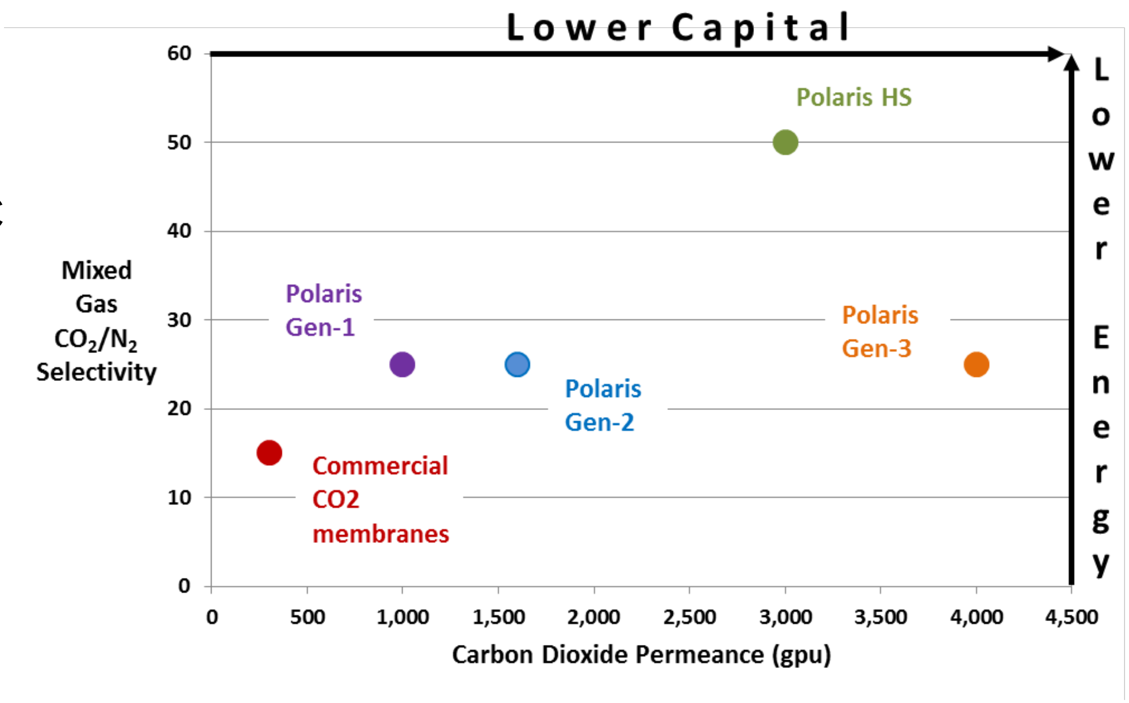
Project Success Criteria

1. Composite membranes produced with transformational performance, based on improved supports and improved selective materials

2. Membrane and modules fabricated at MTR, and tested at MTR and at NCCC

3. Techno-economic analysis validates that the goal of \$30/tonne CO_2 captured can be reached



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Project Objectives

Budget Period 1 (Year 1)

- Complete a detailed technology maturation plan for MTR Polaris membrane CO_2 capture technology showing a route to commercialization at $30/tonne CO_2.
- Composite membrane produced with dual-layer isoporous support and Polaris material has minimum mixed-gas performance values of CO_2 permeance = 3,000 gpu and CO_2/N_2 = 20.
- Films of transformational membrane materials (NYUB) have minimum pure-gas CO_2/N_2 selectivity = 50

Budget Period 2 (Year 2)

- Composite membrane produced with dual-layer isoporous support and Polaris material has minimum mixed-gas performance values of CO_2 permeance = 4,000 gpu and CO_2/N_2 = 25.
- Composite membrane produced with dual-layer isoporous support and NYUB material has minimum mixed-gas performance values of CO_2 permeance = 3,000 gpu and CO_2/N_2 = 40.
- Modules prepared with composite membranes and have pure-gas CO_2/N_2 selectivities within 10% of membrane selectivities.

Budget Period 3 (Year 3)

- Bench-scale system containing transformational membrane modules is built and testing completed at NCCC. System performance (CO_2 removal, pressure drops, etc) is consistent with modeling predictions and mixed-gas tests performed at MTR.
- Updated techno-economic analysis report completed; analysis includes transformational membrane properties developed in this project and confirms the potential to achieve $30/tonne CO_2.
- Complete a technology gap analysis report of the MTR Polaris membrane CO_2 capture process to determine components or systems that should be the focus of future development efforts.
- Environmental health and safety risk assessment report shows negligible chemical emissions due to the membrane capture system and >10% lower water usage compared to conventional capture technology.

