Composite Hollow Fiber Membranes for Post Combustion CO_2 Capture

2013 North American Membrane Society Meeting

Membranes for CO_2 Capture Session

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Acknowledgment

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Project Team

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CO_2 Capture Membranes Technology

Key Challenges

Post-Combustion Carbon Capture Technology

Potential Solution

Hybrid Membrane + Cryogenic Process

CO_2 Capture Membranes Technology

Key Challenges

Post-Combustion Carbon Capture Technology

- Increase in cost of electricity (COE)

Potential Solution

Hybrid Membrane + Cryogenic Process

- Reduce membrane CAPEX
  - ↓ Membrane module cost
  - ↑ Permeance
- Reduce cryogenic CAPEX
  - ↑ Membrane selectivity

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CO_2 Capture Membranes Technology

Key Challenges

Post-Combustion Carbon Capture Technology

- Increase in cost of electricity (COE)
- Low membrane driving force
  - Low CO_2 concentration
  - Low feed gas pressure

Potential Solution

Hybrid Membrane + Cryogenic Process

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- Reduce cryogenic CAPEX
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- Increase driving force
  - ↑ CO_2 concentration
  - ↑ Pressure ratio

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CO_2 Capture Membranes Technology

Key Challenges

Post-Combustion Carbon Capture Technology

- Increase in cost of electricity (COE)
- Low membrane driving force
  - Low CO_2 concentration
  - Low feed gas pressure
- Large feed flow rates
  - Large capture system

Potential Solution

Hybrid Membrane + Cryogenic Process

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- Increase driving force
  - ↑ CO_2 concentration
  - ↑ Pressure ratio
- Scalable system
  - Composite Hollow fiber membranes

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CO_2 Capture Membranes Technology

Key Challenges

Post-Combustion Carbon Capture Technology

- Increase in cost of electricity (COE)
- Low membrane driving force
  - Low CO_2 concentration
  - Low feed gas pressure
- Large feed flow rates
  - Large capture system
- Membrane stability
  - Water vapor
  - SO_2, NO_x
  - Fly-ash

Potential Solution

Hybrid Membrane + Cryogenic Process

- Reduce membrane CAPEX
  - ↓ Membrane module cost
  - ↑ Permeance
- Reduce cryogenic CAPEX
  - ↑ Membrane selectivity
- Increase driving force
  - ↑ CO_2 concentration
  - ↑ Pressure ratio
- Scalable system
  - Composite Hollow fiber membranes
- Robust membrane material
  - Polyphosphazene polymers
  - HF module cleaning methods

Project Summary

- 3-year, $3M program, 20 % cost share from GE
- Budget period 1: October 2011 – June 2013
- Budget period 2: June 2013 – September 2014

Project Objective: Develop bench-scale thin film coated composite hollow fiber membrane materials and processes for CO_2/N_2 separation in coal flue-gas at 60 °C with at least 90% CO_2 capture with less than 35% increase in levelized cost of electricity

GE Global Research
- Hollow fiber fabrication & characterization
- Module design
- Technical & economic feasibility analysis

Idaho National Laboratory
- Polymer development
- Polymer property optimization
- Coating solution development

Georgia Institute of Technology
- Fiber coating process development
- Effect of fly ash on membranes
- Modeling of key membrane properties

Western Research Institute
- Membrane performance validation in coal flue-gas

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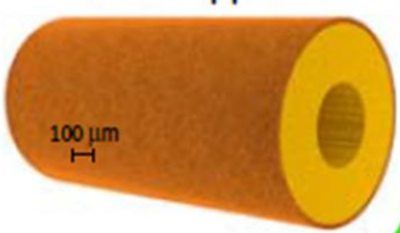
Technology Overview

Develop thin film polymer composite hollow fiber membranes & processes for economical post-combustion CO_2 capture

Idaho National Laboratory

High Performance Polymer Coating Solution

High Porosity Hollow Fiber Support



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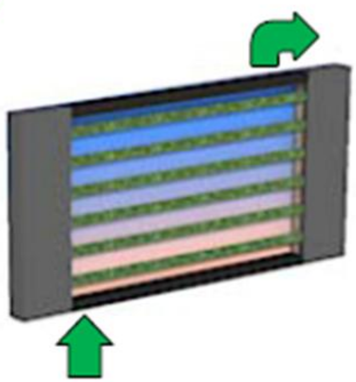
Defect-Free Composite Hollow-Fiber Coating Processes



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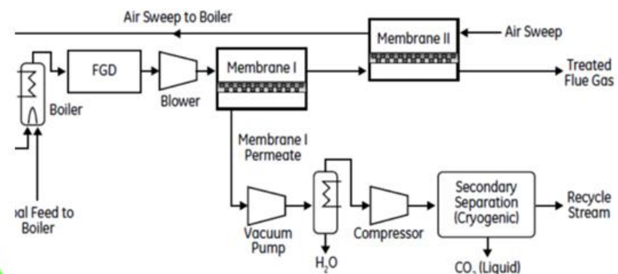
Process and Economic Analysis



Membrane Testing in Flue Gas

Western Research Institute

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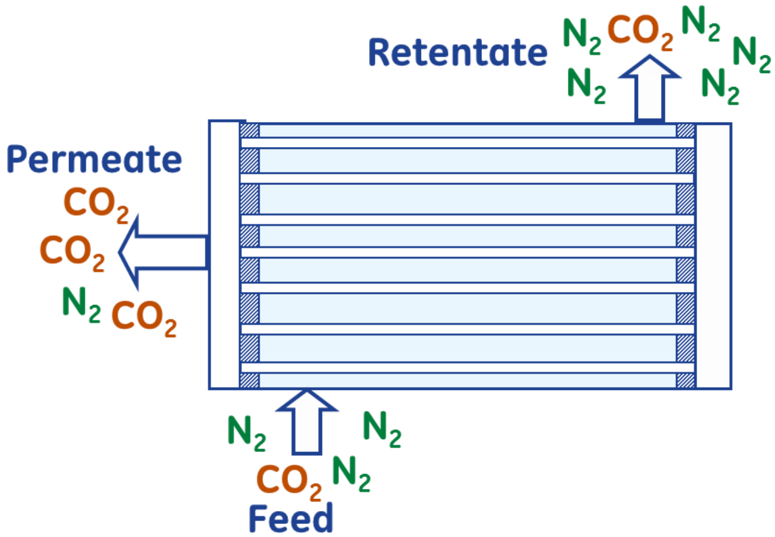
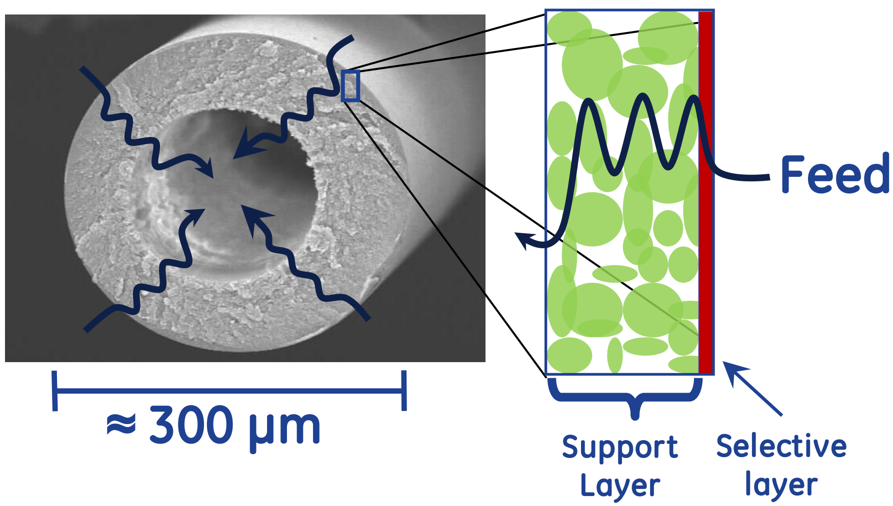
Gas Separations Membrane Fundamentals





