# Low-Pressure Membrane Contactors for $CO_2$ Capture (DE-FE0007553)

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**Membrane Technology and Research, Inc.**

**Project Kickoff Meeting**

Tuesday, November 29, 2011

# Program Objectives

- Low Cost, Large Area Modules (500 $m^2$ +)
- Smaller Foot Print, Less Manifolds
- Reduce Energy Cost by Lowering Module Pressure Drop
  - Pressure Drop in Modules = Parasitic Energy Loss
  - 1 PSI Pressure Drop = 2.5 $MW_e$ of Compression Power for a 500 $MW_e$ Coal-Fired Power Plant
- Year 1- 5 PSI , Year 2- 2.5 PSI , Year 3- 1.5 PSI



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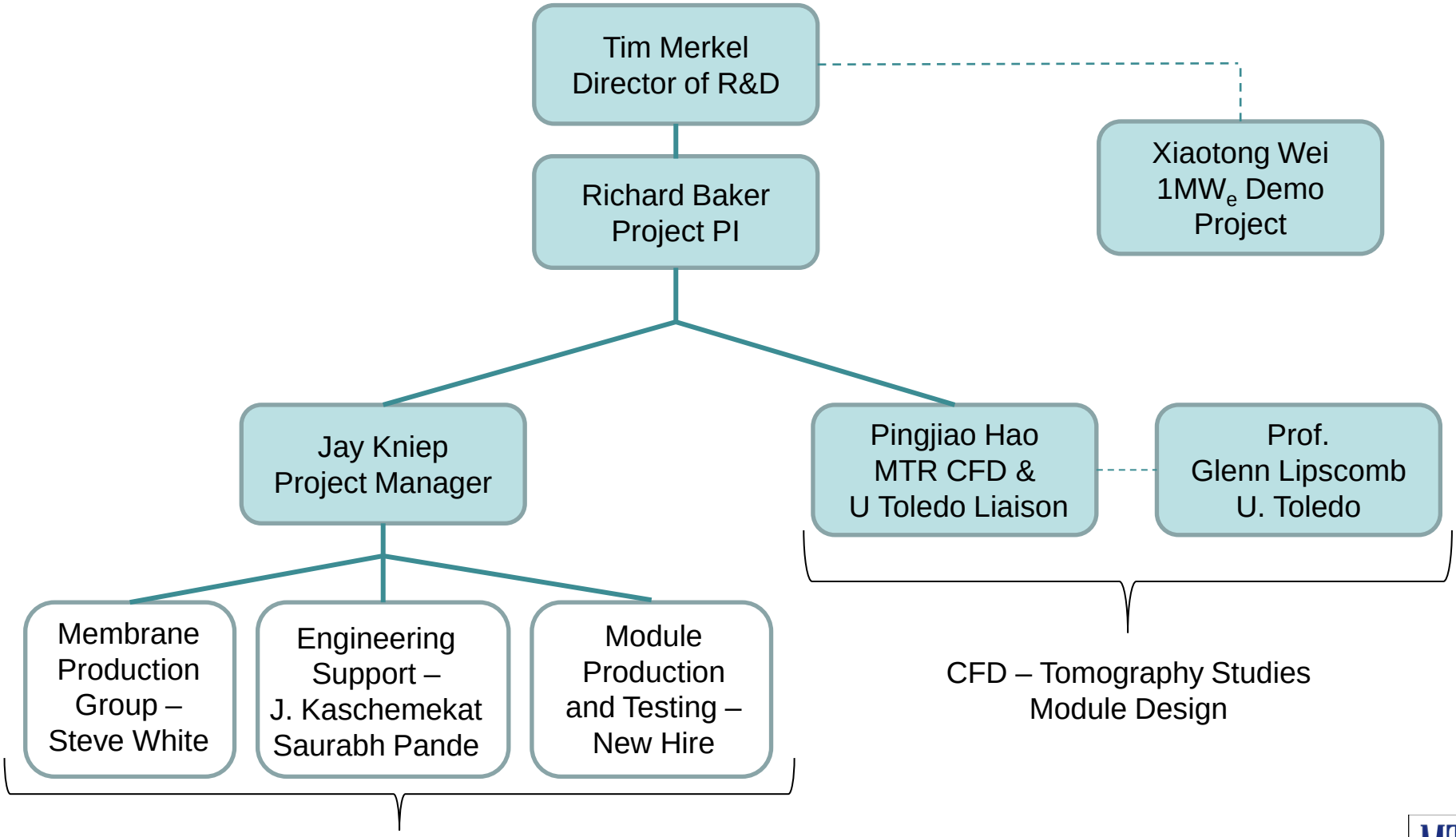
# The Project Team



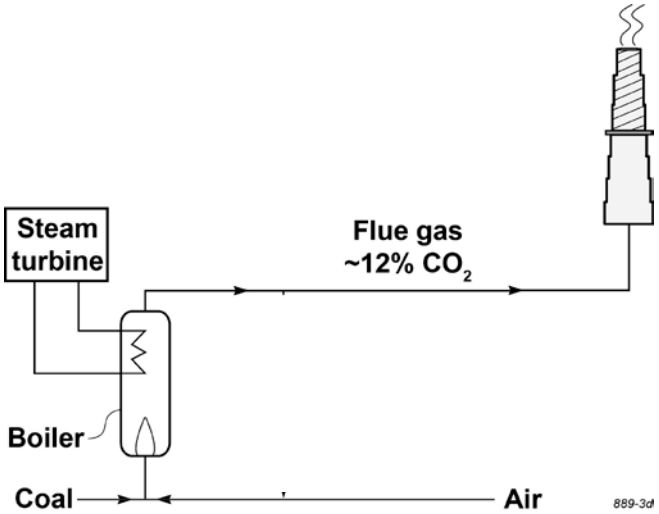
# Program Overview

- Process Introduction
- Our Current Approach
- Issues
- Program Approach
- CFD and Tomography Measurements
- Tasks, Schedule, Budget

# Program Overview

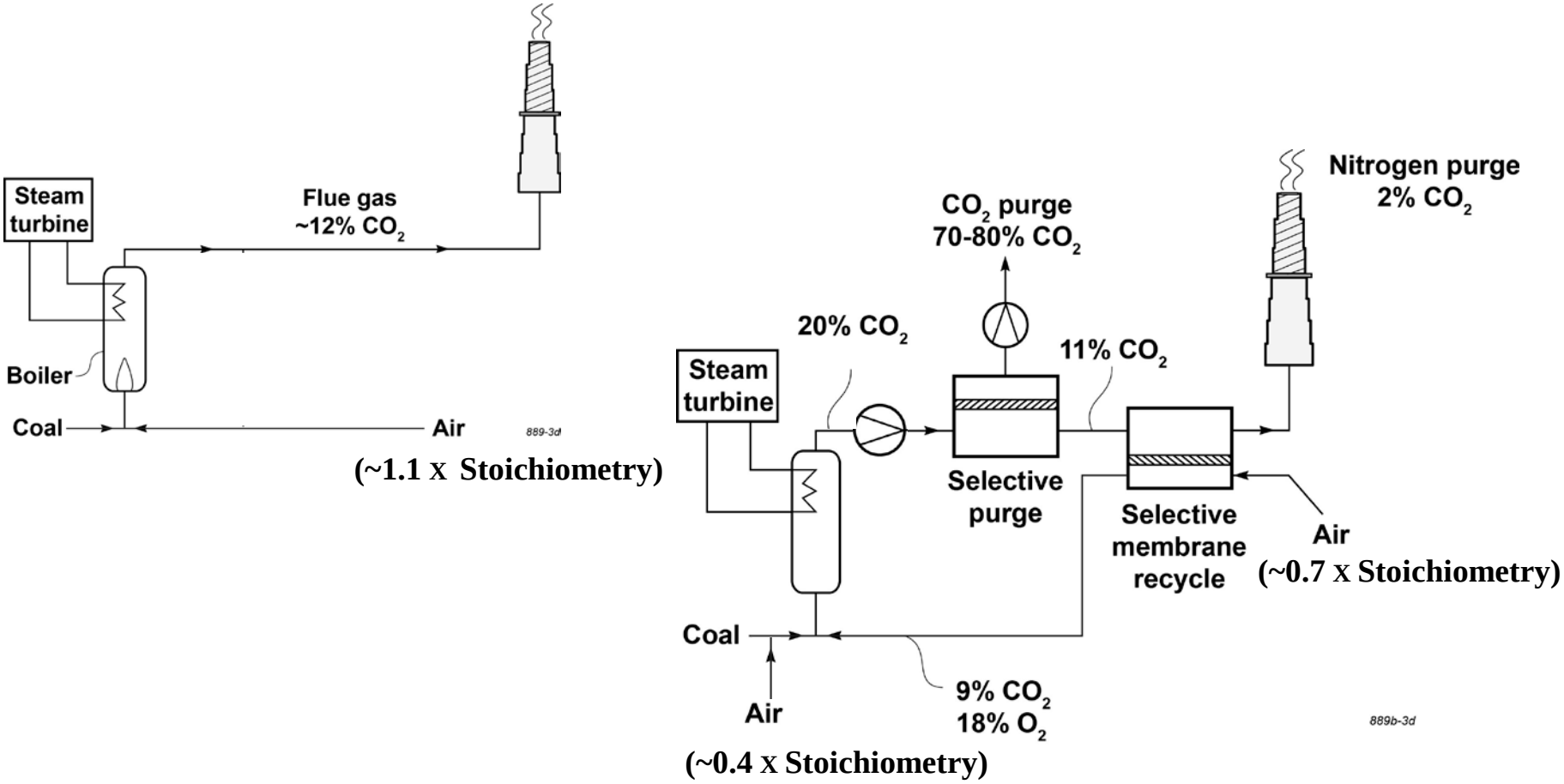
- Process Introduction
  - Coal
  - Gas Turbine
  - Our Vision
- Our Current Approach
  - Nested Spiral-Wound Modules
  - Large Plate and Frame Modules

