A Membrane Process to Capture CO_2 from Coal-Fired Power Plant Flue Gas

Projects NT43085 and NT05312

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NETL review meeting
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Outline

- Project timeline and objectives overview
- Introduction to MTR
- Membrane technology background
- Results to date (project NT43085)
- New project (NT05312) objectives and future plans

Project overview

Project number NT43085

Project period: 4/1/07 to 3/31/09

Funding: $788,266 DOE; $197,066 MTR

DOE program manager: Heino Beckert, Bruce Lani

Participants: MTR, DOE

Project scope: investigate the feasibility of new polymer membranes and process for cost-effective capture of CO_2 from power plant flue gas.

All project objectives were met within time and budget; details to follow.

Project number NT05312

Project period: 10/1/08 to 9/30/10

Funding: $3,439,200 DOE; $957,630 cost share

DOE program manager: Jose Figueroa

Participants: MTR, APS, EPRI, DOE

Project scope: field demonstrate the MTR membrane process with commercial-sized components at APS's Cholla coal-fired power plant; at the conclusion of the project, be in a position to gauge the technical and economic viability of membrane-based CO_2 capture from flue gas.

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Introduction to MTR

MTR designs, manufactures, and sells membrane systems for industrial gas separations

Petrochemicals: Propylene/Nitrogen

Hydrogen (Refinery):