Schematic representation of post-combustion CO_2 capture using hollow fiber membranes

Permeance (Productivity)

$$P_{CO2} = D_{CO2} * S_{CO2} = \frac{(Flux)_{CO2} \cdot \ell}{\Delta p_{CO2}}$$

$$\frac{P_{CO2}}{\ell} [=] 1\,GPU = 10^6 \frac{cm^3(STP)}{cm^2.s.cmHg}$$

Selectivity (Purity)

$$\alpha_{CO2\text{-}N2} = \frac{P_{CO2}}{P_{N2}}$$

Solution–Diffusion Process

Gases dissolve in and then diffuse through a membrane

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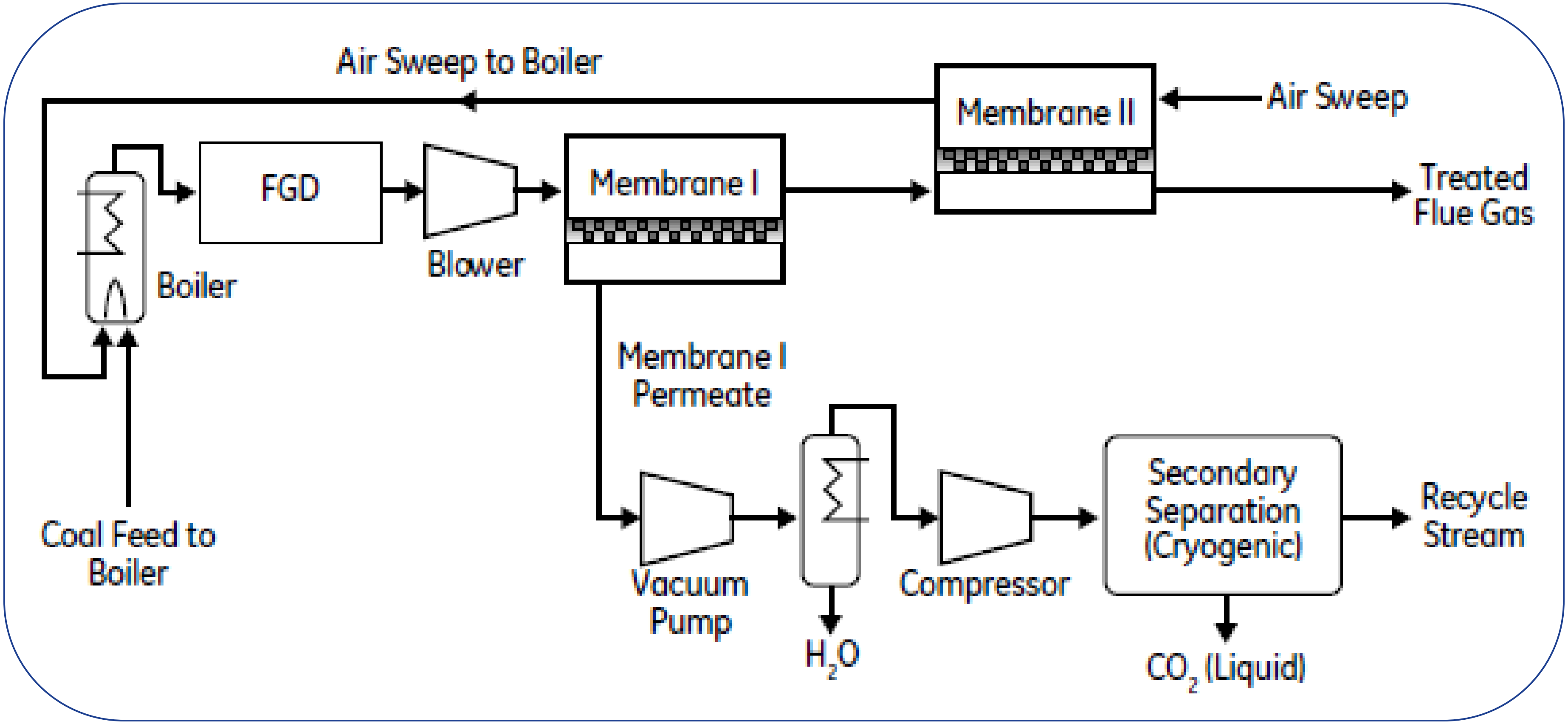
Membrane Systems Considerations



Schematic representation of the membrane process*

- Various membrane process designs considered
- Two stage membrane process shortlisted for further discussion

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*Adapted from Merkel, Tim C., et al. "Power plant post-combustion carbon dioxide capture: An opportunity for membranes." Journal of Membrane Science 359.1 (2010): 126-139.