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Roles of Participants

- **Membrane Technology and Research:**
  - Project lead and liaison with DOE
  - Development of isoporous supports and support scale up
  - Composite membrane development and testing
  - Membrane module development and testing, including at NCCC
- **University of Buffalo, New York University (Professor Lin):**
  - Development and testing of novel high ether content polymers
  - Supply of monomers and polymers to MTR
- **Professor Lynd (University of Texas at Austin):**
  - Consulting services on block copolymer chemistry and self-assembly

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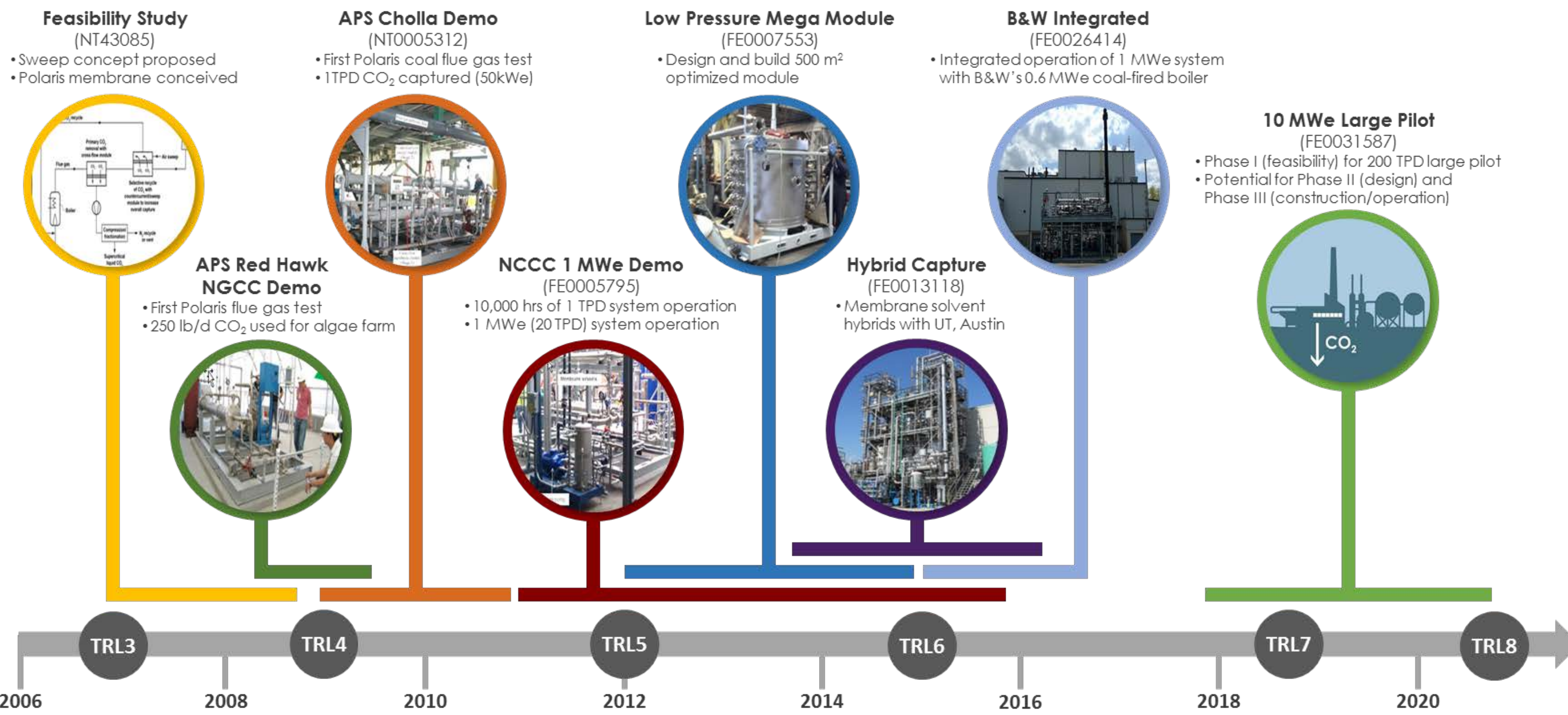
MTR/DOE CO_2 Capture Development Timeline



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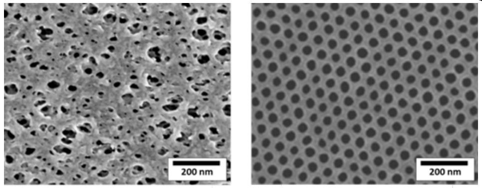
New MTR/DOE Projects

Self-Assembly Isoporous Supports, CA (DE-FE31596)