# $CO_2$ Separation from Coal Flue Gas



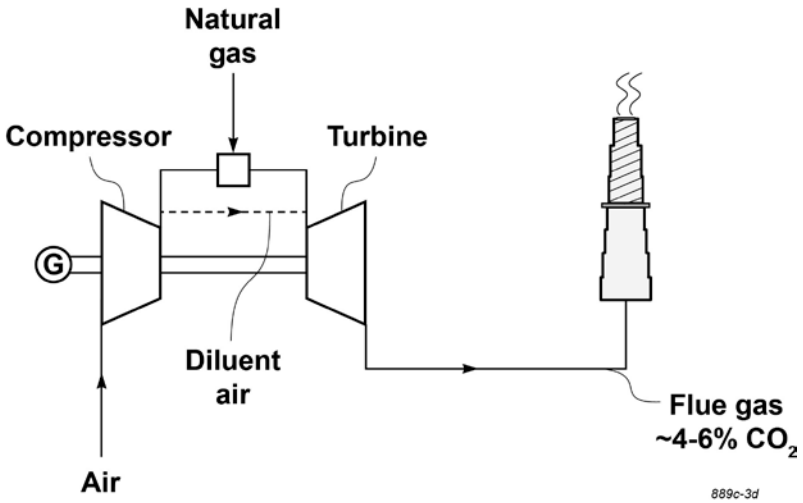

**(~1.1 x Stoichiometry)**

# $CO_2$ Separation from Coal Flue Gas



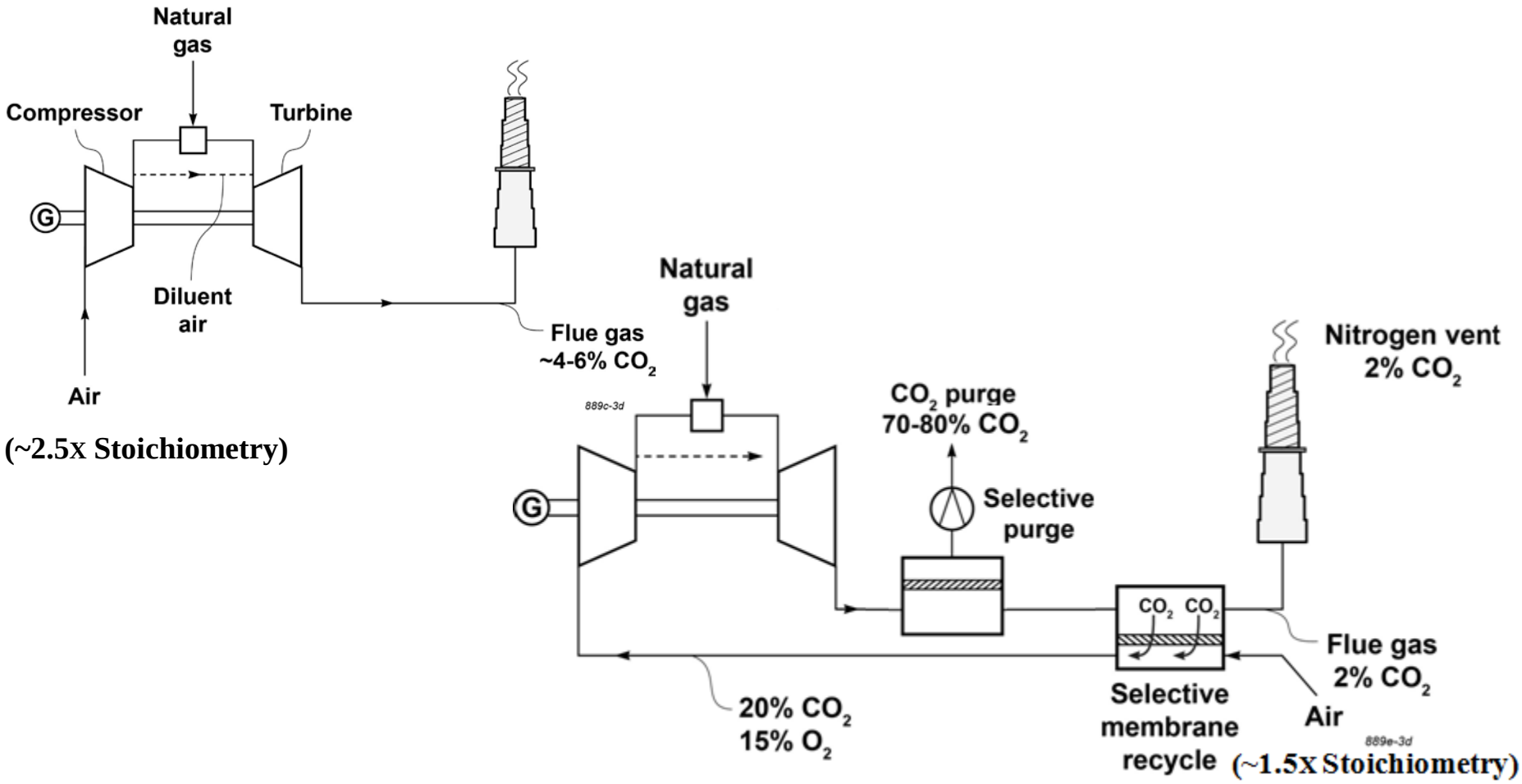

Sweep ratio for a coal contactor is ~0.7

# $CO_2$ Separation from Gas Turbine Flue Gas




**(~2.5x Stoichiometry)**

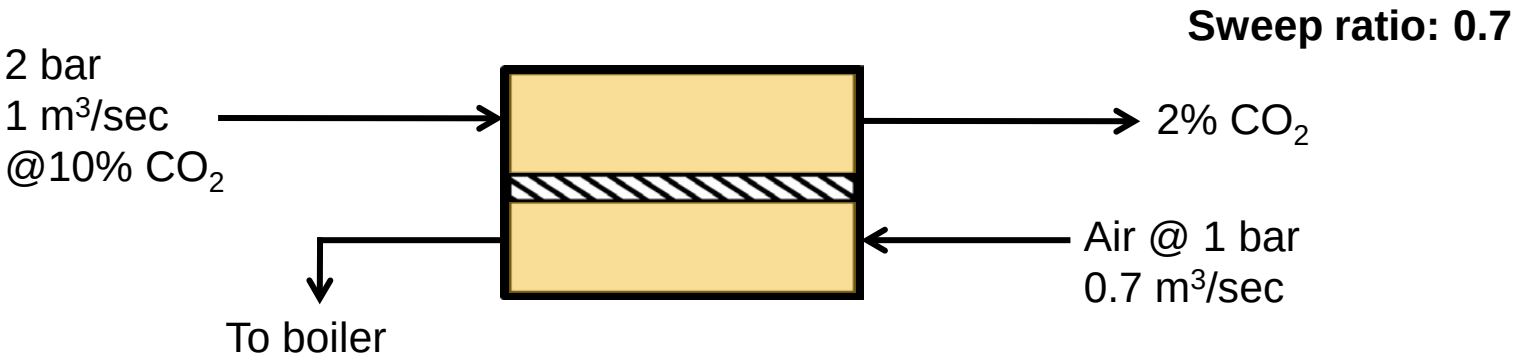
# $CO_2$ Separation from Gas Turbine Flue Gas



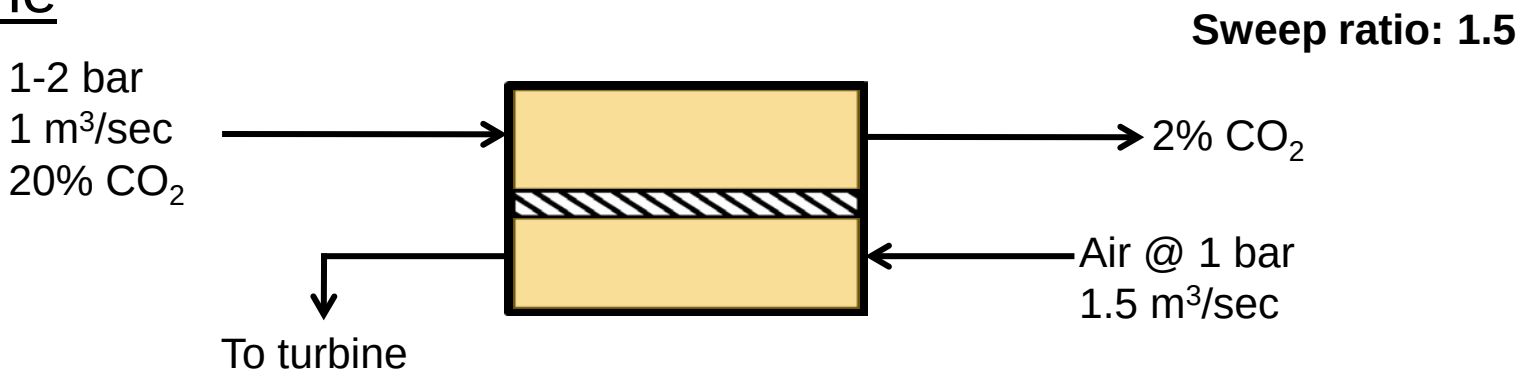

- Sweep ratio for a gas turbine contactor is ~1.5

# Base Case Operating Conditions

## Coal




## Gas Turbine




*Depending on the operating conditions and membrane permeance, a 500 MWe power plant will need 0.5 – 1.0 million $m^2$ of membrane*



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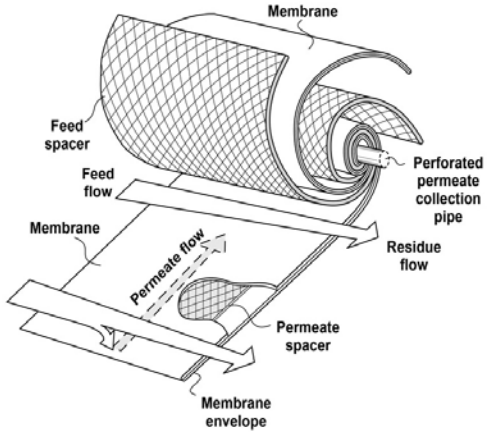
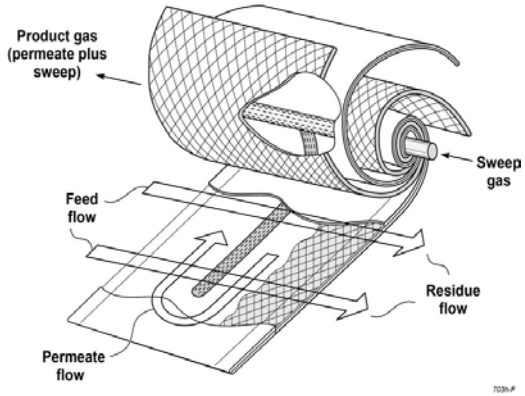
# Current Approach Uses Modified Spiral-Wound Modules in Nested Bundles

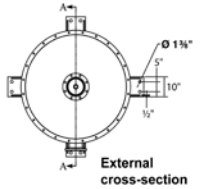
**Conventional spiral-wound module**

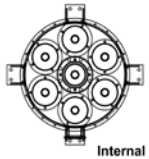


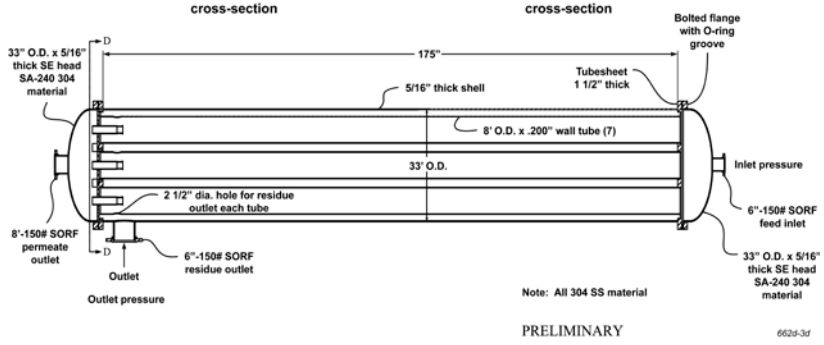

**Spiral-wound countercurrent/sweep module**

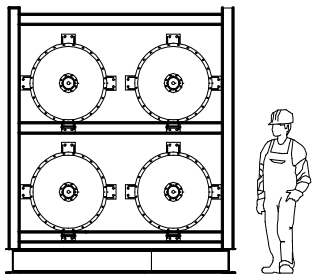



Each module contains 20 to 50 $m^2$ of membrane





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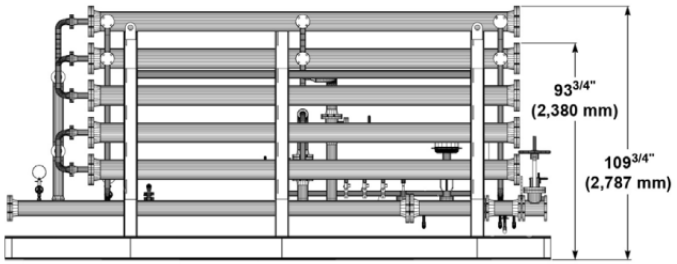
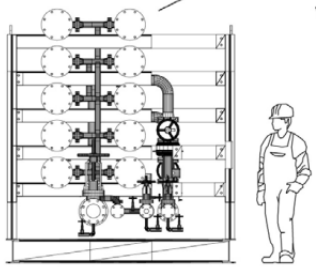
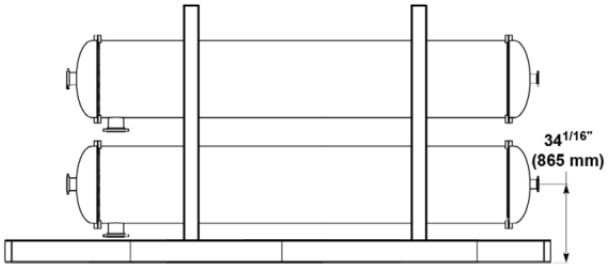
# A Comparison of Skid Designs

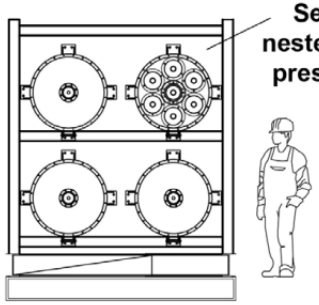
**4 x 10 (8 inch modules) @ 20 $m^2$/modules = 800 $m^2$**



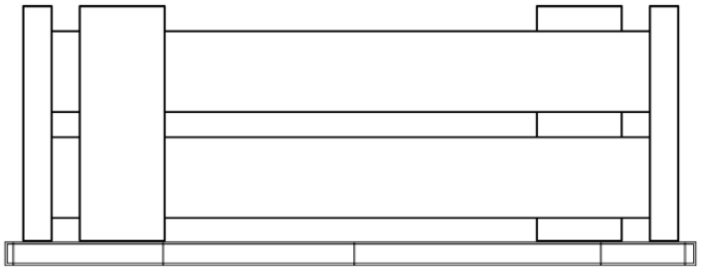



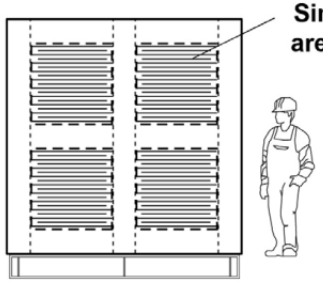

**4 x 4 x 7 (8 inch modules) @ 20 $m^2$/modules = 2,240 $m^2$**




**4 x (1 x 1 x 5 m) modules @ 2,500 $m^2$/modules = 10,000 $m^2$**



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# A Comparison of Skid Designs

| Module Configuration | Membrane Packing Efficiency Contactor Module Only ($m^2/m^3$) | Packing Efficiency Total Contactor Module Skid ($m^2/m^3$) | Housings Needed for a 100 MWe Plant* | Volume of 100 $MW_e$ Plant ($m^3$) |
|---|---|---|---|---|
| 8” Spirals (20 $m^2$ each), 4 modules/tube | 600 | 19 | 2,500 | 10,500 |
| 8” Spirals (20 $m^2$ each), 4 modules/tube, 7 nested tubes/pressure vessel | 600 | 54 | 360 | 3,700 |
| 2,500 $m^2$ large area contactor (1m x 1m x 5m) | 500 | 240 | 80 | 830 |