Membrane Systems Considerations

Parameter	Values
Membrane-I/Membrane-II	Vacuum/air sweep
Flue gas composition	DOE baseline case 11* $CO_2/N_2/H_2O/O_2$(vol.%) 13.53/68.08/15.17/2.40
Flue gas flow rate	540 m^3/s
Flue gas pressure	1.2-3 Bar
Flue gas temperature	45 °C
Membrane Selectivity (CO_2/N_2)	30-80
Membrane Permeance	100-2500 GPU

Summary of economic model assumptions

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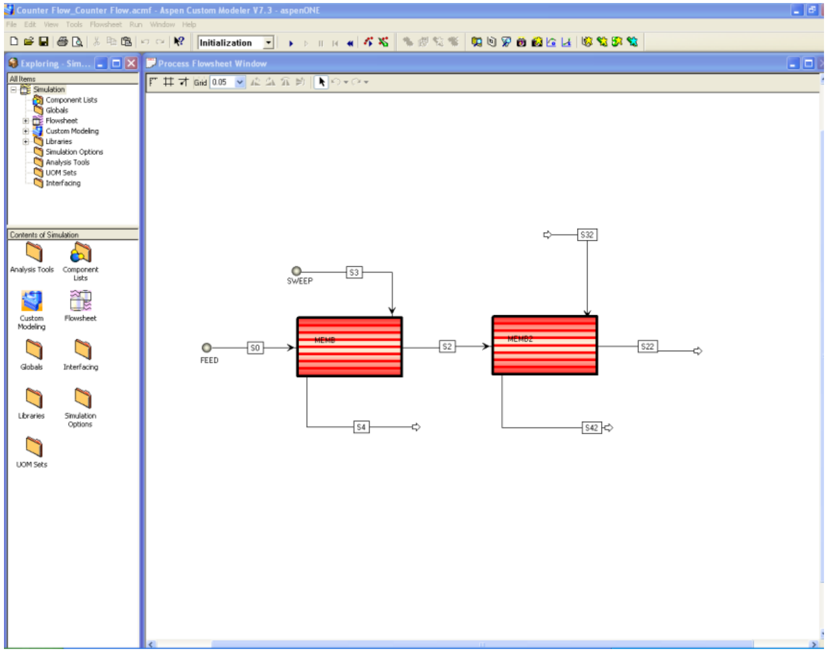
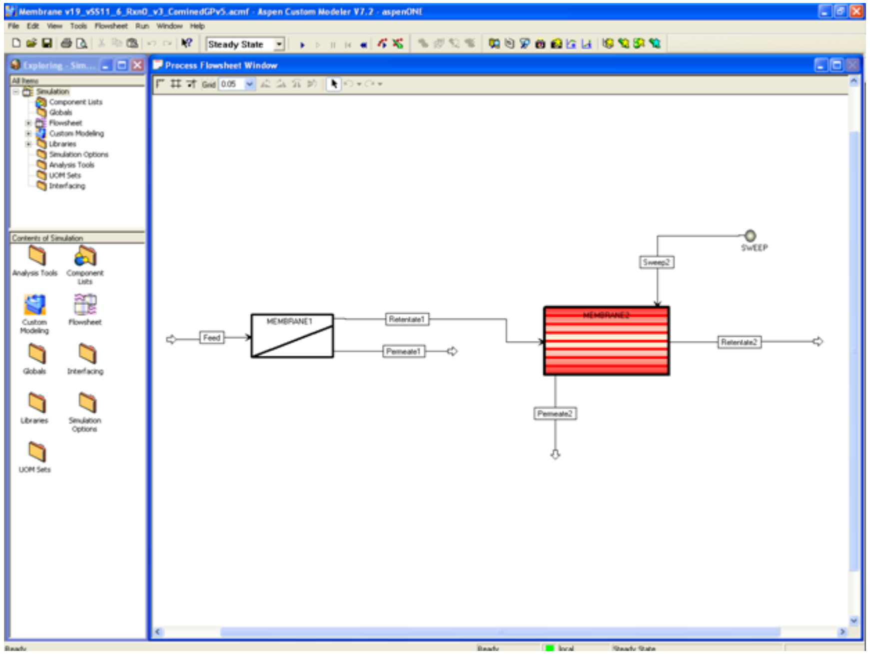
*Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, November 2010.,DOE/NETL-2010/1397

Membranes Systems Model



Aspen custom model® of counter-current/counter-current membranes



Aspen custom model® of cross-current/counter-current membranes

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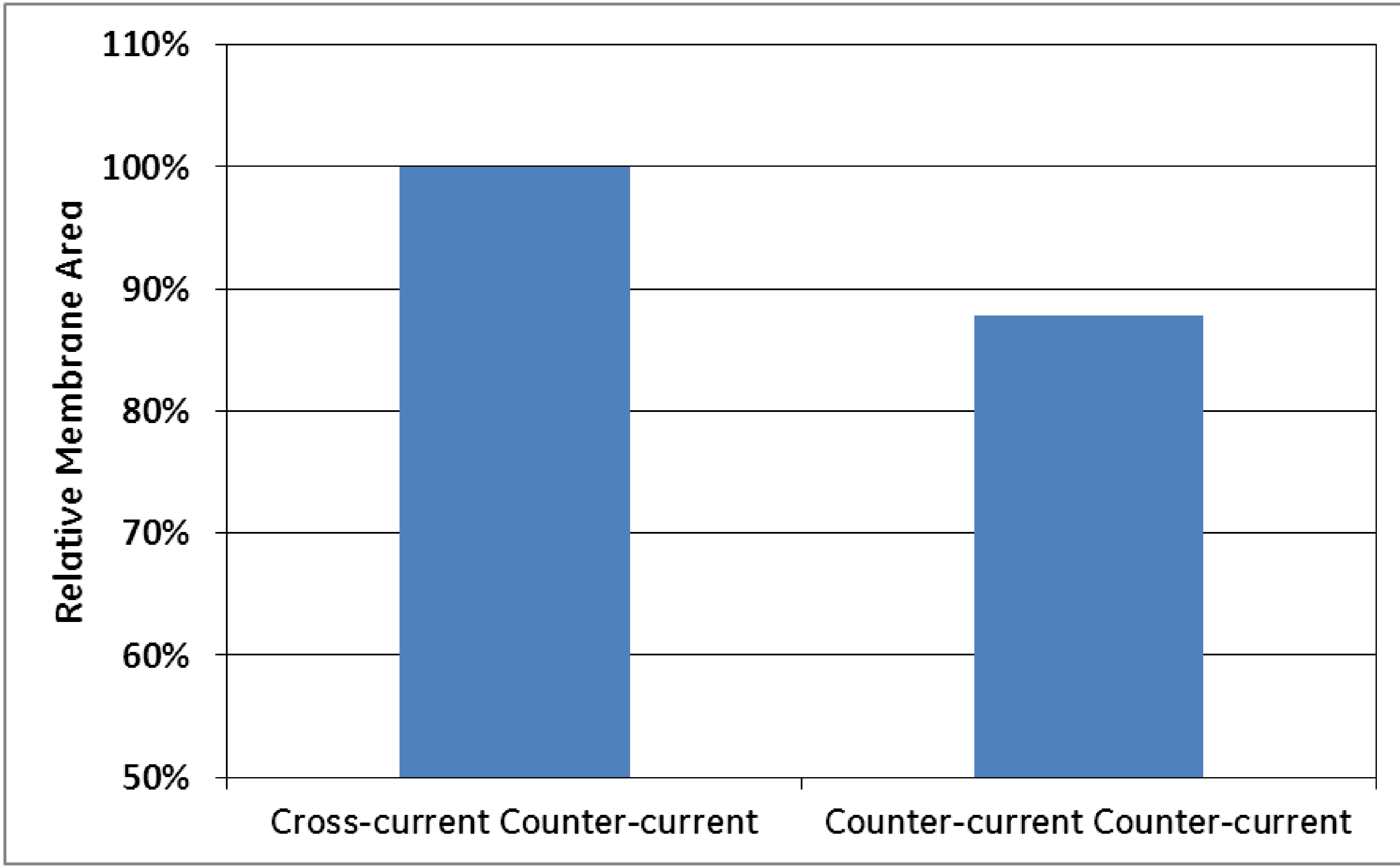
Membranes Model Analysis