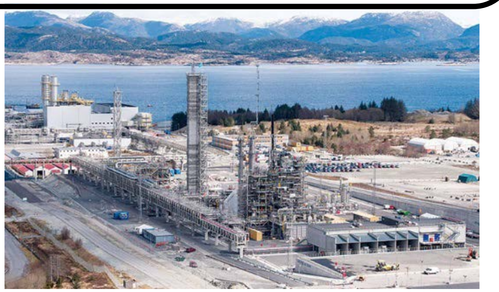
- Transformational new membrane (TRL 3 – 4)
- Reduces membrane area and energy use
- Build small system and test new membrane at NCCC



Surface of Conventional Support   Surface of Isoporous Support

Pilot Testing at TCM, Norway (DE-FE0031591)

- Advanced Gen 2 Polaris™ membrane and modules
- Containerized skid
- Partial capture for low cost-of-capture



Full-Scale FEED at Duke Energy's East Bend Station, KY (DE-FE31589)

- EPRI is lead
- 460 MWe – using Advanced Polaris™
- Partial capture / Rapid retrofit deployment

Large-Pilot Testing at WY ITC, WY (DE-FE31587)

- Phase I – Design ~16 MWe pilot; secure host site
- Phase II – FEED and permitting
- Phase III – Fabricate, install and operate (TRL 7 – 8)

2018 2019 2020 2021 2022 2023 2024 2025

Membrane Gas Separation Background

Membranes separate via selective permeation of molecules through a selective layer consisting of a polymer.

$$\text{Membrane Permeance} = \frac{\text{Permeability of Selective Layer}}{\text{Thickness of Selective Layer}}$$

$$\text{Membrane Selectivity for A over B} = \frac{\text{Permeance of A}}{\text{Permeance of B}}$$

Membrane Optimization:

- Select materials with high selectivities
- Select materials with high permeabilities
- Make the selective layer as thin as possible

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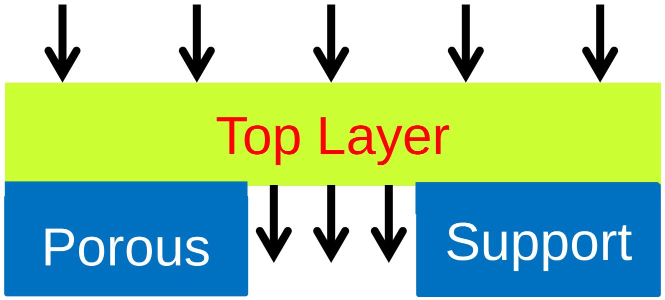
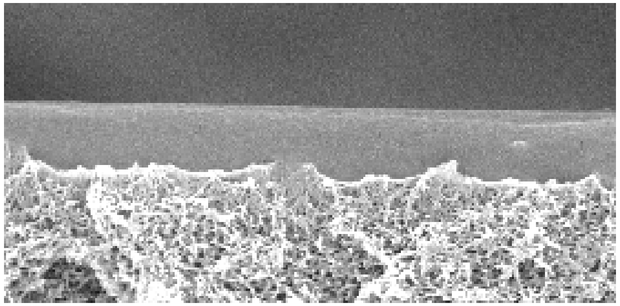
Influence of the Porous Support on Composite Membrane Performance





- Transport through the porous support membrane is only through the pore openings, which restricts the diffusion process in the top layer
- The porous support membrane itself is assumed to have negligible resistance to transport
- Lonsdale *et al* were the first to consider the pore restriction effect (“Transport in composite reverse osmosis membranes”, chapter in “Membrane Processes in Industry and Biomedicine”, M. Bier (Ed.), Plenum Press, New York, 1971)