* 100 MWe requires about 200,000 $m^2$ of membrane

Large-area modules reduce manifolding and plant footprint



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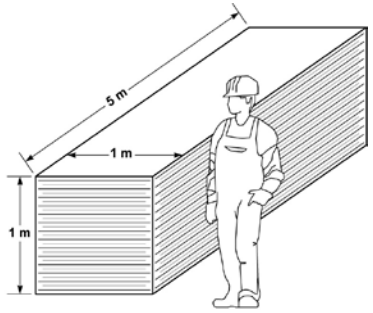
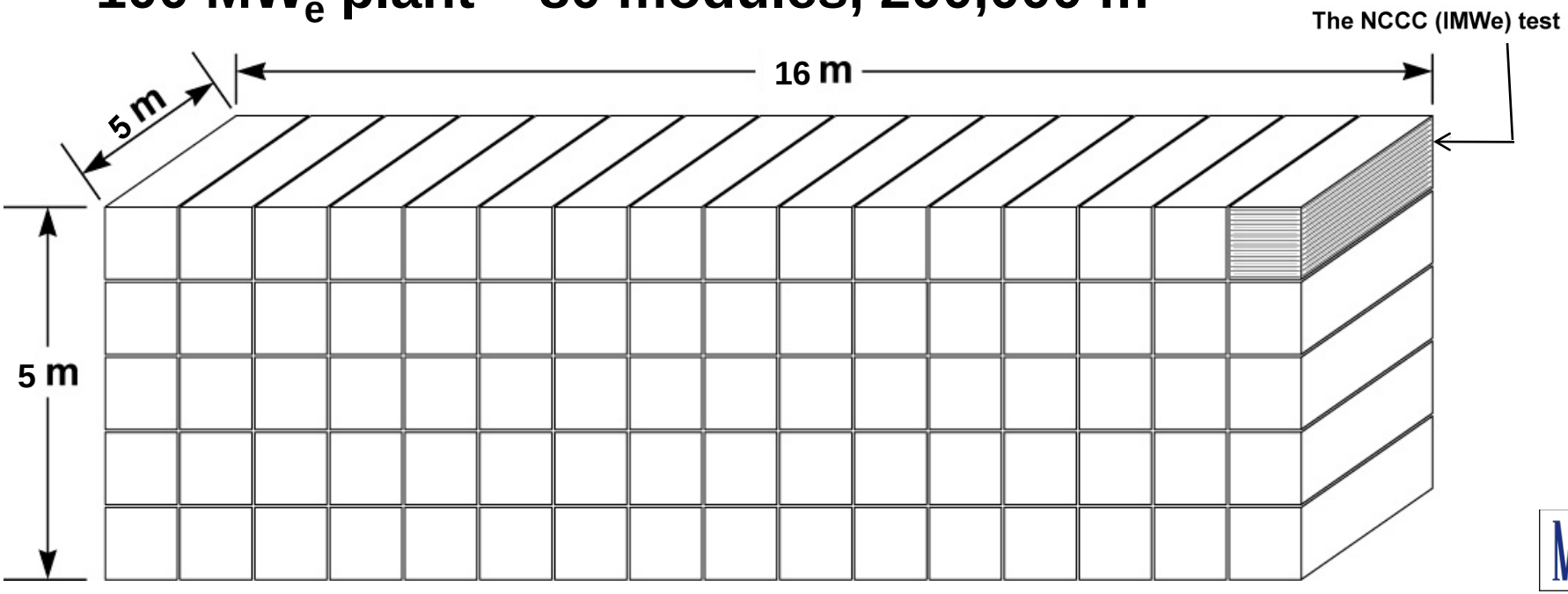
# Membrane Unit Size




**One module skid, 2500 m$^2$**

**100 MW$_e$ plant ~ 80 modules, 200,000 m$^2$**

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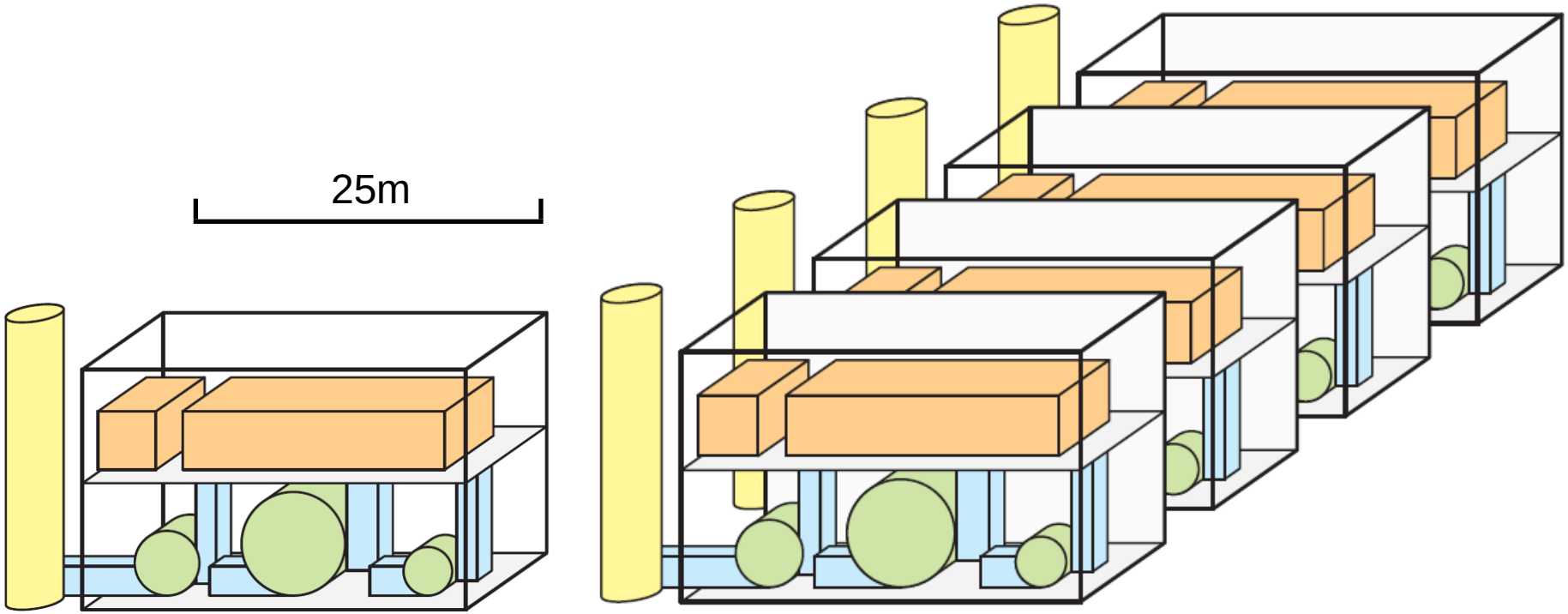
# Membrane Skid Scale Up



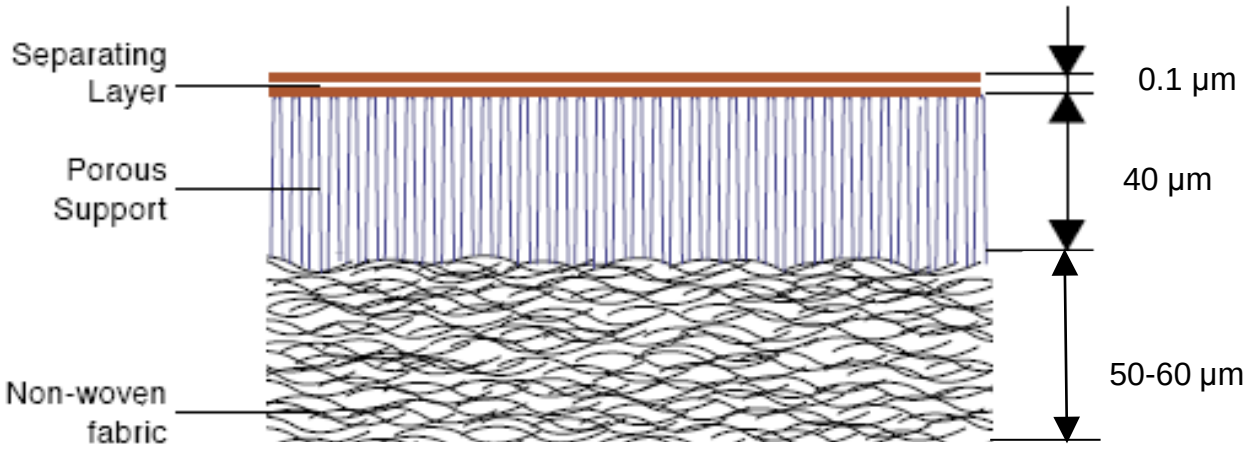

**100 $MW_e$ plant**

**400 $MW_e$ plant**

# Program Overview

- Issues
  - The Membrane
  - Concentration Polarization/Bypass/Flow Maldistribution
  - Module Pressure Drop
  - Does Sweep Work?
  - Counter-Flow Sweep
  - Cross-Flow Sweep