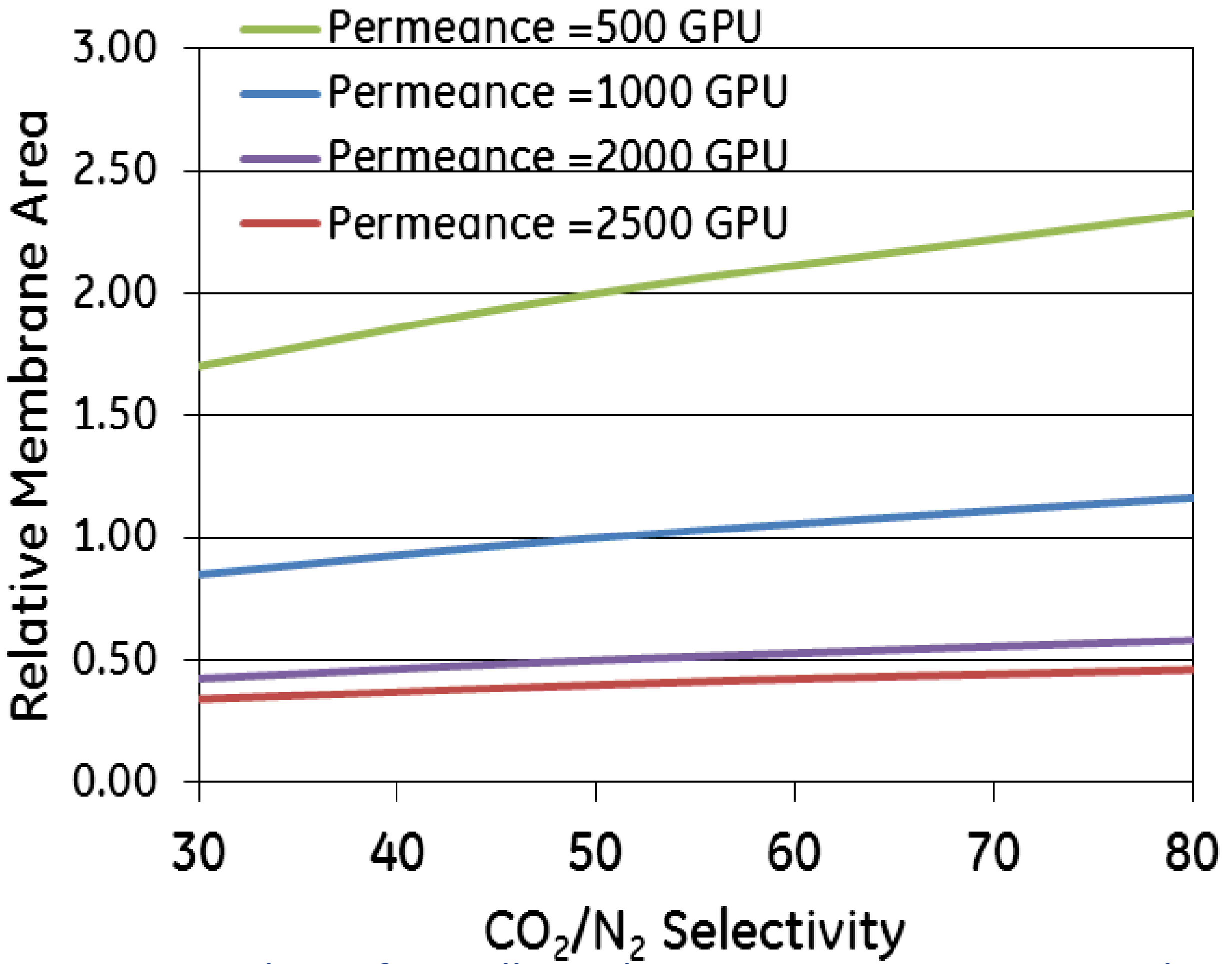


Comparison of membrane configurations

- Counter-current/counter-current configuration preferable

*Assumptions – Membrane-I pressure ratio = 10, $Selectivity_{CO2/N2}$= 50, $Permeance_{CO_2}$ = 1000 GPU

Membranes Model Analysis



Sensitivity analysis of overall membrane area to permeance & selectivity*

- Overall membrane area highly dependent on permeance and mildly on selectivity in the selected range