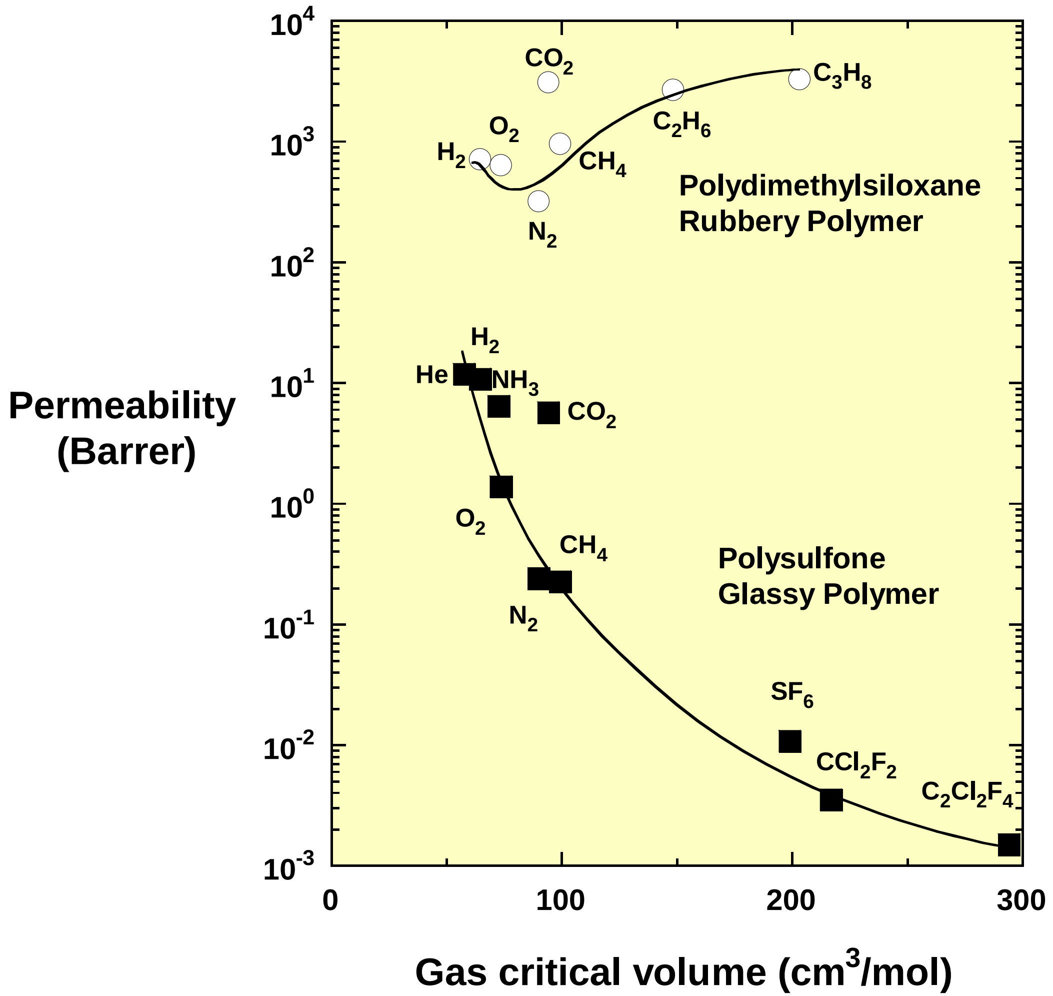
H_2/CH_4, CO, CO_2

Natural Gas:

CO_2/CH_4, CH_4/N_2

NGL/CH_4

Membrane technology basics



1 Barrer = 10^{-10} cm^3 (STP) cm / (cm^2 s cmHg)

Diffusivity selectivity: favors small molecules

$$\alpha_{A/B} = \frac{P_A}{P_B} = \left(\frac{S_A}{S_B}\right) \times \left(\frac{D_A}{D_B}\right)$$

Solubility selectivity: favors large molecules

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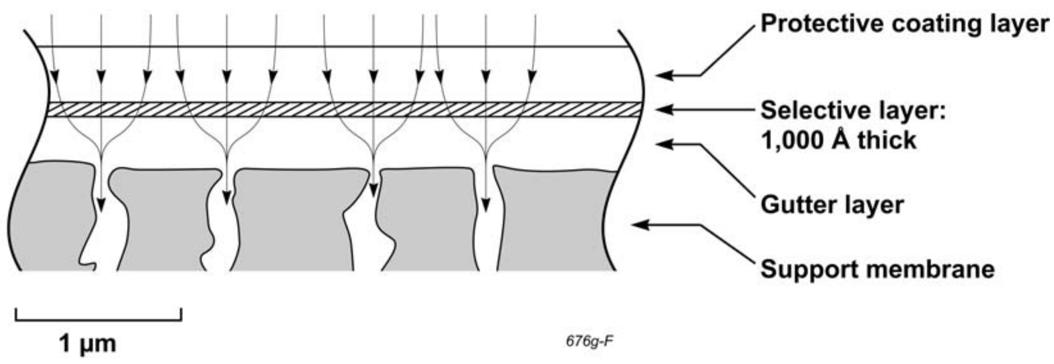
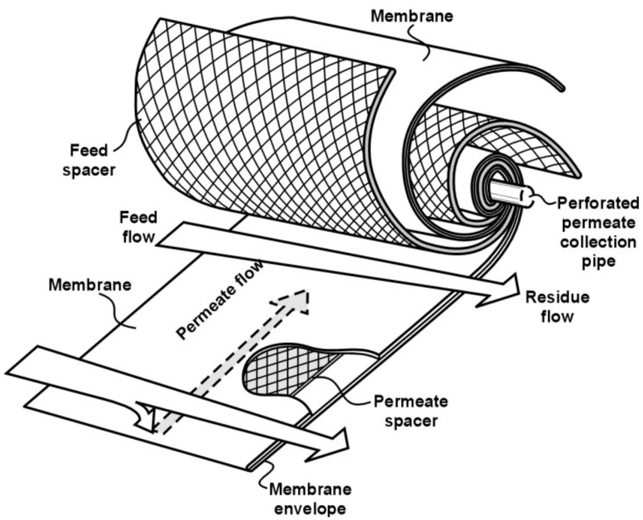
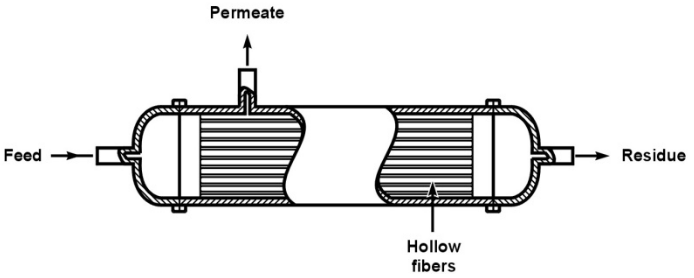
Membrane technology basics

- Membranes have to be thin to provide useful fluxes.