Improving manufacturing techniques are producing very thin top layers

→

Restriction effect is becoming significant

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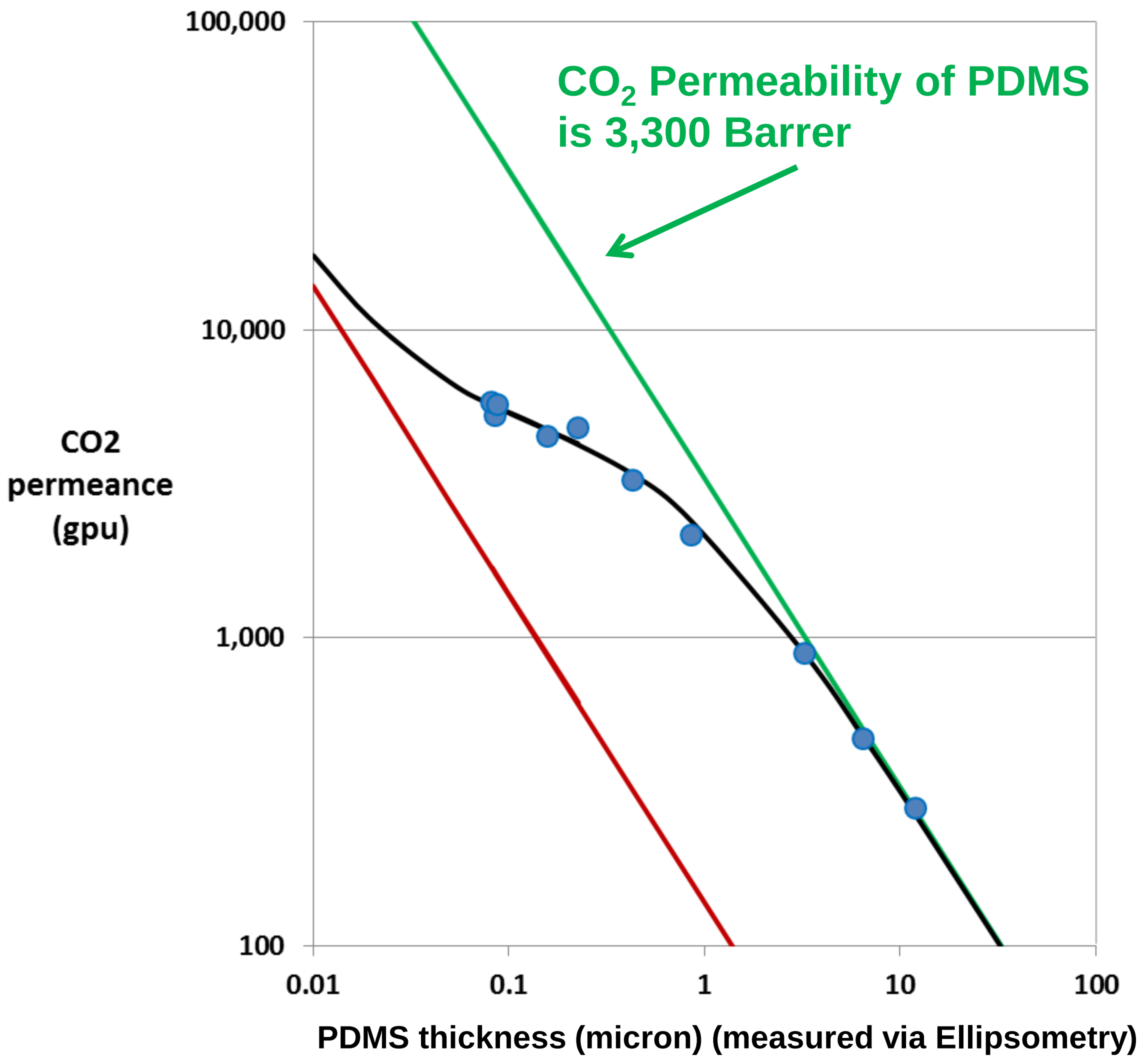
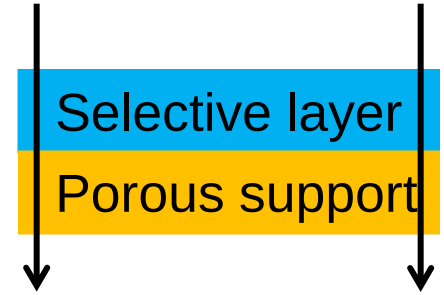
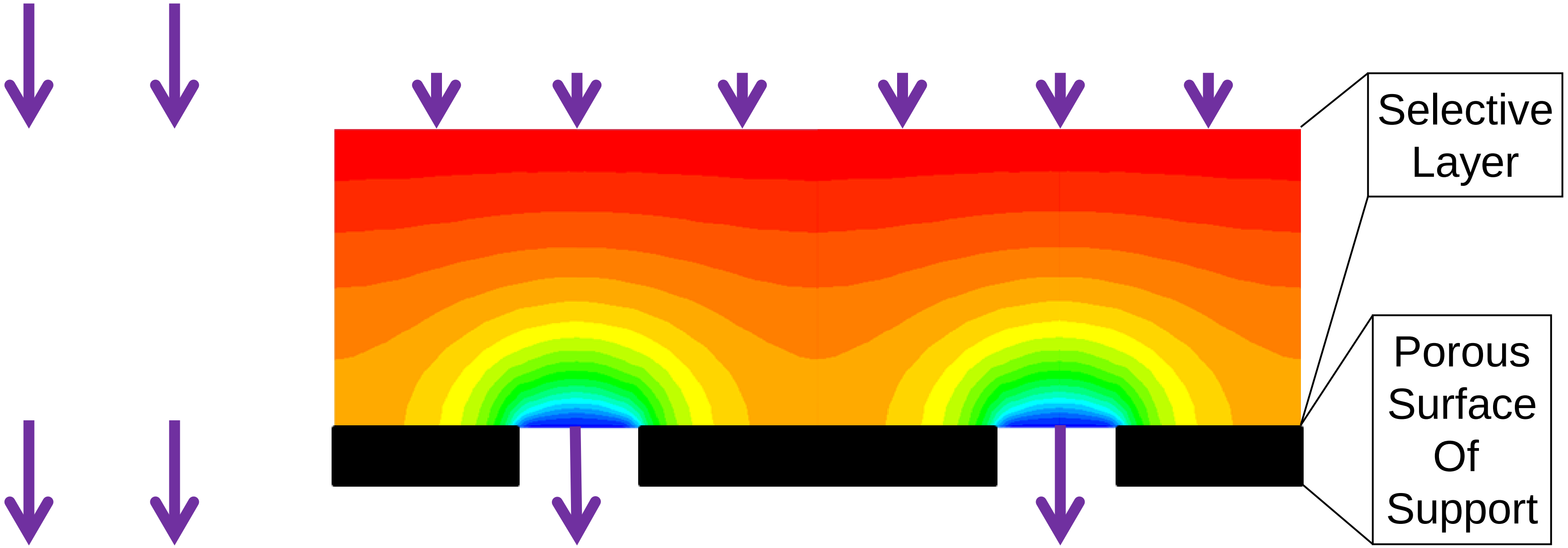
The Issue: Reducing the Thickness of the Selective Layer Improves Permeance, but Less than Expected