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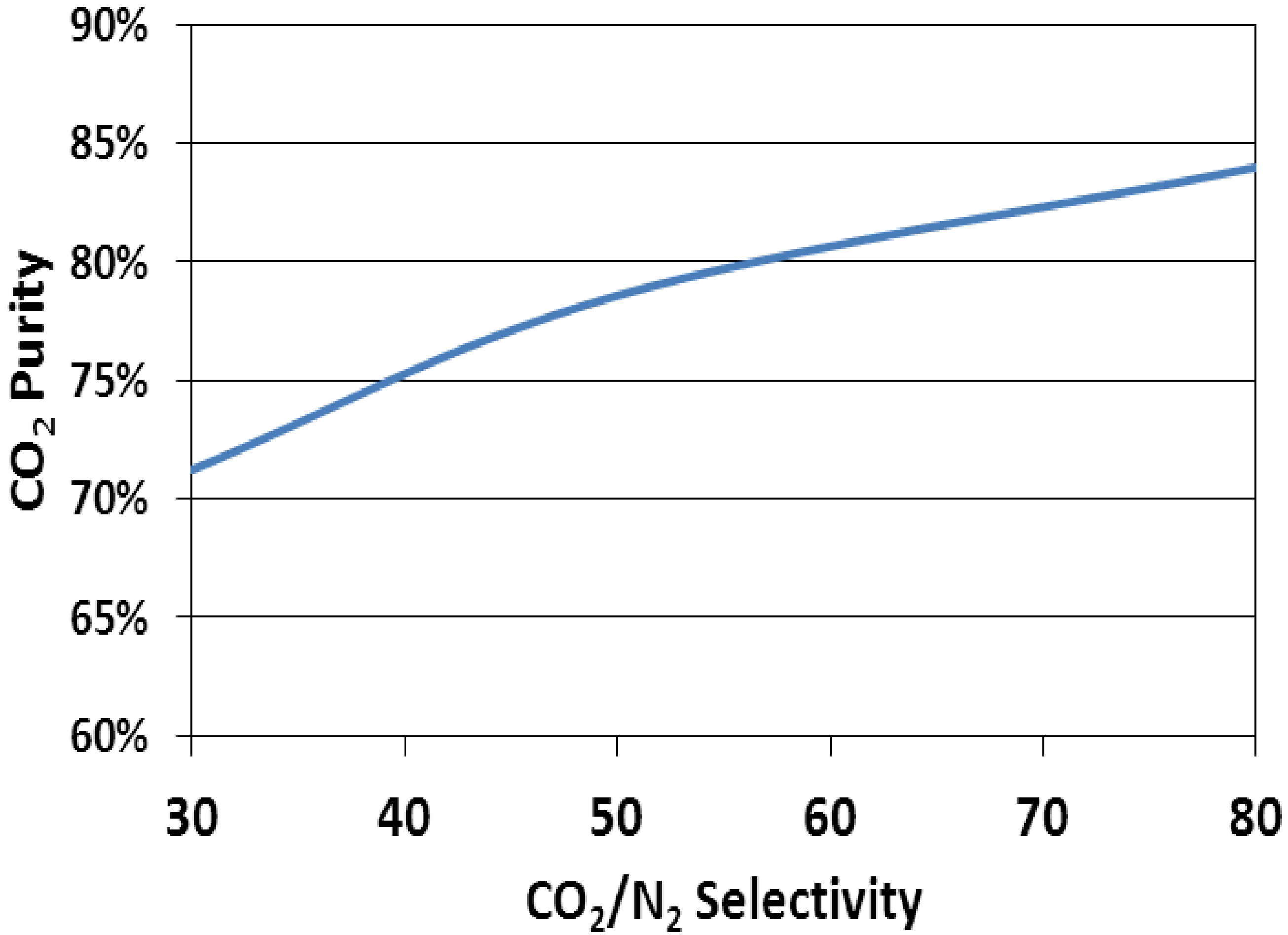
*Assumptions – Counter/counter-current membranes, membrane-I pressure ratio = 10

Membranes Model Analysis

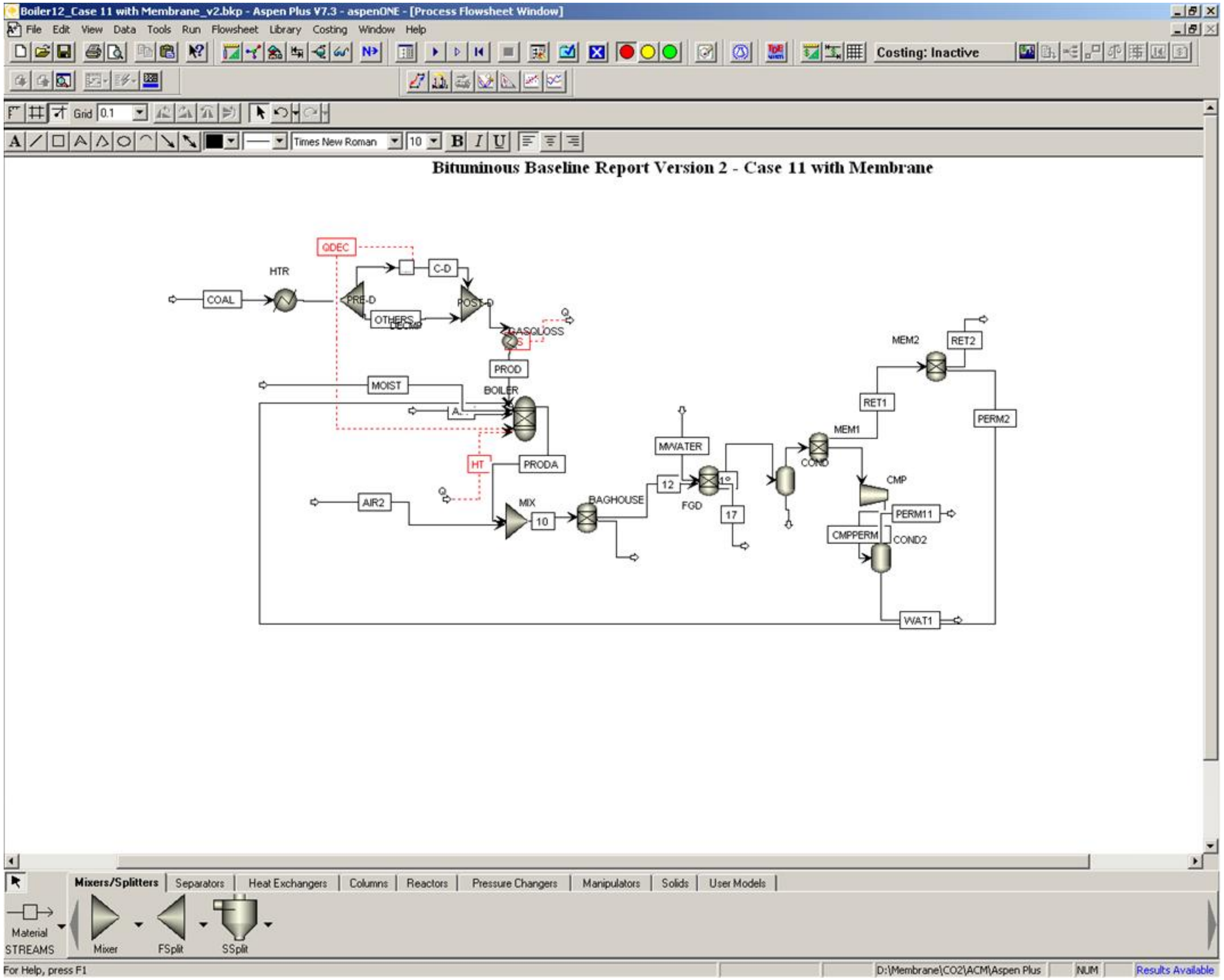


Sensitivity analysis of membrane process CO_2 purity to selectivity

- Overall membranes process CO_2 purity strongly dependent on selectivity

*Assumptions - Counter/counter-current membranes, membrane-I pressure ratio = 10

Overall Membranes System Analysis



Aspen Plus® systems model of PC-boiler integrated with CO_2 capture membranes model