# The Issues:
# The Membrane




<u>Current standard:</u>
$CO_2$ permeance=1000 gpu, α = 40

<u>Target:</u>
$CO_2$ permeance=2500 gpu, α = 40



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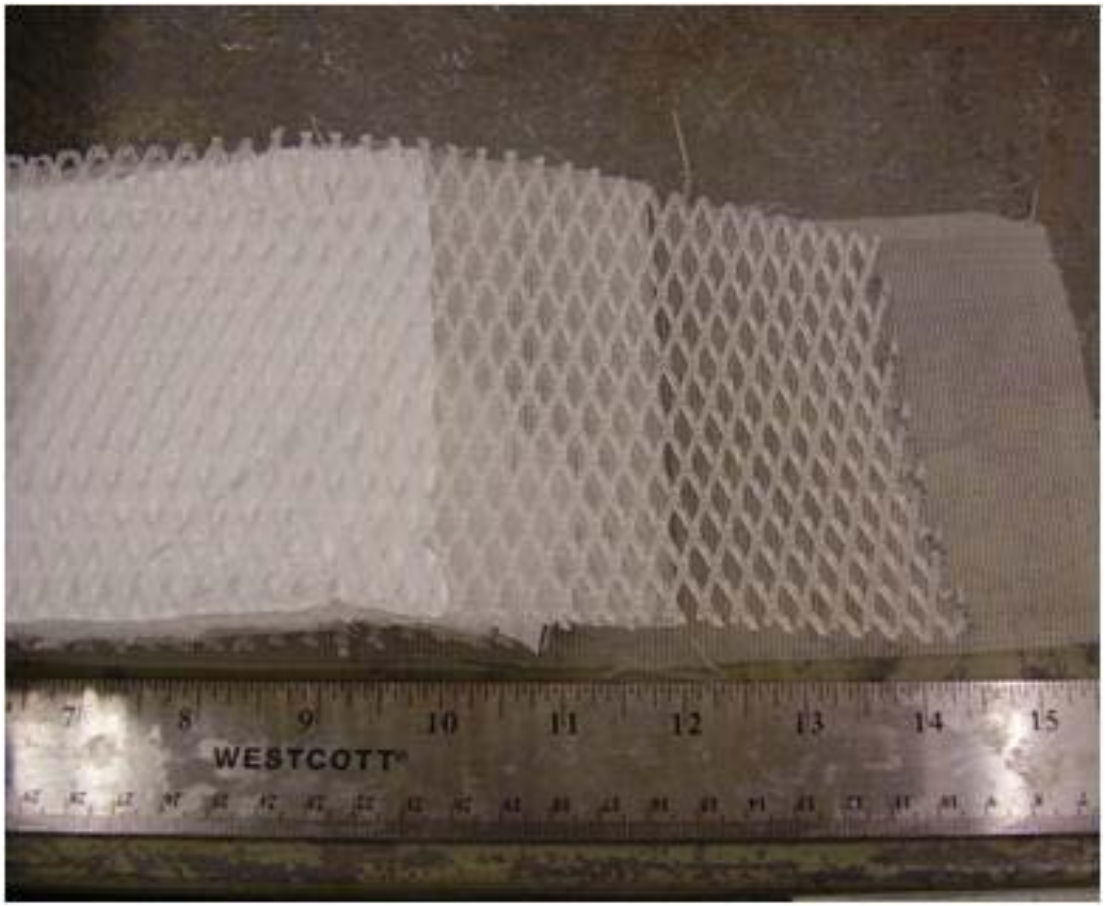
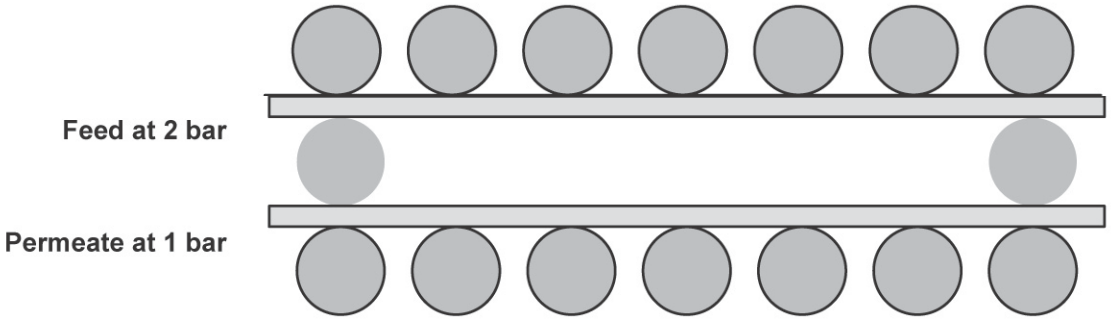
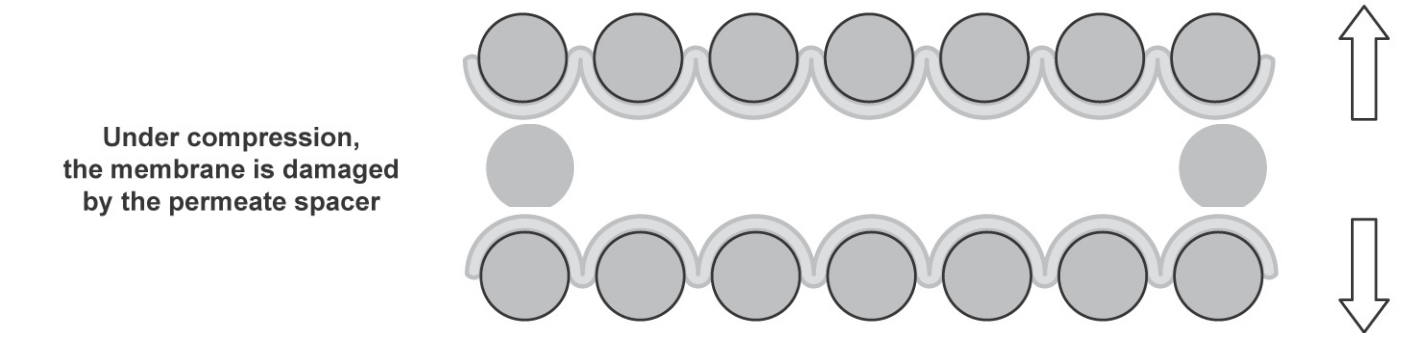
# The Issues: Spacer Selection and Design

- Wide Range of Commercially Available Spacers
  - Material
  - Geometry
  - Weave
  - Thickness

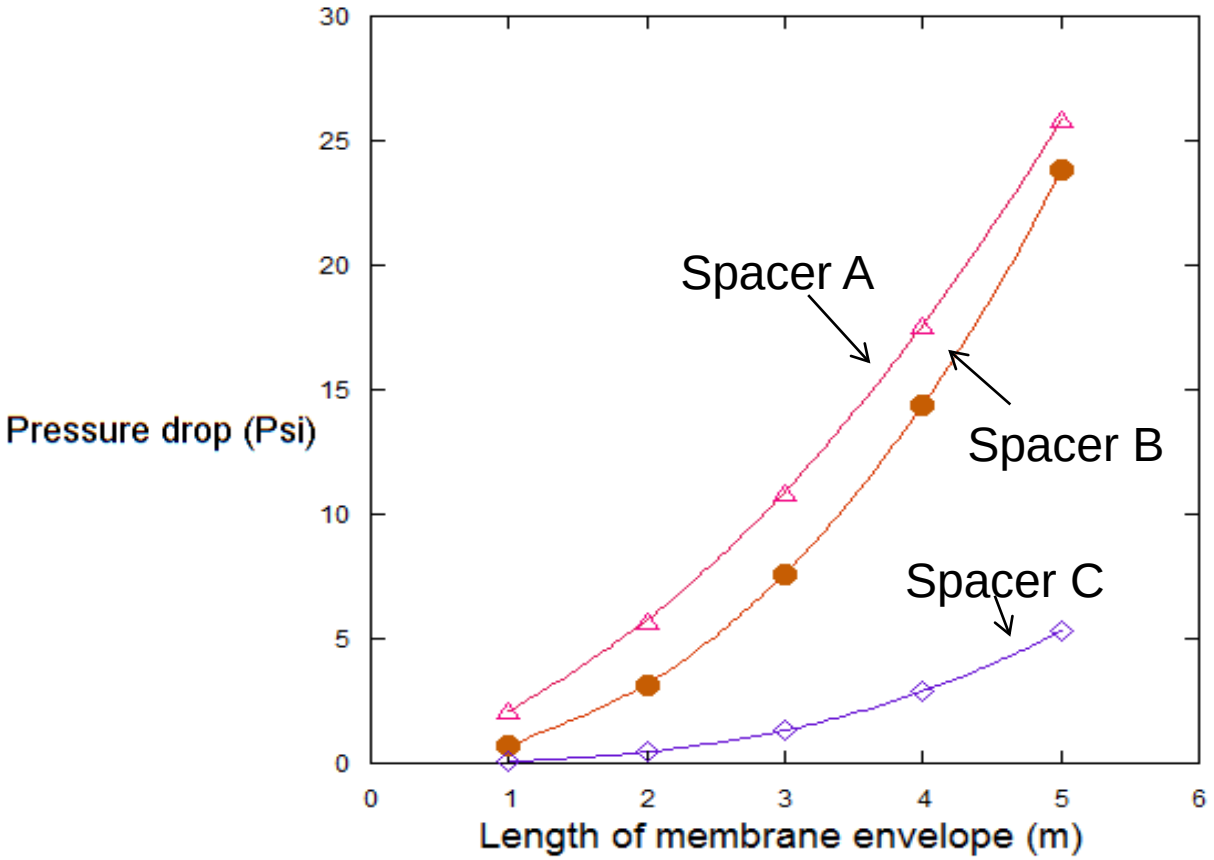


# The Issues:
# Mechanical Damage to The Membrane



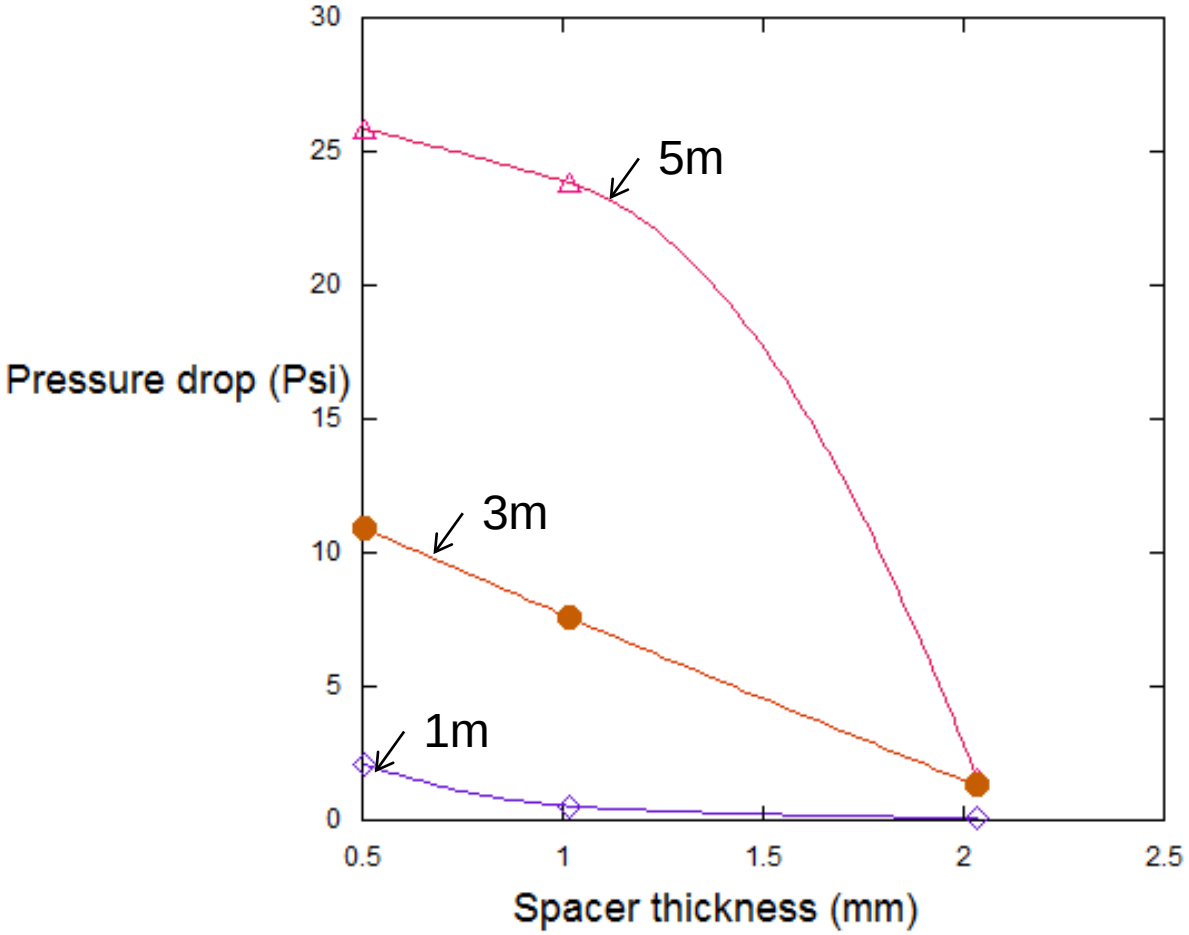



# Spacer Pressure Drop



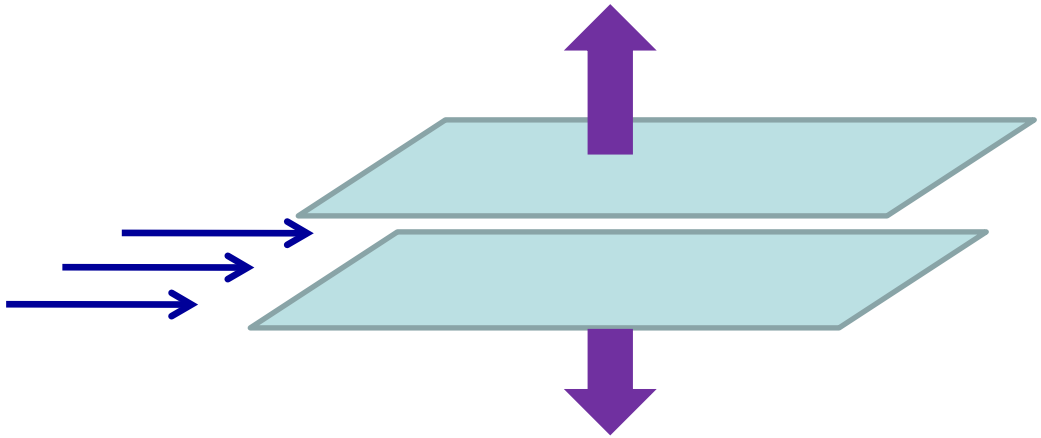

– Pressure drop goes up as the square of the envelope length
– Pressure drop is a function of weave & orientation

# Spacer Pressure Drop




– Pressure drop goes down as the spacer thickness increases

# Concentration Polarization/Bypass/ Flow Maldistribution



Feed velocity
1~5 m/s

Permeate velocity through the membrane
~ 0.005 cm/sec

- Concentration polarization with the membrane unlikely to be a problem ( Peclet ~ $1X10^{-3}$)
- Bypass and maldistribution will be more important