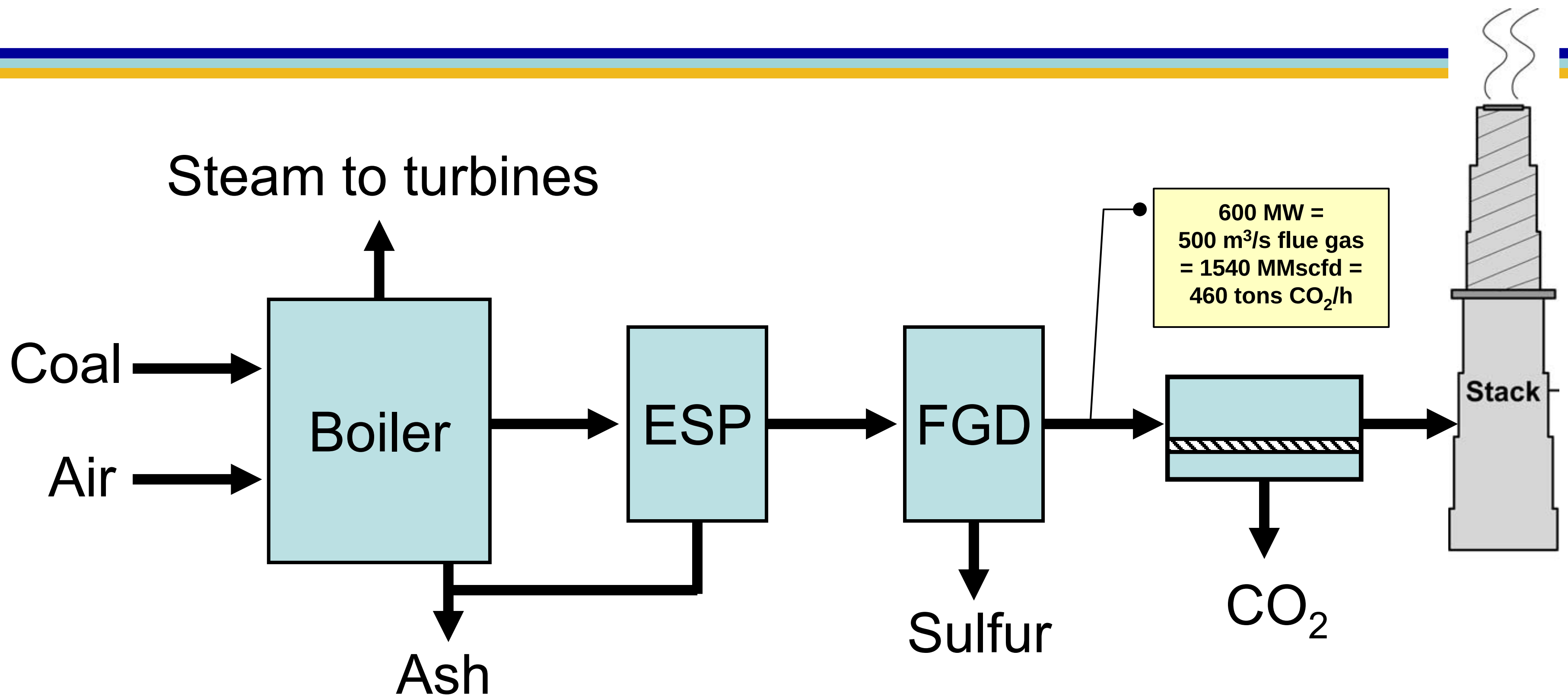


- Spiral-wound and hollow fiber modules are used.





Flue gas cleanup in a coal-fired power plant



Membrane challenges for treating this large volume of low-pressure gas:

- Large membrane area needed → high CO_2 permeance is a must!
- How to generate driving force w/o using large compression or vacuum power
- Potential harmful contaminants include fly ash, SO_2, water, and trace metals.