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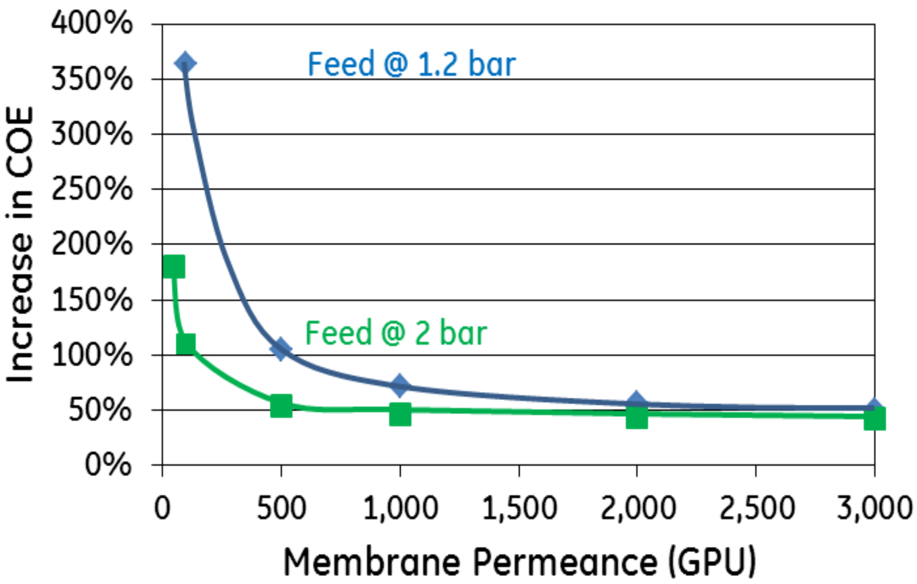
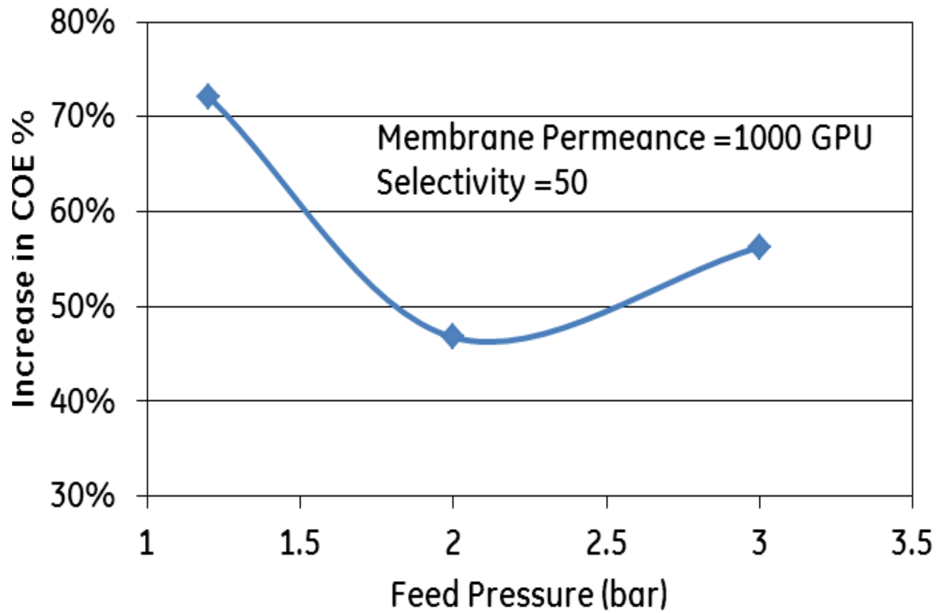
Membrane Process COE Analysis



Sensitivity analysis of increase in COE with membrane permeance



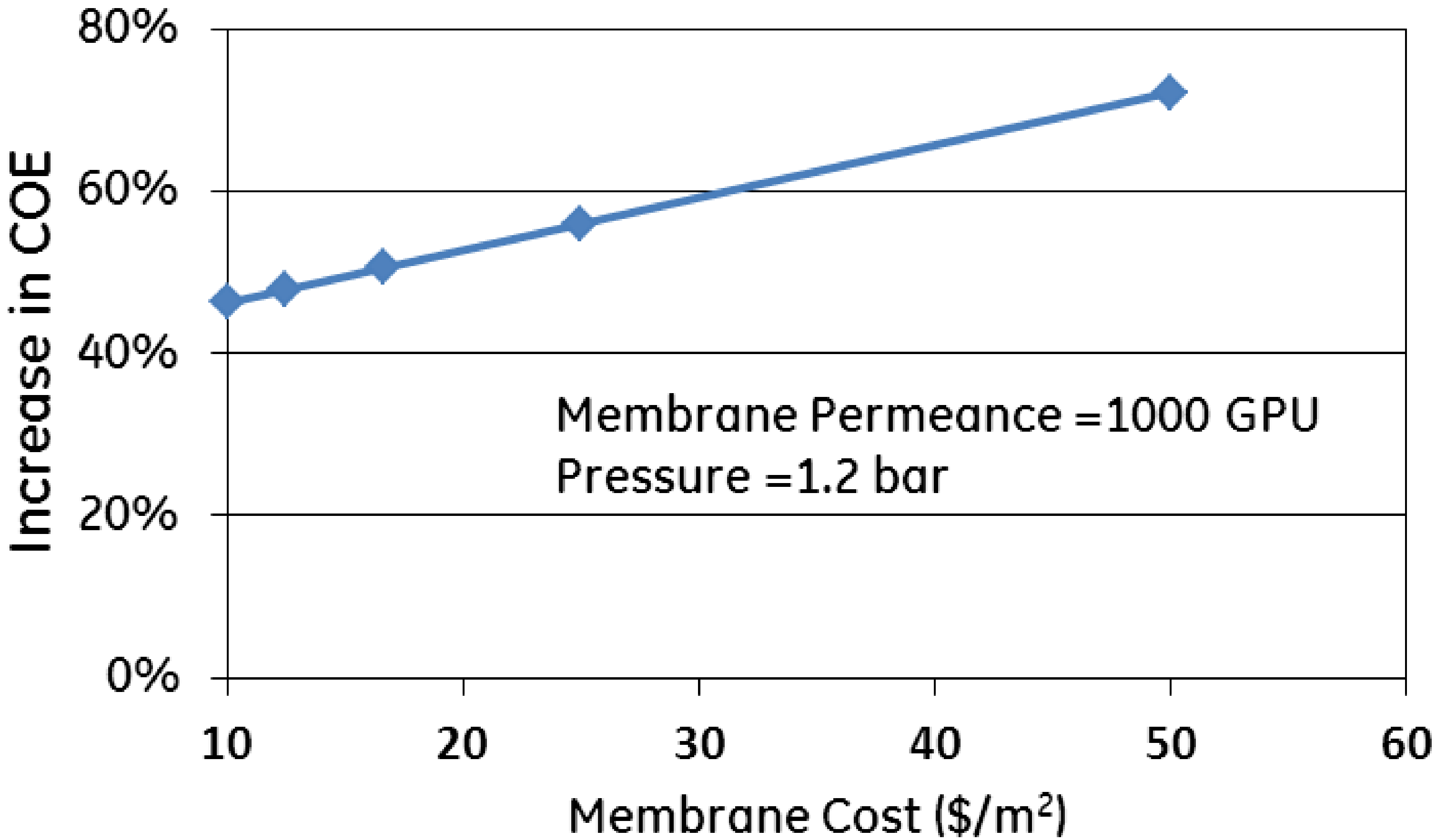
Sensitivity analysis of increase in COE with membrane feed pressure