Influence of the support is significant for selective layers below 1 micron thickness

Analysis of Support Influence using Computational Fluid Dynamics



What the CDF results tell us:

- Currently used supports reduce membrane permeance by several factors if the selective layer is thinner than one micron
- Higher porosities and smaller pore sizes reduce this effect (as expected)
- Uniform distribution of the pores is VERY beneficial in reducing the effect (this is a new observation)

Highly Ordered Surfaces can be Obtained by Combining Self-Assembly and Phase Inversion

Asymmetric superstructure formed in a block copolymer via phase separation

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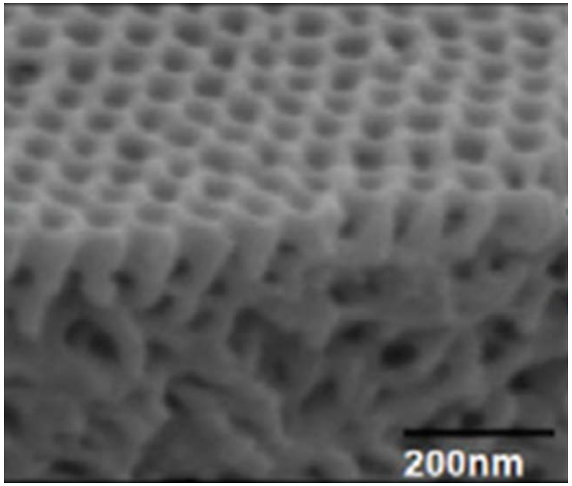
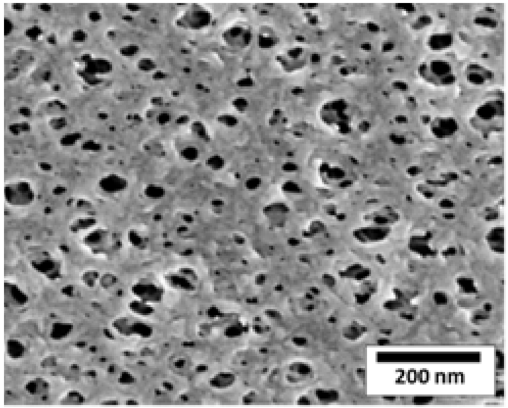
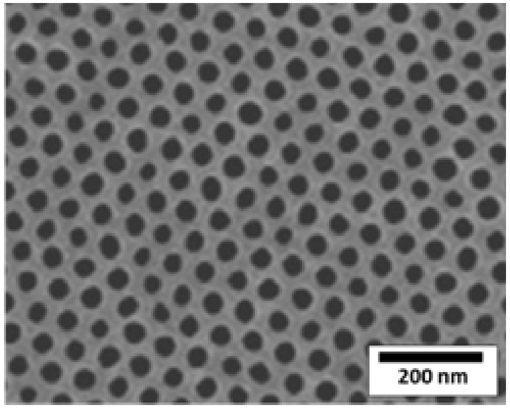