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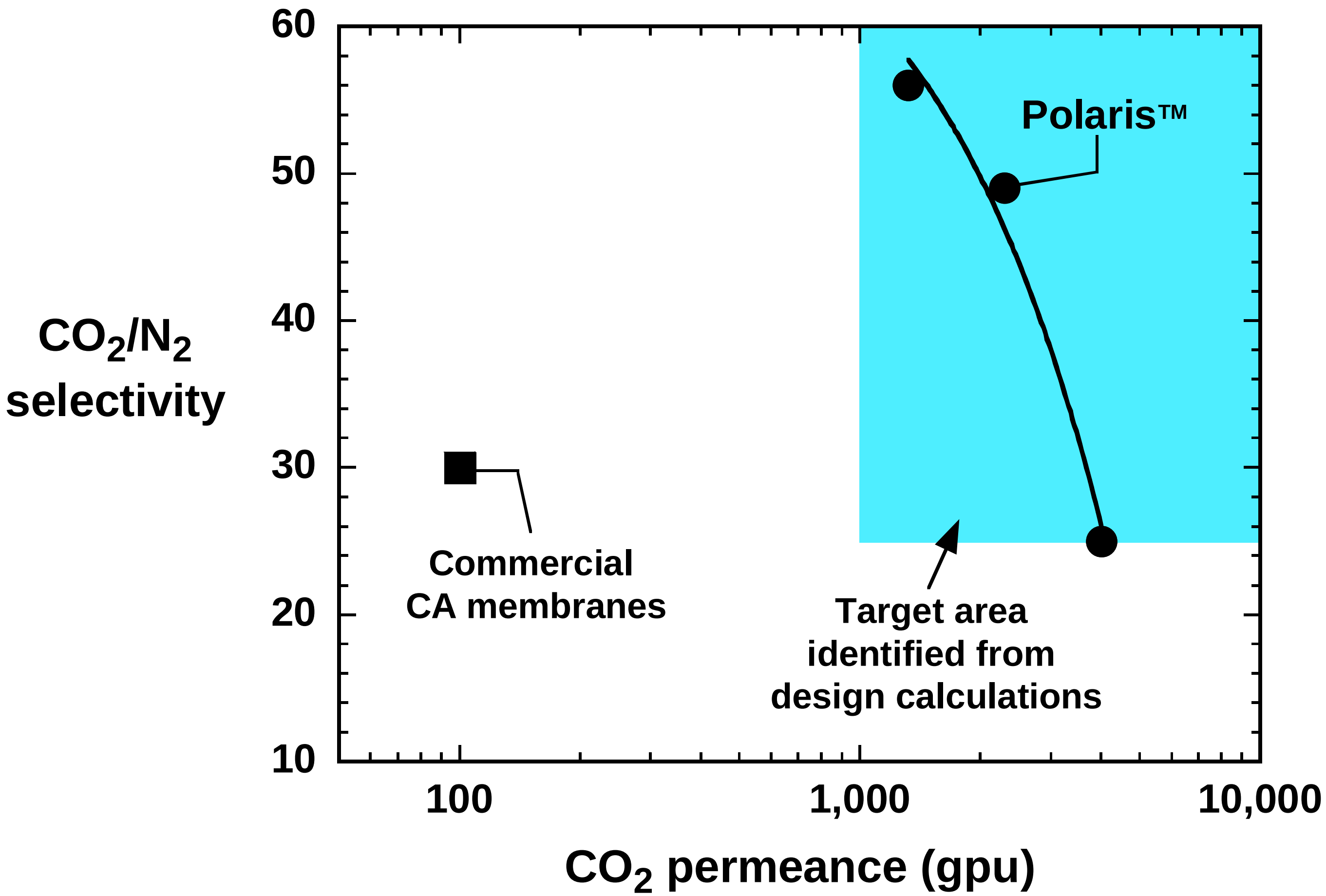
Polaris™ membranes are extremely permeable to CO_2