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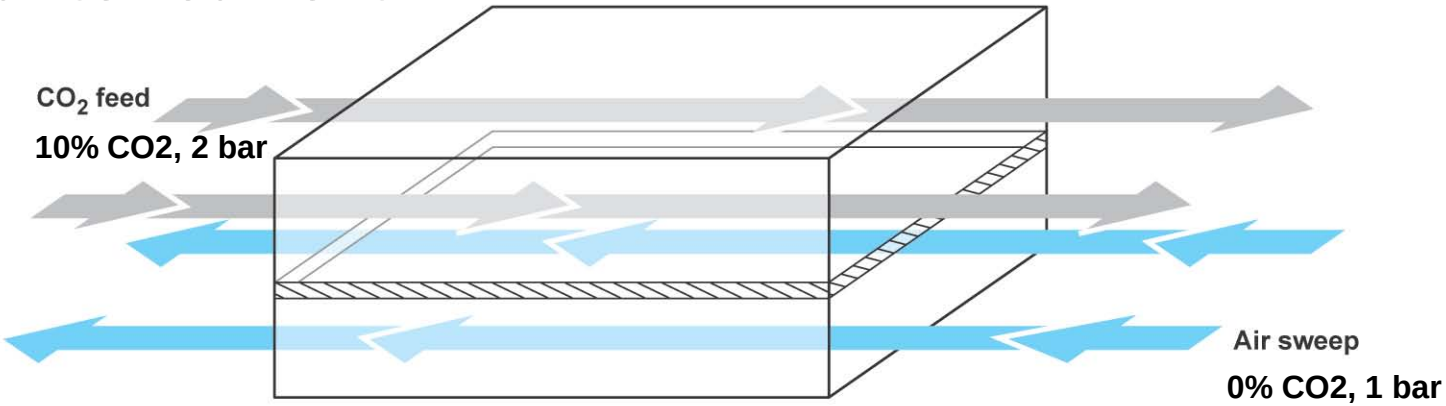
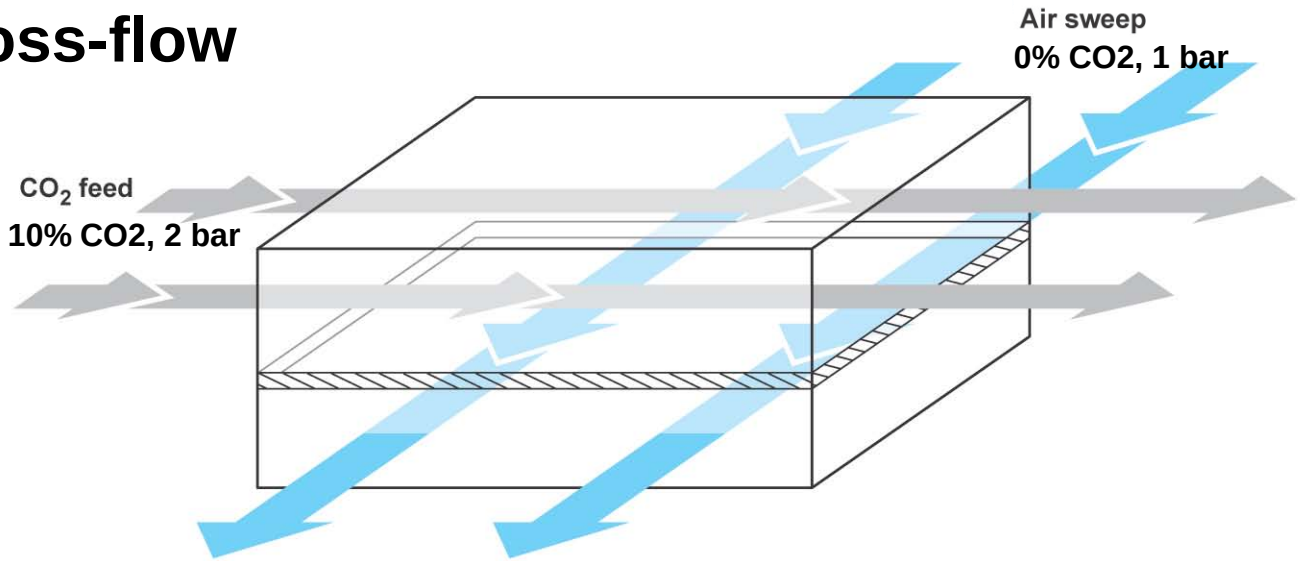
# The Issues:
# Does Sweep Work?

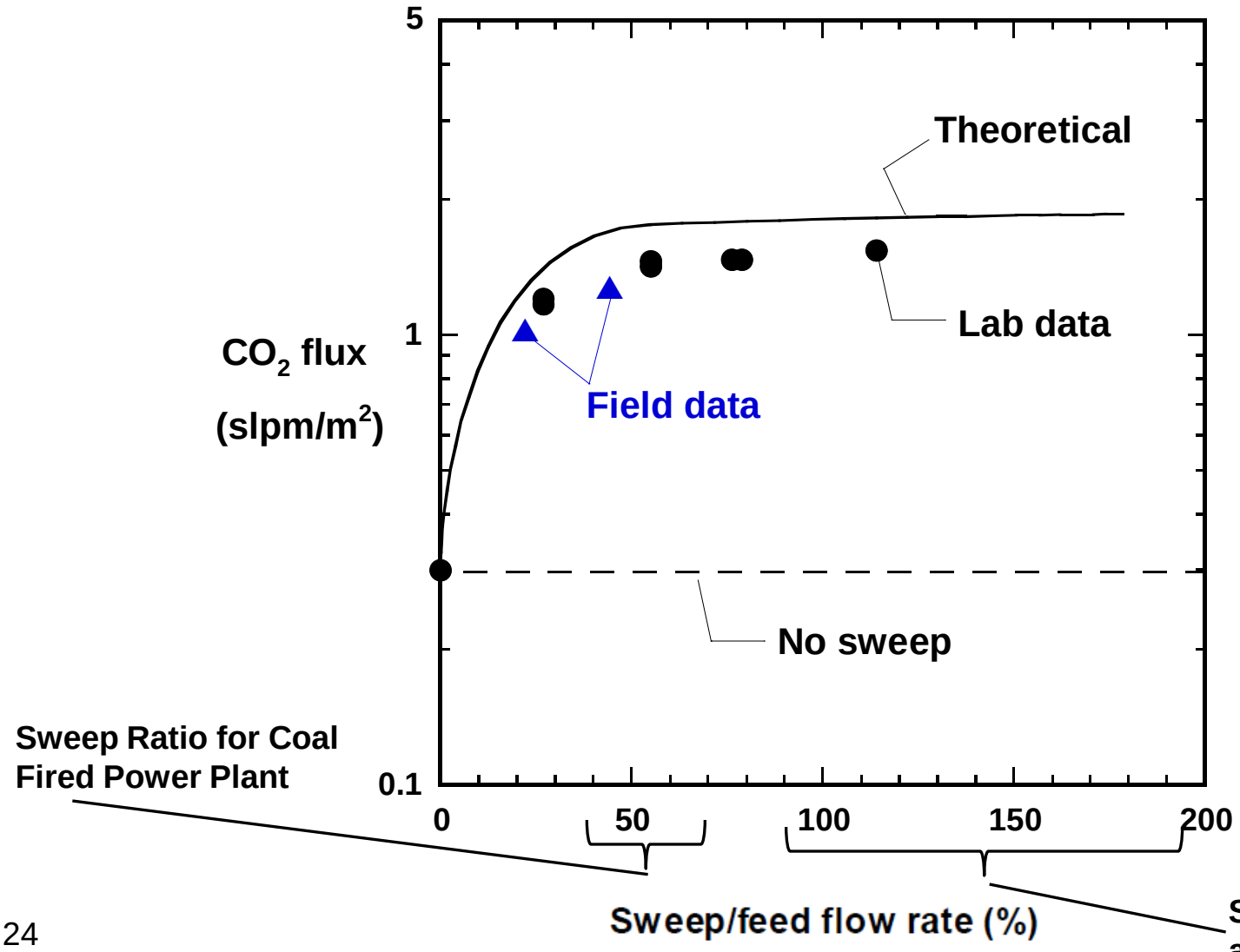
## Counter-current




## Cross-flow

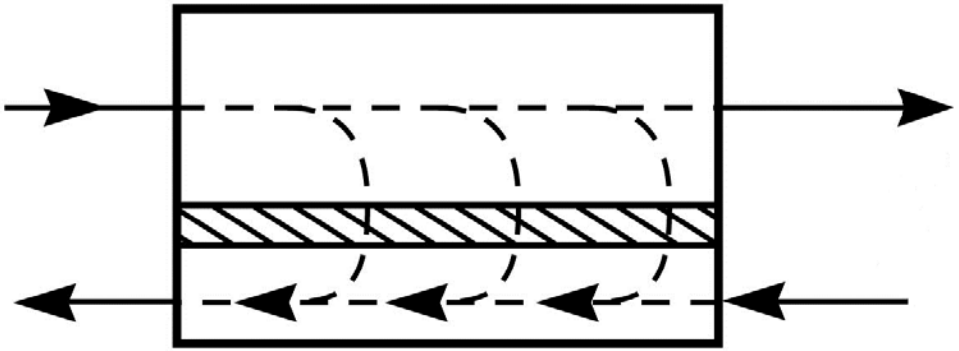


# Sweep Does Work!



# Counter Current Sweep: The Effect of Sweep Ratio

**Feed**
**-1 $m^3/s$**
**-10% $CO_2$**
**-1 bar**



**-2% $CO_2$**

**Sweep**
**-1 $m^3/s$ Air**
**-0% $CO_2$**
**-1 bar**

**Assume Perfect Membrane**
**-$CO_2$ Permeance = 1,000 GPU**
**-$N_2$, $O_2$ Permeance < 1 GPU**



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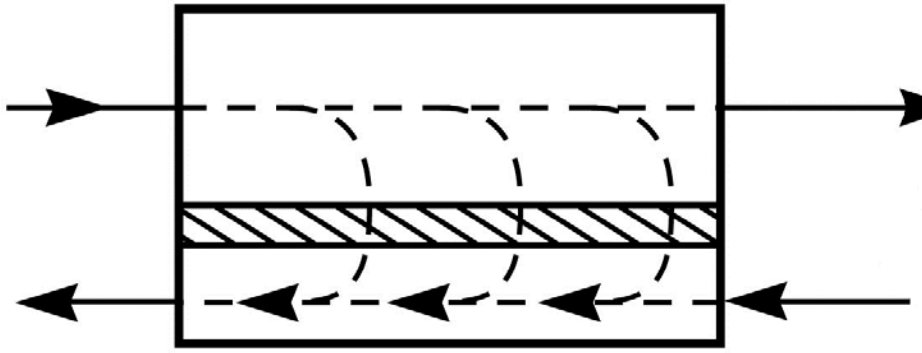
# Counter Current Sweep: The Effect of Sweep Ratio

**Feed**
**-1 $m^3/s$**
**-10% $CO_2$**
**-1 bar**



**-2% $CO_2$**
***-0.92 $m^3/s$***

***-7.41% $CO_2$***
***-1.08 $m^3/s$***

**Sweep**
***-1 $m^3/s$ Air***
**-0% $CO_2$**
**-1 bar**

**Assume Perfect Membrane**
**-$CO_2$ Permeance = 1,000 GPU**
**-$N_2$, $O_2$ Permeance < 1 GPU**

***Sweep Ratio: 1.0***
***Membrane Area: 5,000 $m^2$***



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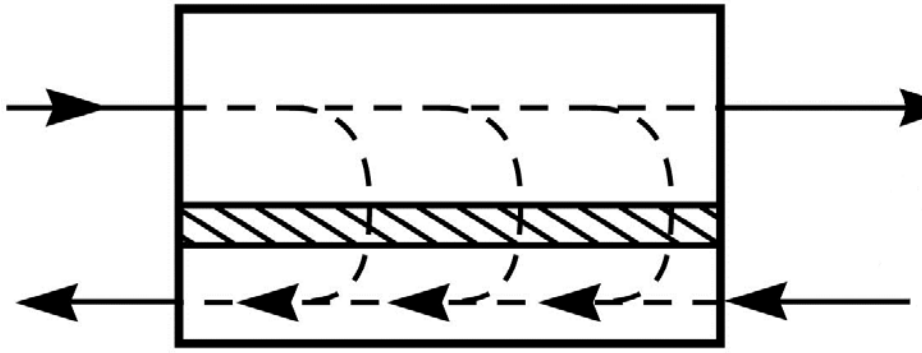
# Counter Current Sweep: The Effect of Sweep Ratio