Increase in COE

- Decreases with increase in membrane permeance in the lower range, plateaus at higher permeance range
- Minimum at ~2 bar feed pressure

*Assumptions – Counter/counter-current membranes, Membrane-I pressure ratio = 10, Selectivity $_{CO2/N2}$ = 50

Membrane Process COE Analysis



Sensitivity analysis of increase in COE with membrane module cost ($/m²)

Increase in COE

- Decreases with decrease in membrane module cost

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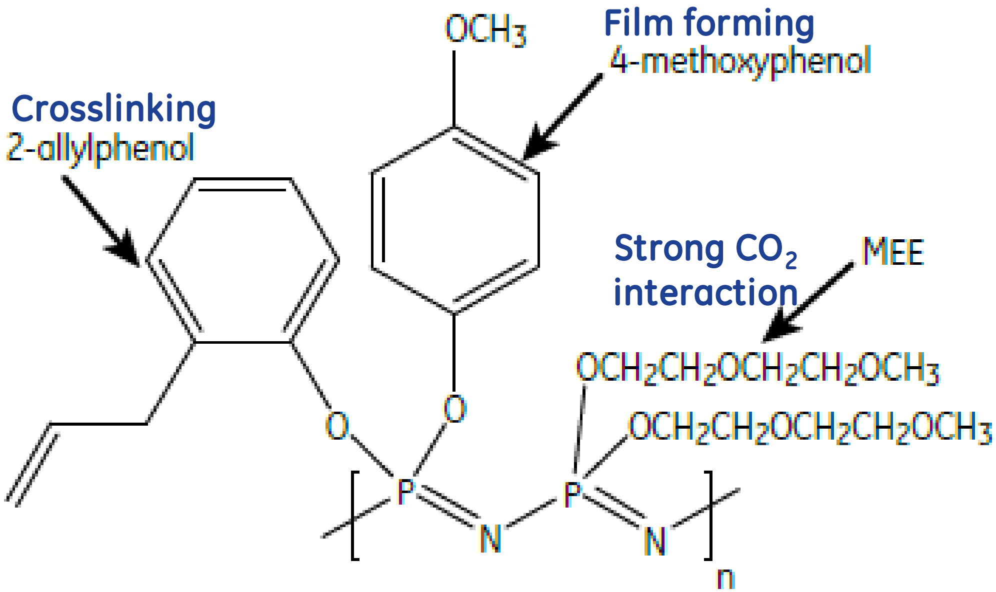
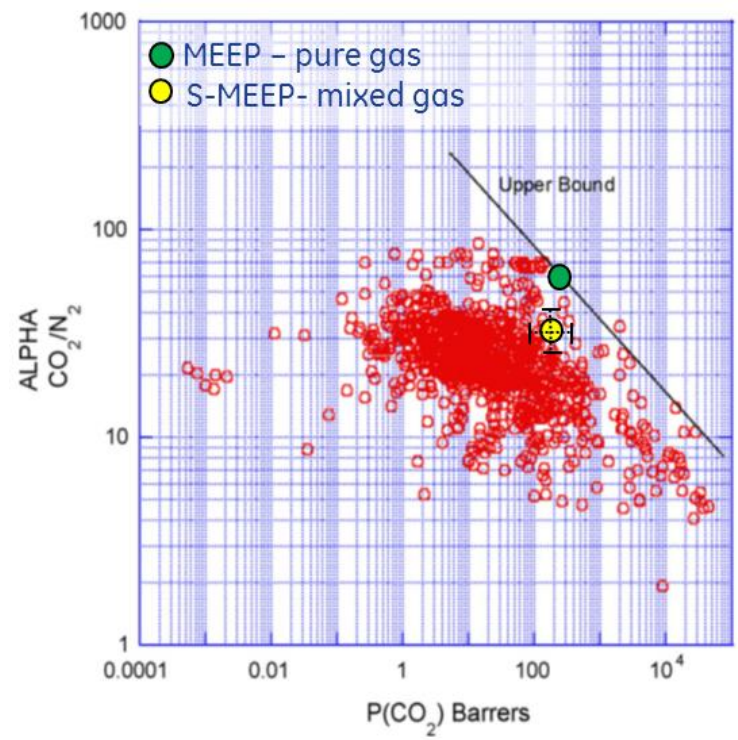
*Assumptions - Counter/counter-current membranes, selectivity$_{CO2/N2}$ = 50, Membrane-I pressure ratio = 5

Polyphosphazene Materials



General structure of stabilized (methoxyethoxy) ethanol phosphazene (MEEP)



Permeability-selectivity plot for CO_2/N_2 gas pair*+

- Low T_g polymers with good CO_2 separation & permeability
- Polymer properties tuned for HF coatability

* L. M. Robeson, The Upper Bound Revisited. J. Membr. Sci. 2008, 320, 390
+C.J. Orme, M.K. Harrup, T.A. Luther, R.P. Lash, K.S. Houston, D.H. Weinkauf, F.F. Stewart, Characterization of gas transport in selected rubbery amorphous polyphosphazene membranes, J. Membr. Sci. 186 (2001) 249