Pure-gas data at 25°C and 50 psig feed pressure

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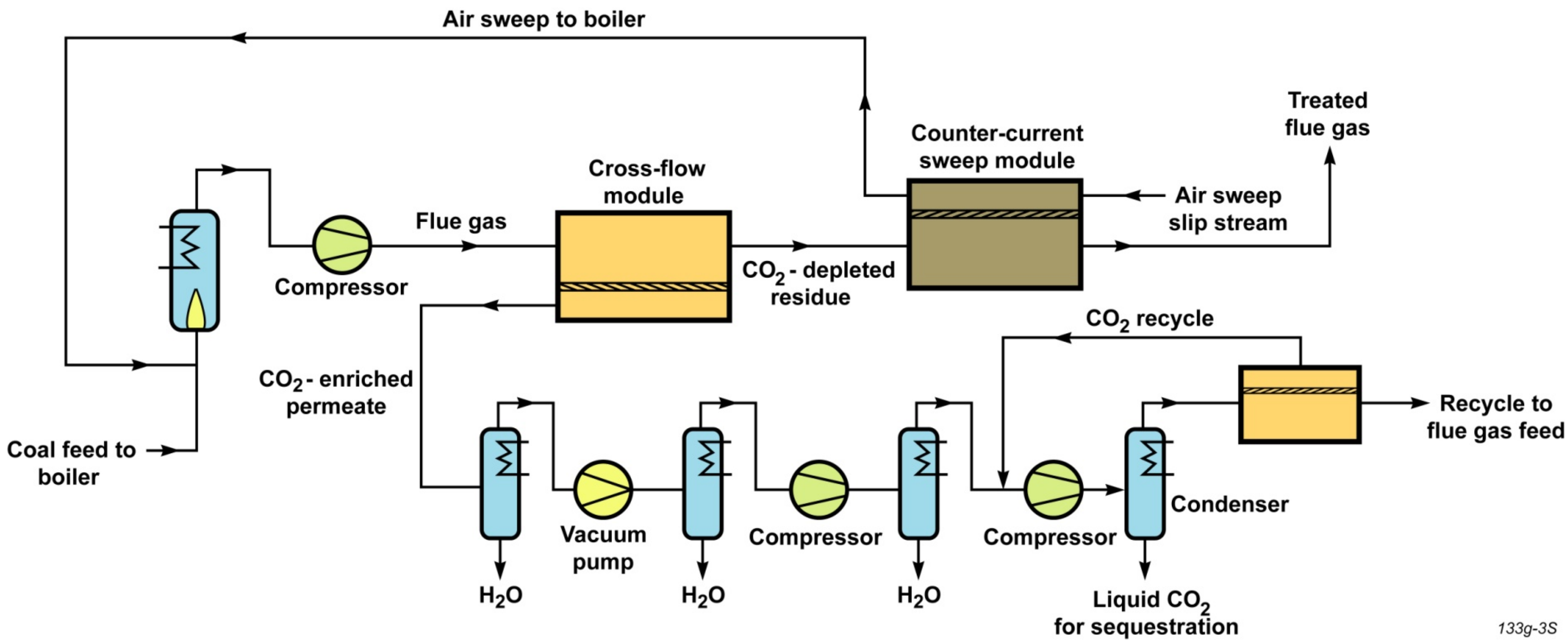
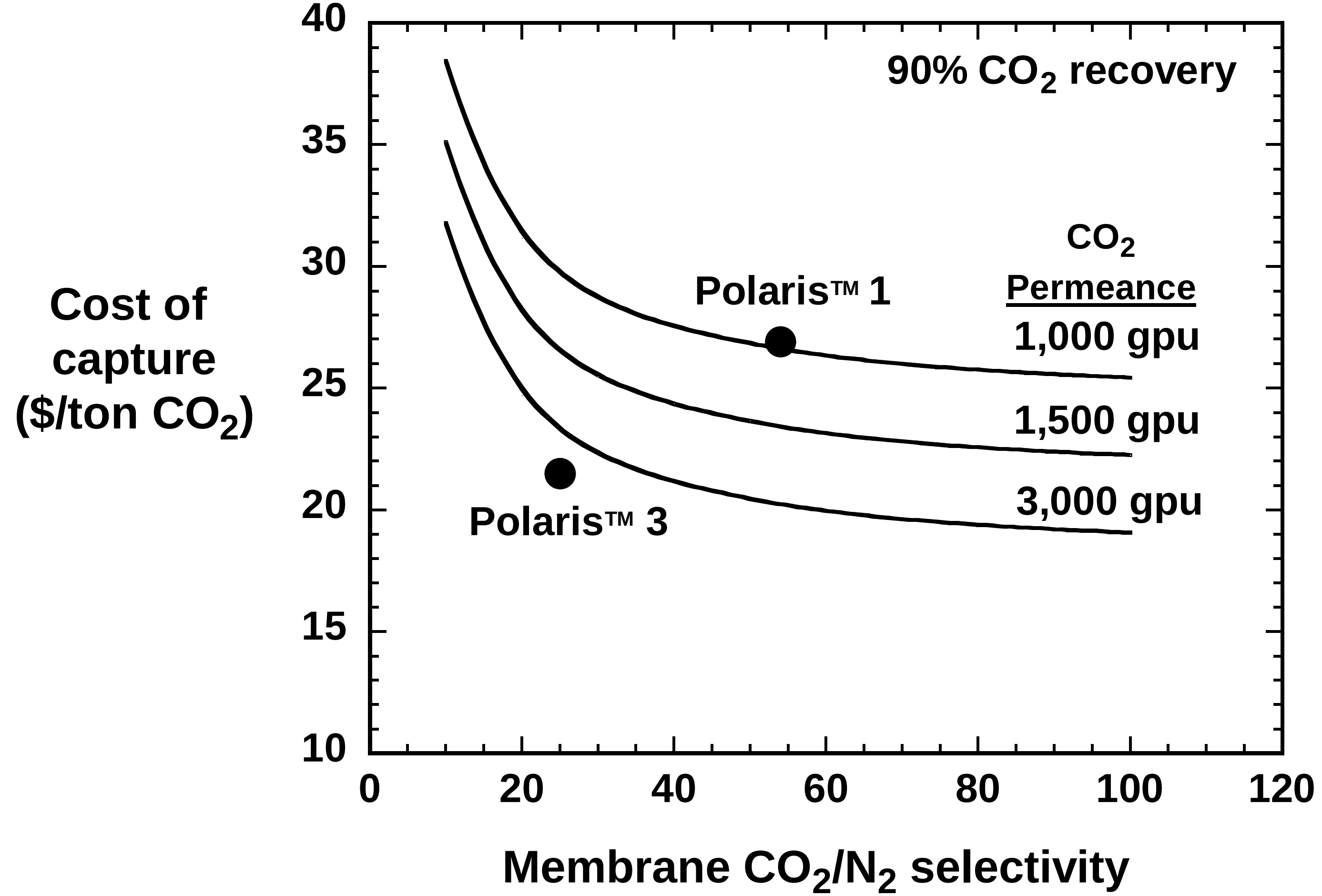
MTR's process design for flue gas CO_2 capture