- Amphiphilic Block Copolymer in mixed solvent, evaporation step followed by immersion precipitation
- Creates top surface with highly ordered porous structure
- “Perfect” support for composite membranes, makes it possible to effectively use thinner selective layers, achieving higher membrane permeances

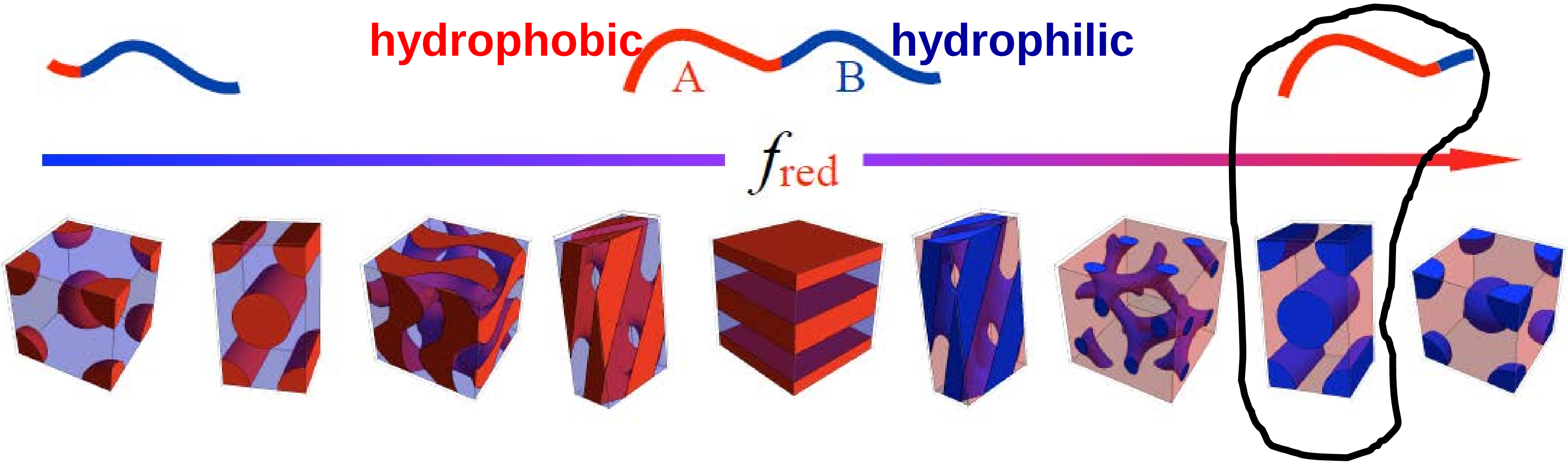


Surface of Conventional Support



Surface of Isoporous Support

Block Copolymer Self-Assembly



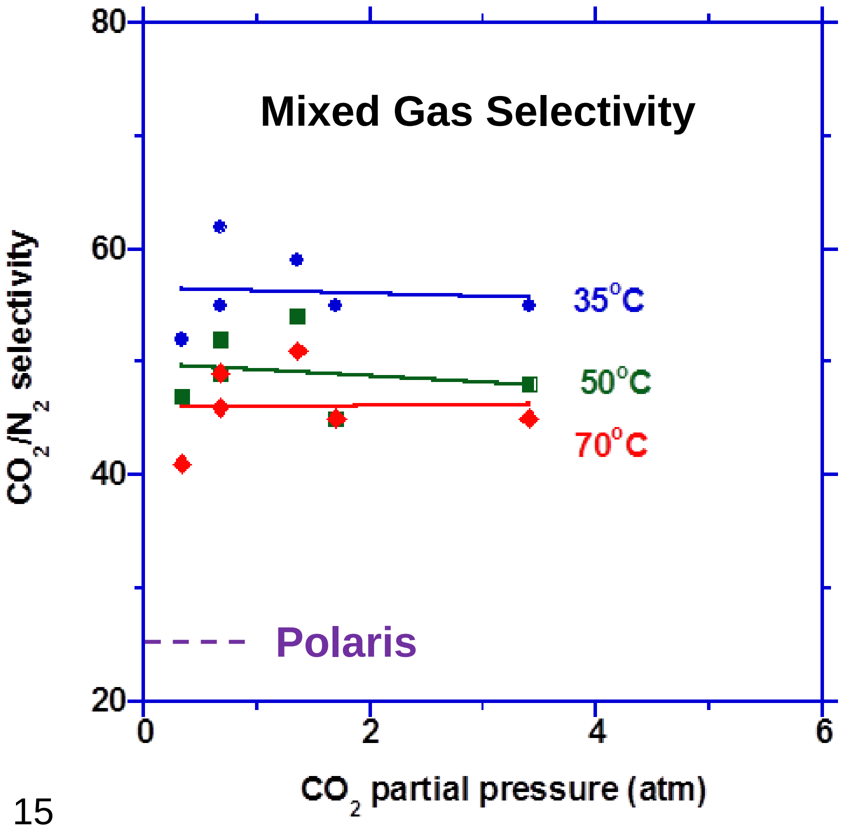
- Pores in the support are produced via immersion precipitation in water →