**Feed**
-1 $m^3/s$
-10% $CO_2$
-1 bar



-2% $CO_2$
*-0.92 $m^3/s$*

*-8.33% $CO_2$*
*-0.98 $m^3/s$*

**Sweep**
*-0.9 $m^3/s$ Air*
-0% $CO_2$
-1 bar

**Assume Perfect Membrane**
-$CO_2$ Permeance = 1,000 GPU
-$N_2$, $O_2$ Permeance < 1 GPU

***Sweep Ratio: 0.9***
***Membrane Area: 6,000 $m^2$***



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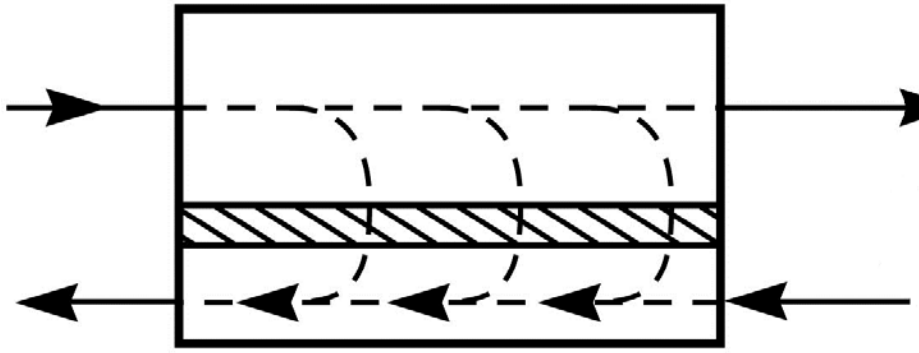
# Counter Current Sweep: The Effect of Sweep Ratio

**Feed**
**-1 $m^3/s$**
**-10% $CO_2$**
**-1 bar**



**-2% $CO_2$**
***-0.92 $m^3/s$***

***-9.27% $CO_2$***
***-0.88 $m^3/s$***

**Sweep**
***-0.8 $m^3/s$ Air***
**-0% $CO_2$**
**-1 bar**

**Assume Perfect Membrane**
**-$CO_2$ Permeance = 1,000 GPU**
**-$N_2$, $O_2$ Permeance < 1 GPU**

***Sweep Ratio: 0.8***
***Membrane Area: 8,500 $m^2$***



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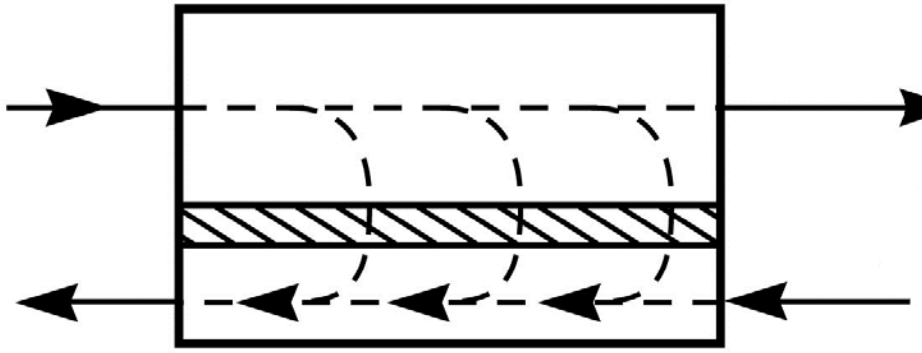
# Counter Current Sweep: The Effect of Sweep Ratio

**Feed**
-1 $m^3/s$
-10% $CO_2$
-1 bar



-2% $CO_2$
*-0.92 $m^3/s$*

*-~10% $CO_2$*
*-~0.78 $m^3/s$*

**Sweep**
*-0.7 $m^3/s$ Air*
-0% $CO_2$
-1 bar

**Assume Perfect Membrane**
-$CO_2$ Permeance = 1,000 GPU
-$N_2$, $O_2$ Permeance < 1 GPU

***Sweep Ratio: 0.7***
***Membrane Area: INFINITE!!***



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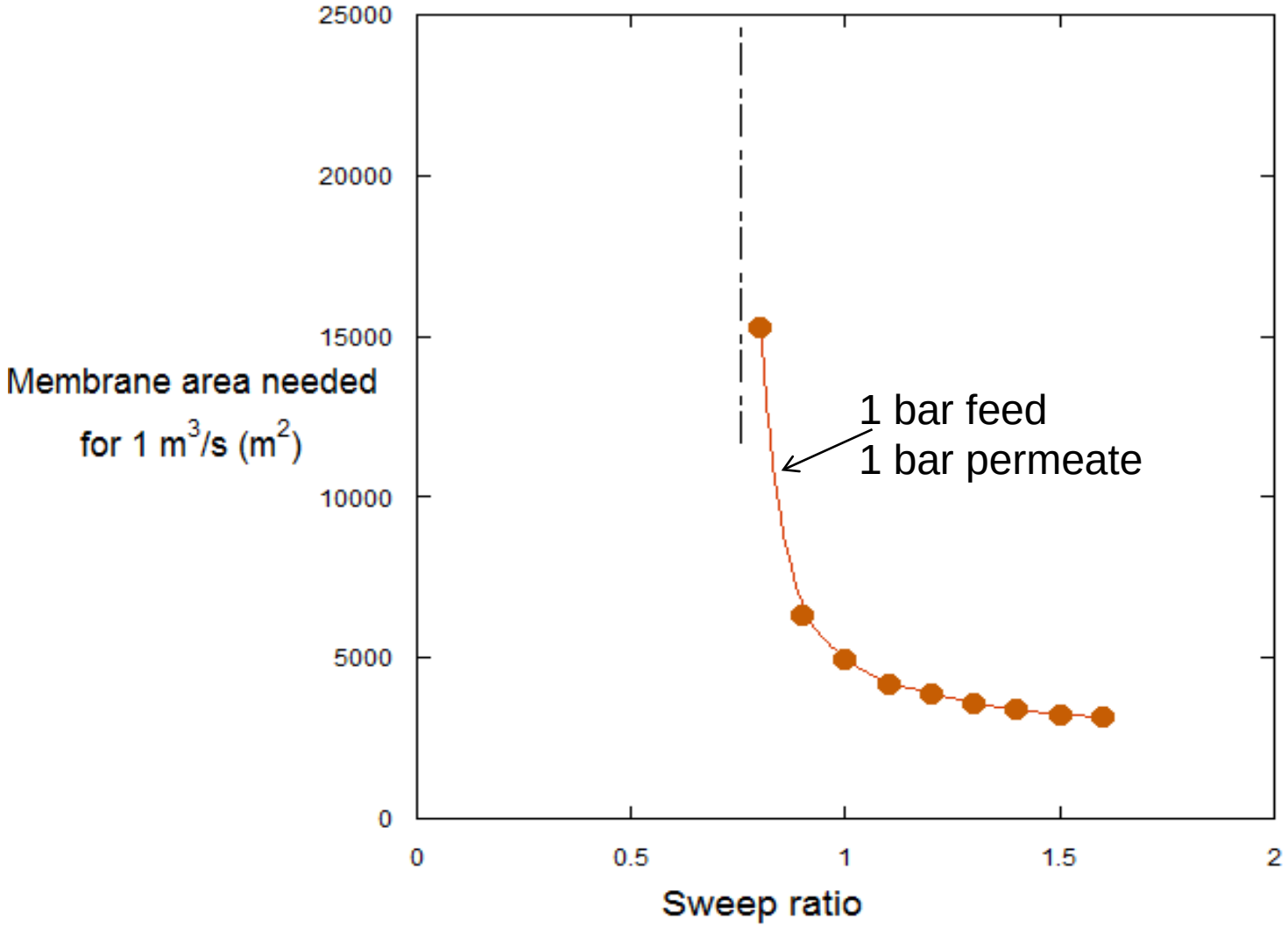
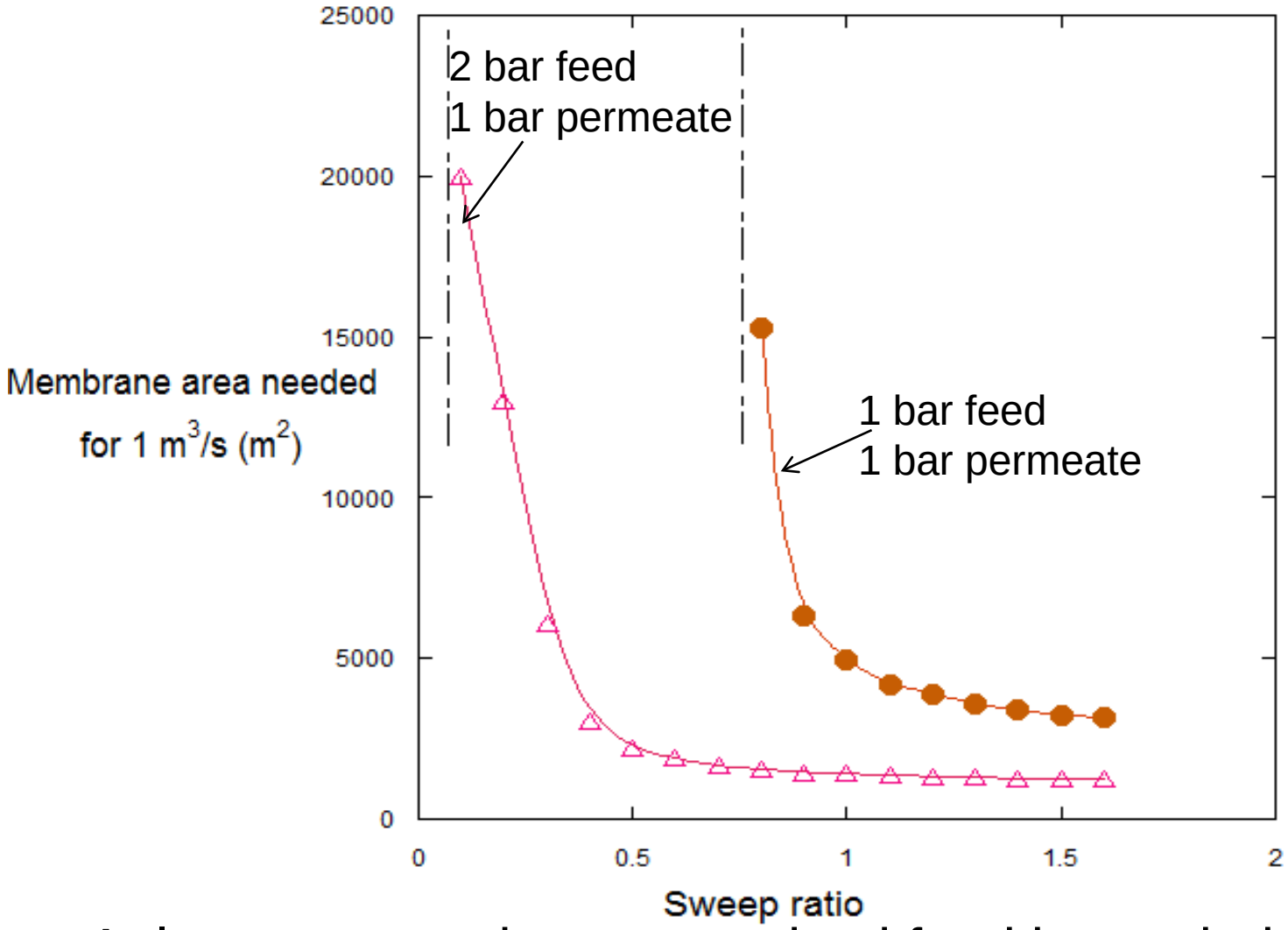
# Counter Current Sweep
# The Effect of Sweep Ratio