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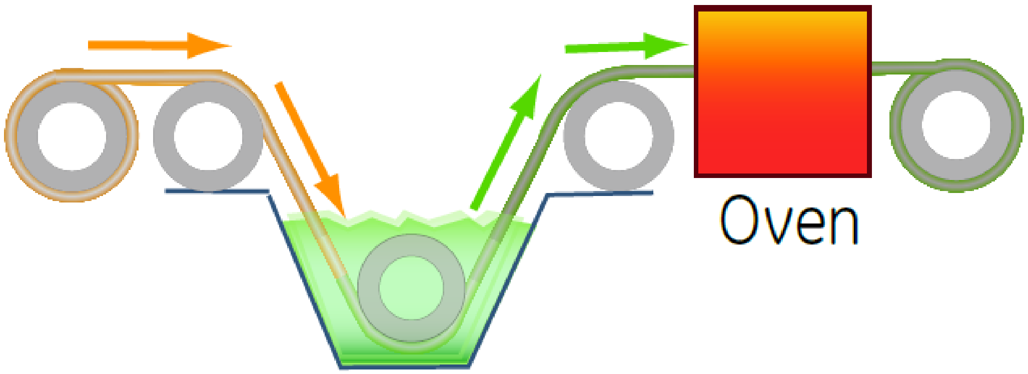
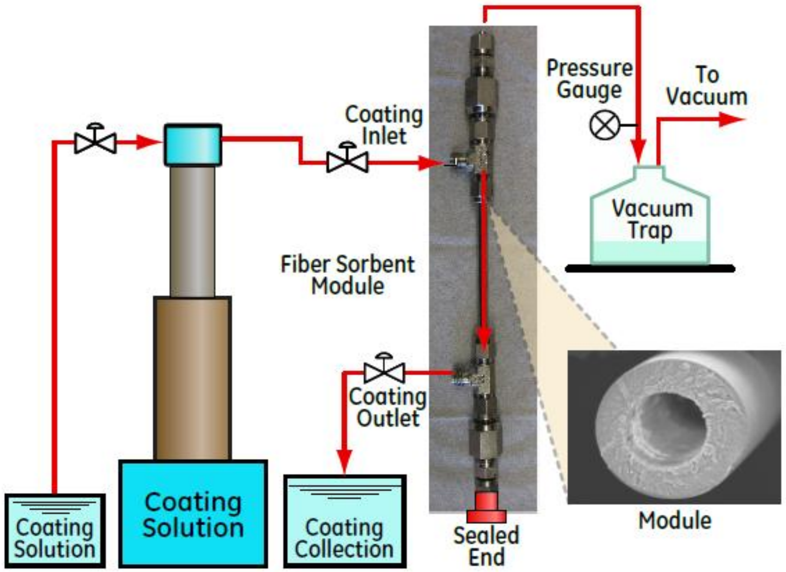
Composite HF Fabrication



Continuous 'roll-to-roll' coating process



Batch 'repair' coating process

- Key factors affecting HF support coatability
  - Reduced surface pore size
  - Substrate pore uniformity
  - Reduced physical handling
- Defect-free membrane modules fabricated & studied for long term performance testing

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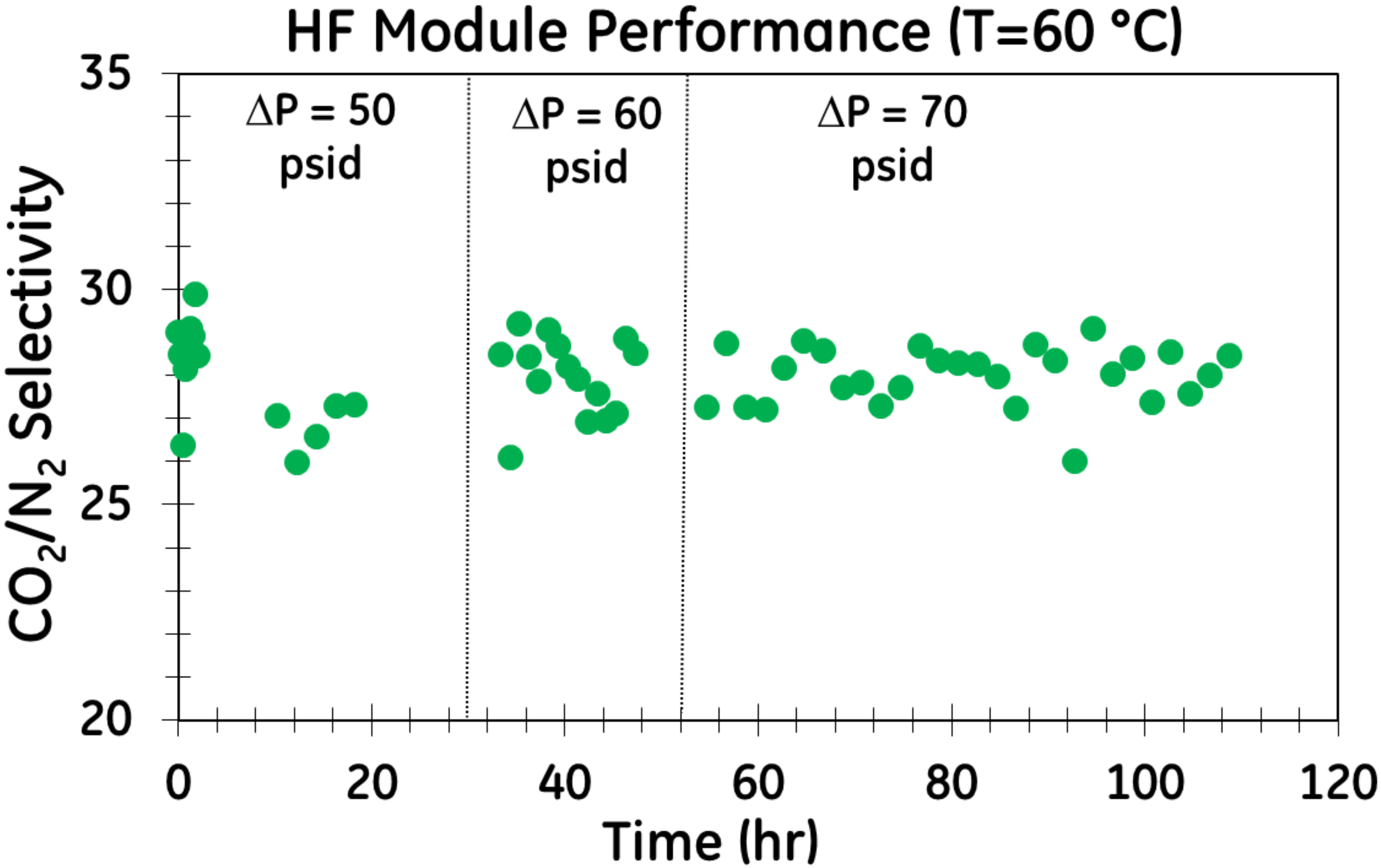
Membranes Testing

WRI flue gas membrane testing rig (flat sheet & HF modules)

- Membranes tested under realistic flue gas mixture: $N_2/CO_2/O_2/NO/SO_2$ - 80/15/5/80 ppm/50 ppm (vol. %) saturated with water vapor

HF Membranes Testing



HF membrane module performance testing

- HF membrane mini-modules (10" length) performance found to be stable

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Conclusions & Work-in-Progress

- ✓ Preliminary techno-economic analysis conducted to determine membrane performance targets
- ✓ Composite hollow fiber membranes developed & performance validated
- Optimize membrane performance & improve coating solution properties
- Optimize coating protocols for continuous & batch processes
- Scale-up membrane module & study HF membrane long-term performance

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Thank You