  → cylinders have to be formed by the hydrophilic block

  → hydrophilic block has to be the minority block (10 to 25 v%)

New Selective Materials (NYU Buffalo)

- Alternatively, improved supports will make it possible to use less permeable selective materials with higher selectivity, and to compensate for the lower permeability by making very thin selective layers.



- New polymer chemistries developed at University of Buffalo have high selectivities, even at high CO_2 partial pressures as well as at high temperatures
- Benefits:
  - Higher temperature operation in coal fired power plants
  - Reduced oxygen loss in sweep step
  - Higher pressure operation in gasification, steel and cement applications

Project Gantt Chart

Project Tasks	Start Date	End Date	4/1/2018 - 3/31/2019				4/1/2019 - 3/31/2020				4/1/2020 - 3/31/2021			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1. Project Management and Reporting	4/1/2018	3/31/2021												
Task 2. Develop Dual-Layer Isoporous Supports	4/1/2018	3/31/2020												
Task 2.1. Lab-scale Equipment	4/1/2018	3/31/2019												
Task 2.2. Commercial-scale Equipment	4/1/2019	3/31/2020												
Task 3. Develop Selective Materials with Improved Selectivity	4/1/2018	3/31/2021												
Task 3.1. Twenty materials, batch size 1 to 5 gram scale	4/1/2018	3/31/2019												
Task 3.1. Five materials, batch size 10 to 20 gram scale	4/1/2019	3/31/2020												
Task 3.1. Two materials, batch size 100 to 500 gram scale	4/1/2020	3/31/2021												
Task 4. Prepare and Test Composite Membranes with Isoporous Supports	7/1/2018	12/31/2020												
Task 4.1 Lab-scale Equipment	7/1/2018	3/31/2019												
Task 4.2 Commercial-scale Equipment	4/1/2019	3/31/2020												
Task 4.3 Membrane Runs for NCCC Modules	4/1/2020	12/31/2020												
Task 5. Prepare Modules and Test at MTR	4/1/2018	3/31/2020												
Task 5.1 Module Fabrication	4/1/2018	3/31/2019												
Task 5.2 Module Testing and Optimization	4/1/2019	3/31/2020												
Task 5.3 Continued Optimization and Modules for NCCC Test	4/1/2020	12/31/2020												
Task 6. Build Module Test Skid	4/1/2020	8/1/2020												
Task 7. Test Modules at NCCC	8/1/2020	1/31/2021												
Task 8. Prepare Techno-Economic Analysis	12/1/2020	3/31/2021												

NOTES: ▲ = Milestone

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Budget Summary

Section A - Budget Summary

	Grant Program Function or Activity	Catalog of Federal Domestic Assistance	Estimated Unobligated Funds		New or Revised Budget		
			Federal	Non-Federal	Federal	Non-Federal	Total
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
1.	Budget Period 1				$1,036,984	$272,186	$1,309,170
2.	Budget Period 2				$1,041,453	$226,851	$1,268,304
3.	Budget Period 3				$827,184	$227,768	$1,054,952
4.							
5.	Totals				$2,905,620	$726,805	$3,632,425

Section B - Budget Categories

6.	Object Class Categories	Grant Program, Function or Activity				Total (5)
		Budget Period 1	Budget Period 2	Budget Period 3		
	a. Personnel	$309,148	$267,110	$264,577		$840,835
	b. Fringe Benefits	$0	$0	$0		$0
	c. Travel	$7,143	$7,143	$21,703		$35,988
	d. Equipment	$128,074	$213,330	$70,000		$411,404
	e. Supplies	$94,000	$94,000	$34,000		$222,000
	f. Contractual	$152,509	$152,501	$131,518		$436,528
	g. Construction	$0	$0	$0		$0
	h. Other	$0	$0	$4,000		$4,000
	i. Total Direct Charges (sum of 6a-6h)	$690,874	$734,084	$525,798		$1,950,755
	j. Indirect Charges	$618,296	$534,220	$529,154		$1,681,670
	k. **Totals** (sum of 6i-6j)	$1,309,170	$1,268,304	$1,054,952		$3,632,425
7.	Program Income					$0