– At low sweep ratios, pressurized feed is needed

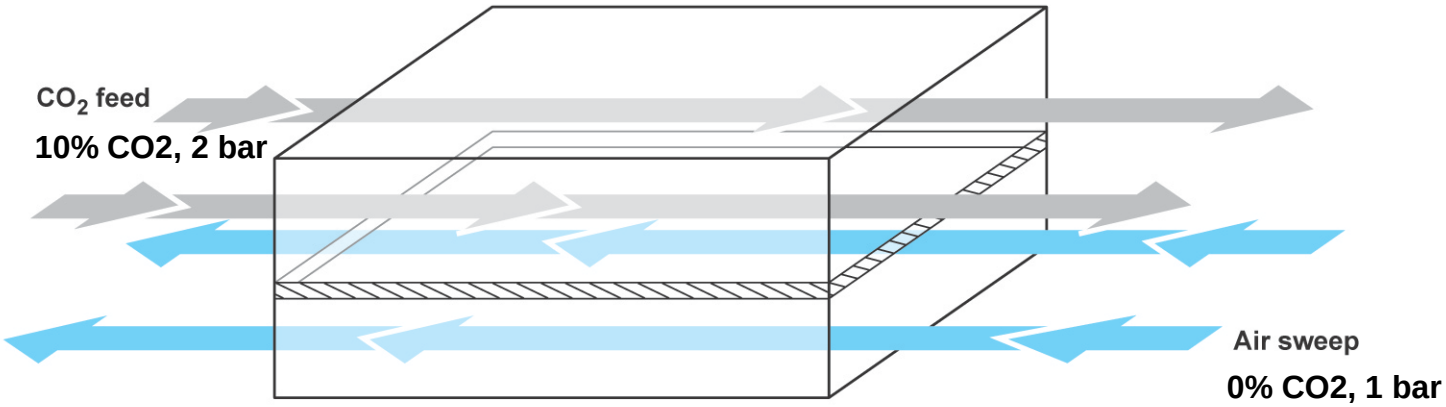
# Counter Current Sweep
# The Effect of Sweep Ratio






At low sweep ratios, pressurized feed is needed

# Counter-Current Sweep




**Counter-current sweep is the most efficient design but most difficult to make.**



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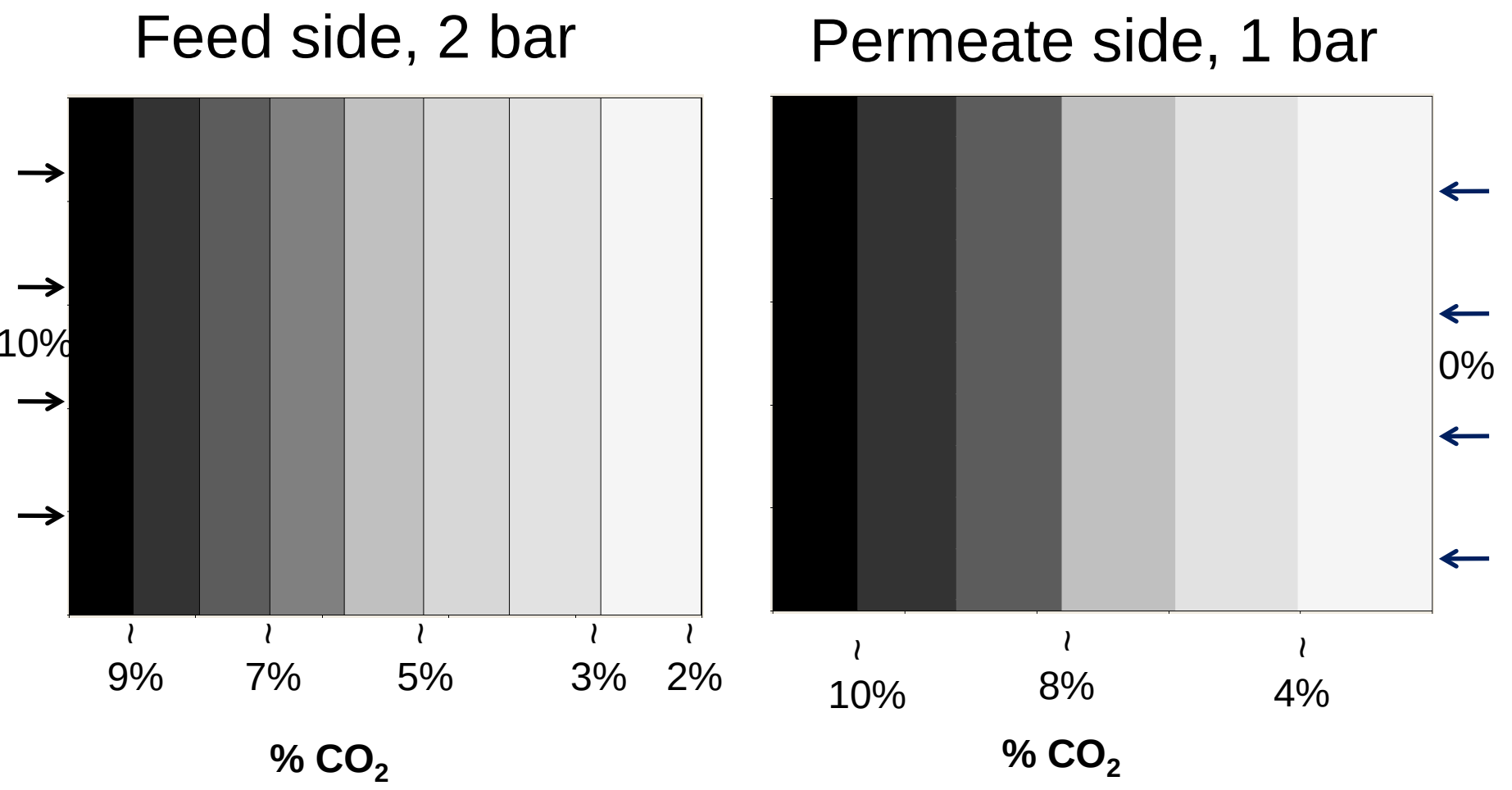
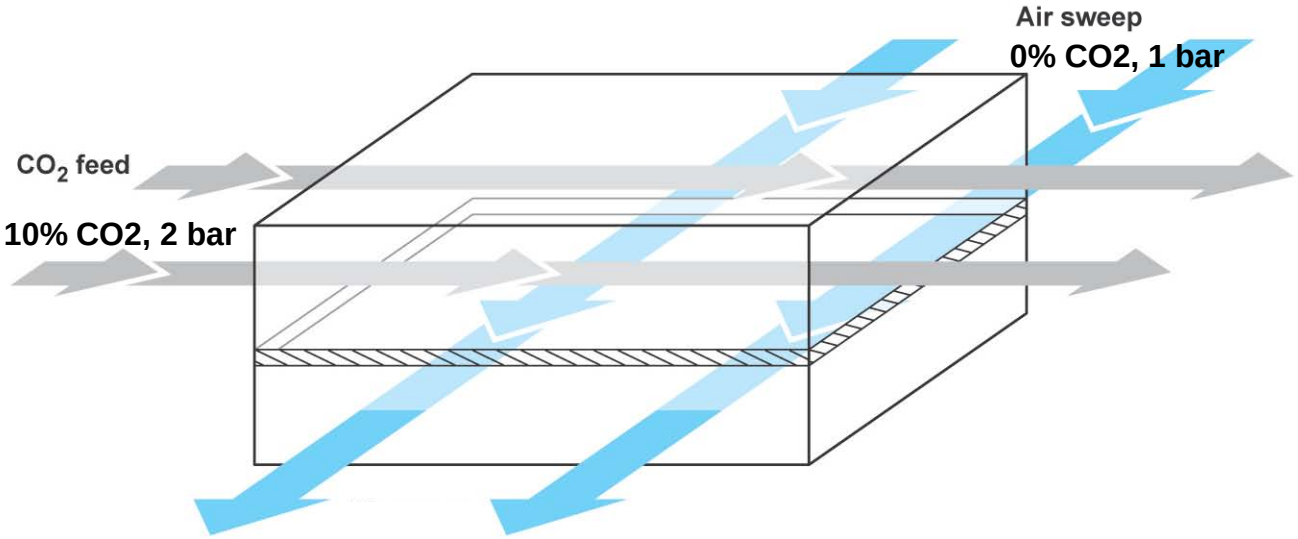
# Counter-Current Sweep

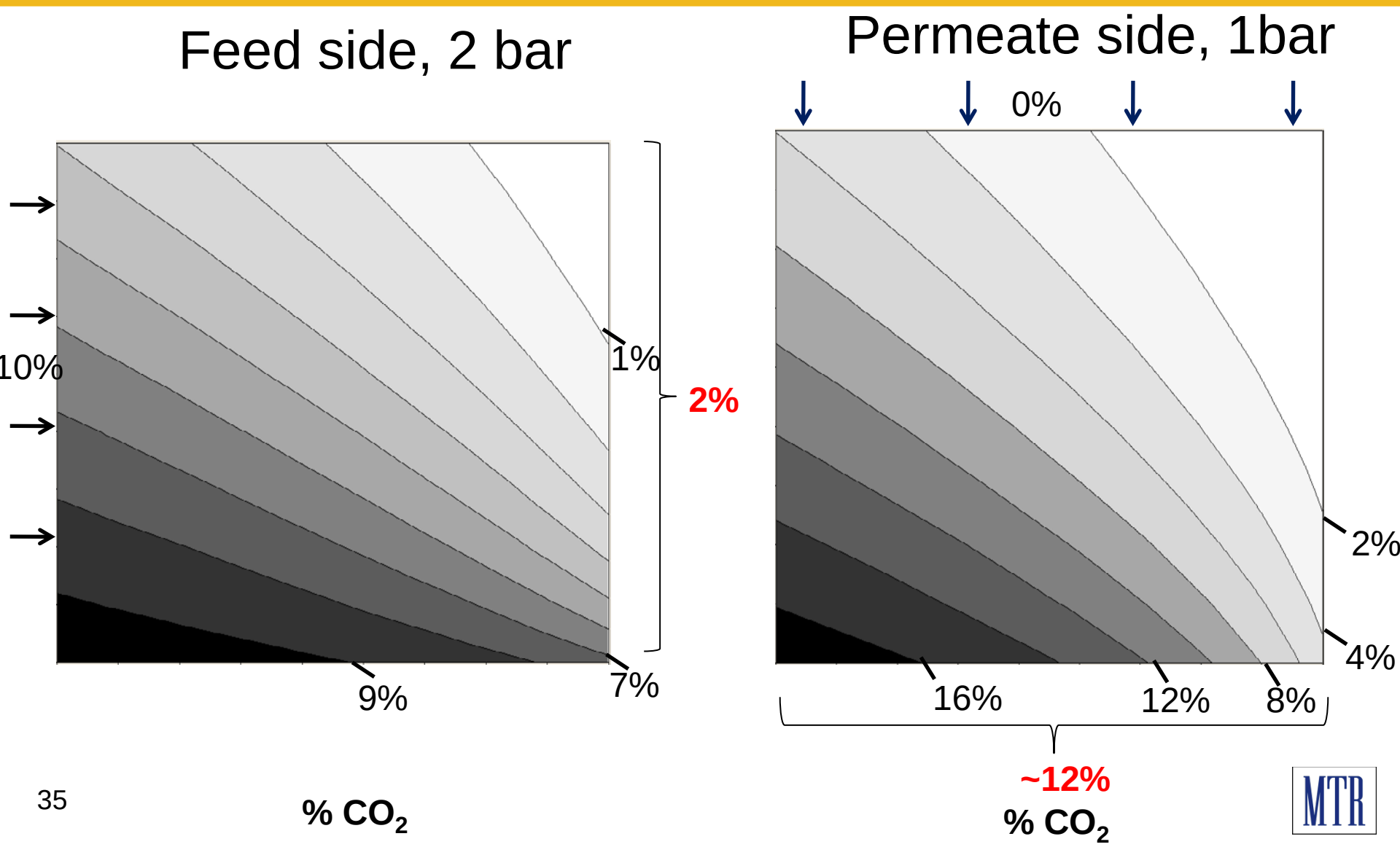


# Cross-Flow Sweep

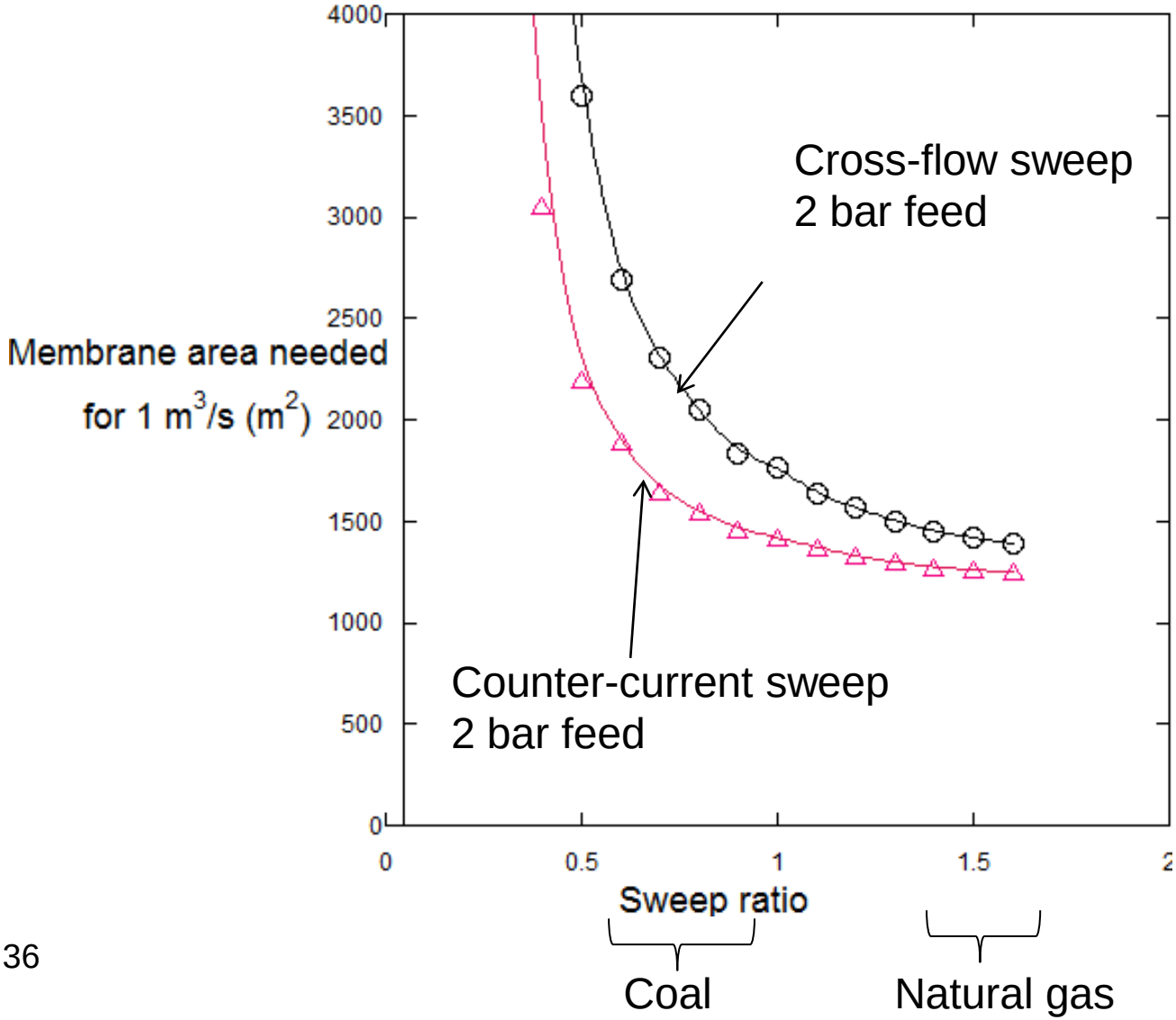



**Cross-flow sweep is a less efficient design but easier to make and has less pressure drop on the permeate side.**

# Cross-Flow Sweep



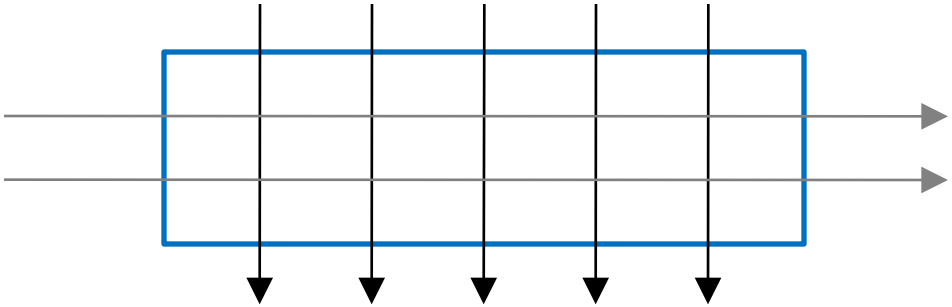
# Comparison Between Counter-Current Sweep And Cross-Flow Sweep




**Sweep ratio @ 0.7, 40% more membrane area is needed for cross-flow module**

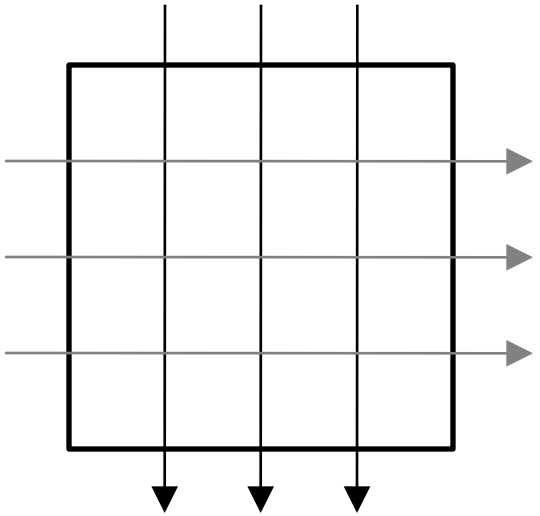
# Our Approach

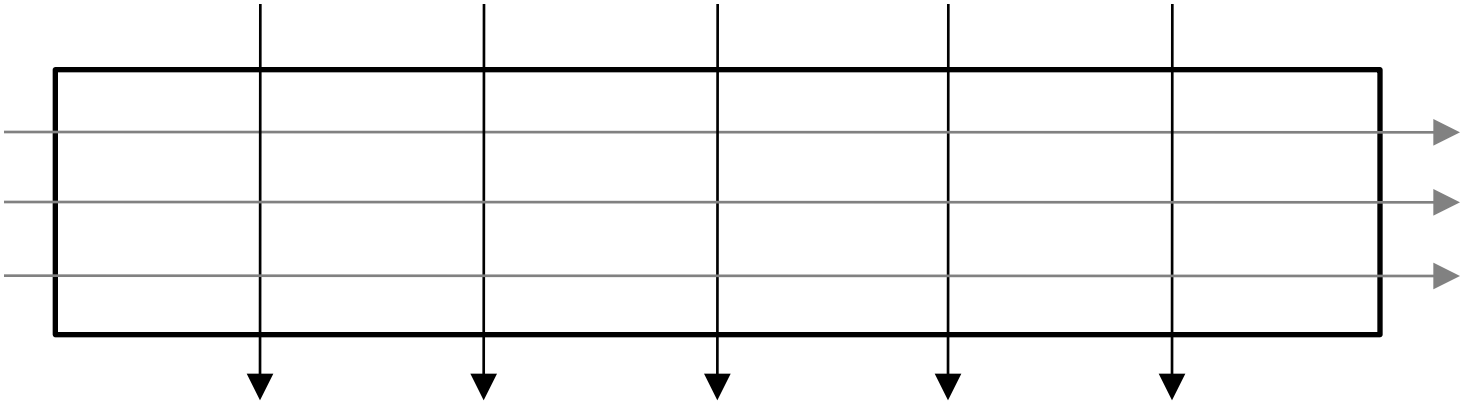
- Develop the Module in Stages
  - Increasing Module Size
  - Moving from Cross-Flow to Counter-Flow
- Year 1
  - Develop Sealing Techniques
  - Select the Optimum Spacers
  - Pressure Drop Milestone:  < 5 PSI
  - Cross-Flow Modules (~20 $m^2$)
    - 0.3 m X 1.0 m Sheets



# Our Approach - Year 2

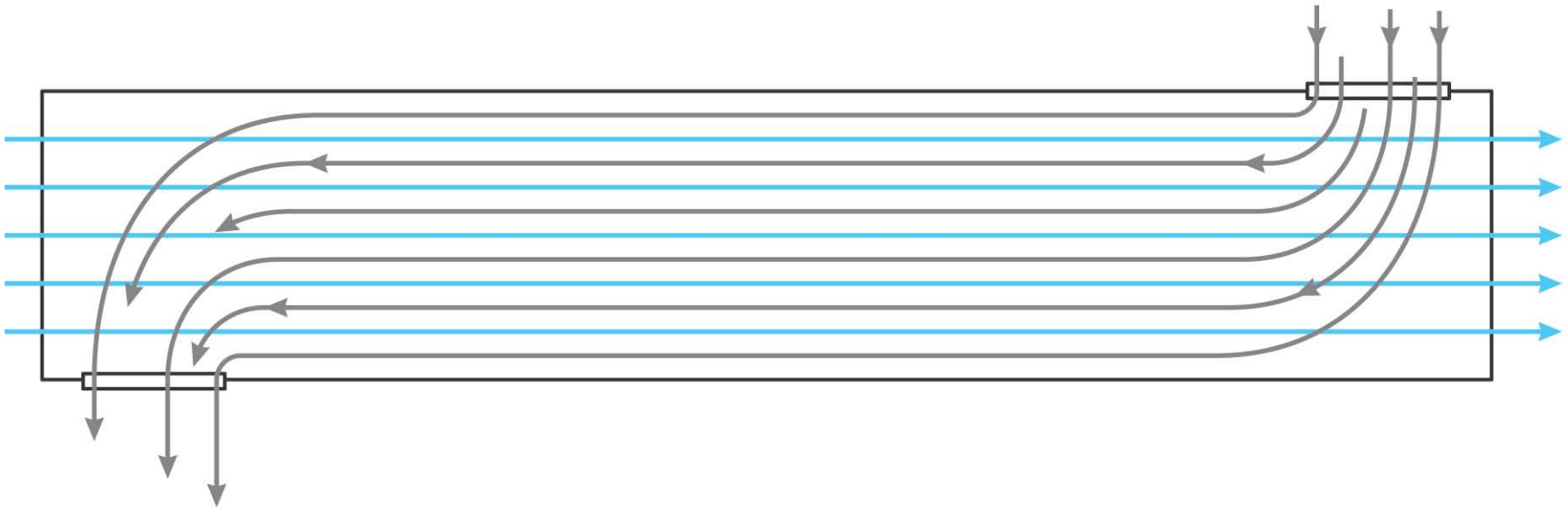
- Solve Scale-Up Issues
- Develop Larger Cross-Flow Modules
  - 1 m X 1 m (~100 $m^2$)
  - 1 m X 5 m (~100 $m^2$)
- Pressure Drop Milestone: < 2.5 PSI
- Test at MTR and
  on the 1 TPD NCCC Skid





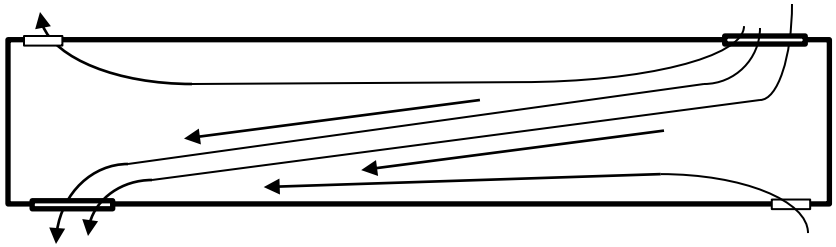
# Our Approach - Year 3

- Develop Counter-Flow, Full Scale Modules
  - 1 m X 5 m (500 $m^2$)
- Evaluate Different Spacer and Flow Configurations
- Pressure Drop Milestone: ≤ 1.5 PSI
- Test on the 20 TPD NCCC Skid (?)



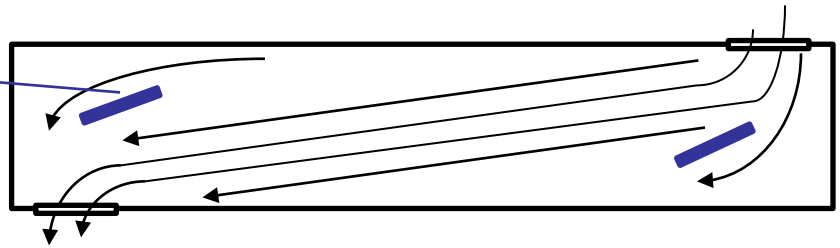
# CFD Calculations and Tomography Measurements

- Use CFD Calculations to Analyze Various Spacers and Membrane Sheet Aspect Ratio
- Make Model Modules and Evaluate with Tomography Measurements



**Small Side Ports to Eliminate Low Flow Areas**

**Flow Directing Baffles**



**Use Baffles to Even Out Flow**



MTR

# Program Plan/Schedule – See proposal

| Task # | Task Description | Year 1 | Year 2 | Year 3 |
|---|---|---|---|---|
| 1 | Project Management | | | |
| 2 | Make Modules | | | |
| 3 | Make Small Modules | | | |
| 4 | Construct Test Unit | | | |
| 5 | Test Modules | | | |
| 6 | Initial CFD Design | | | |
| 7 | Make Membrane | | | |
| 8 | Make Full Footprint Modules | | | |
| 9 | Prepare Tooling for Large-Scale Modules | | | |
| 10 | Refine CFD/Tomography | | | |
| 11 | Evaluate Process Designs | | | |
| 12 | Make Membrane | | | |
| 13 | Prepare Full-Scale Modules | | | |
| 14 | Test Full-Scale Modules | | | |
| 15 | Evaluate and Cost Process Designs | | | |
| 16 | Select and Prepare Best Integrated Scheme | | | |