Project Milestones

Milestone Number	Task/ Subtask No.	Milestone Description	Planned Completion Date (*)	Verification Method
Budget Period 1				
1	1	Complete Updated Project Management Plan	5/1/18	Revised PMP
2	1	Complete Technology Maturation Plan	6/30/18	Topical Report
3	2	Dual Layer Isoporous Supports Produced on Lab Casting Equipment	3/31/2019	Quarterly Report
Budget Period 2				
4	2	Dual Layer Isoporous Supports Produced on Commercial Casting Equipment	9/30/2019	Quarterly Report
5	3	Membrane materials selected for scale-up production	12/31/2019	Quarterly Report
6	4,5	Thin film composite membrane and module design chosen for use in field test	3/31/2020	Quarterly Report
Budget Period 3				
7	7	Test System Commissioned on Flue Gas	7/31/20	Quarterly Report
8	7	Field Test at NCCC Completed	1/31/21	Quarterly Report
9	8	Complete Techno-Economic Analysis Report	3/31/21	Topical Report
10	1	Complete Technology Gap Analysis Report	3/31/21	Topical Report
11	1	Complete Environmental Health and Safety Risk Assessment Report	3/31/21	Topical Report
12	1	Submit Final Report	3/31/21	Final Report

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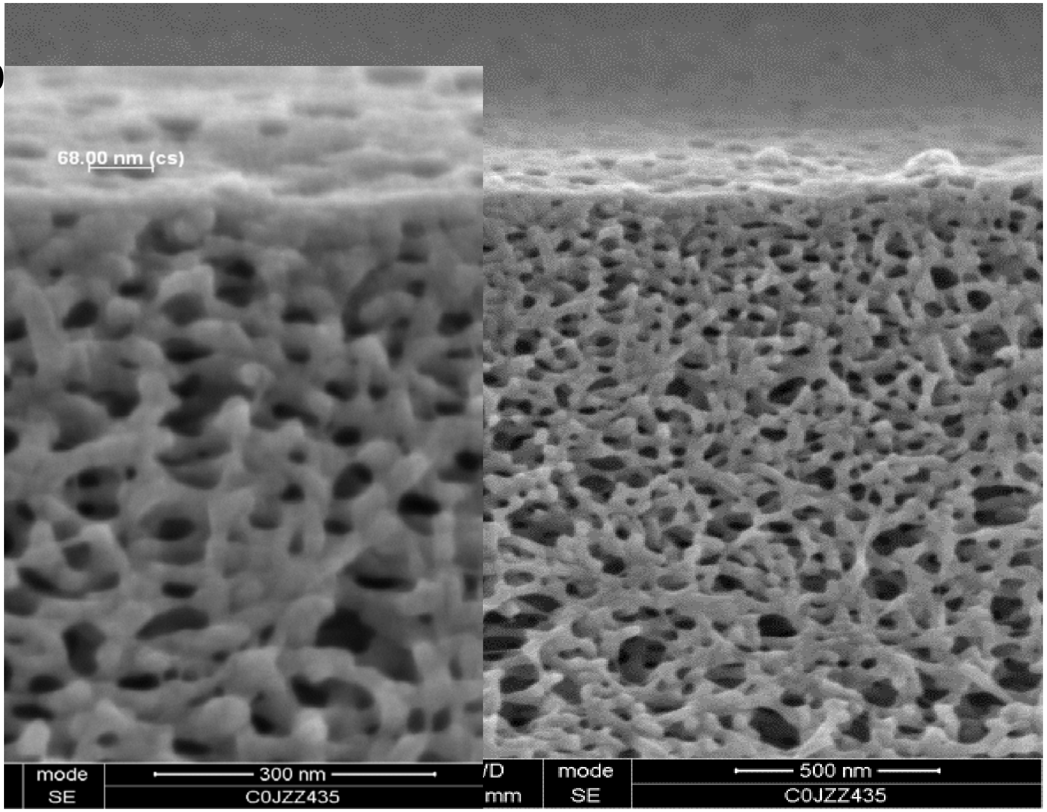
Project Status

- Project started three months ago
- Purchased commercially available block copolymers
- Produced the first examples of block copolymer phase inversion at MTR



- University of Buffalo has started synthesis of the novel selective materials
- First batch has been delivered to MTR

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Acknowledgements

- **U.S. Department of Energy,**
  National Energy Technology Laboratory
  - José Figueroa
  - Bruce Lani

- University of Buffalo