- Countercurrent sweep with combustion air provides "free" driving force.
- 90% capture as liquid CO_2 can be achieved using about 15% of plant energy.
- Even with Polaris™, 0.5 to 1 million m^2 of membrane area are required for 90% CO_2 capture from a 600 MW_e plant.

High CO_2 permeance reduces capture cost more than high selectivity



Cost assumes membrane at $150/m² and includes CO_2 compression

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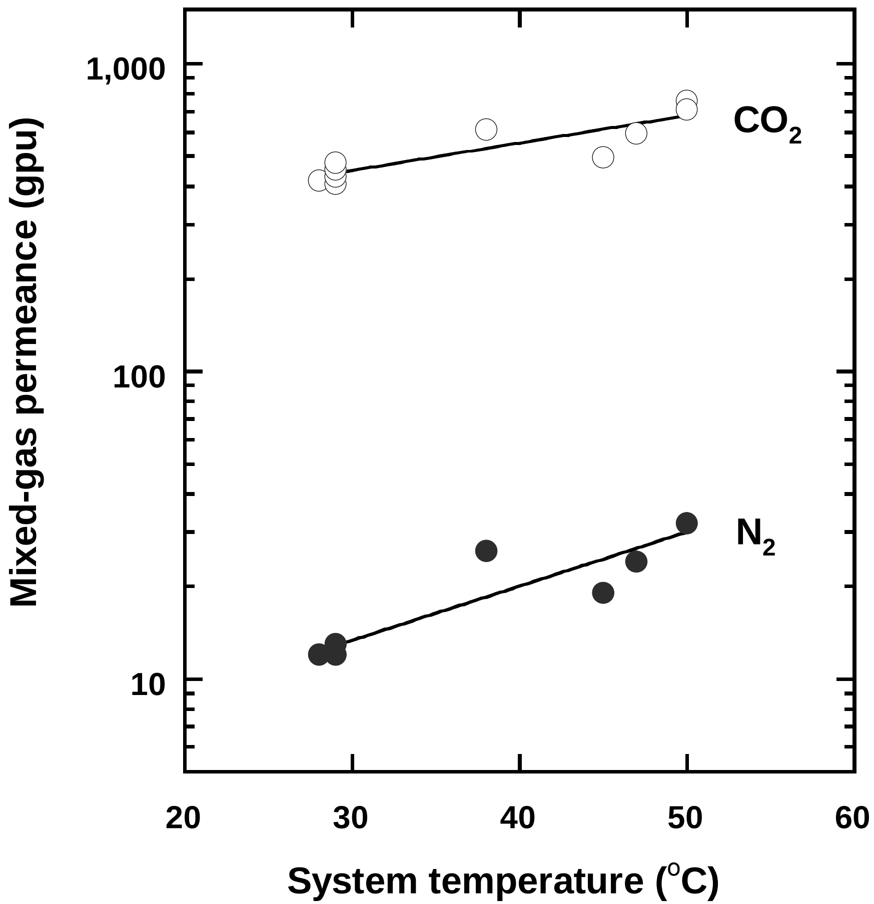
Polaris™ membrane has been scaled-up to commercial size

Polaris™ membrane and module scale-up

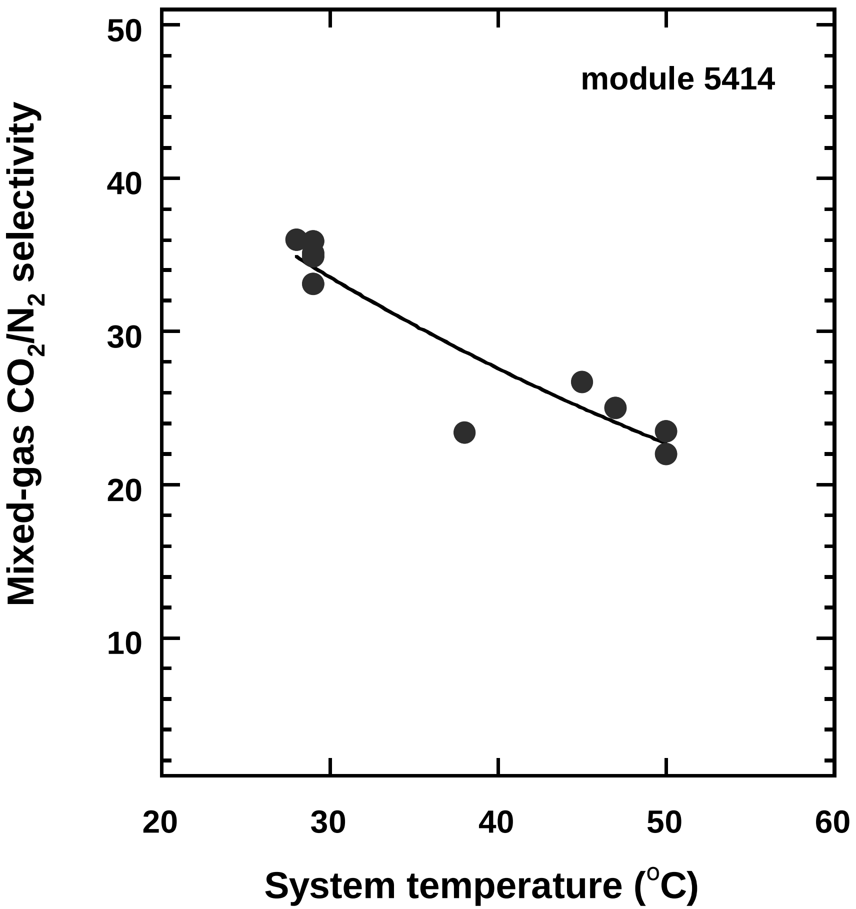
- More than 500 m^2 of membrane were produced on commercial-sized equipment.
- 8-inch diameter modules were fabricated and tested.

Mixed-gas module performance

Permeance

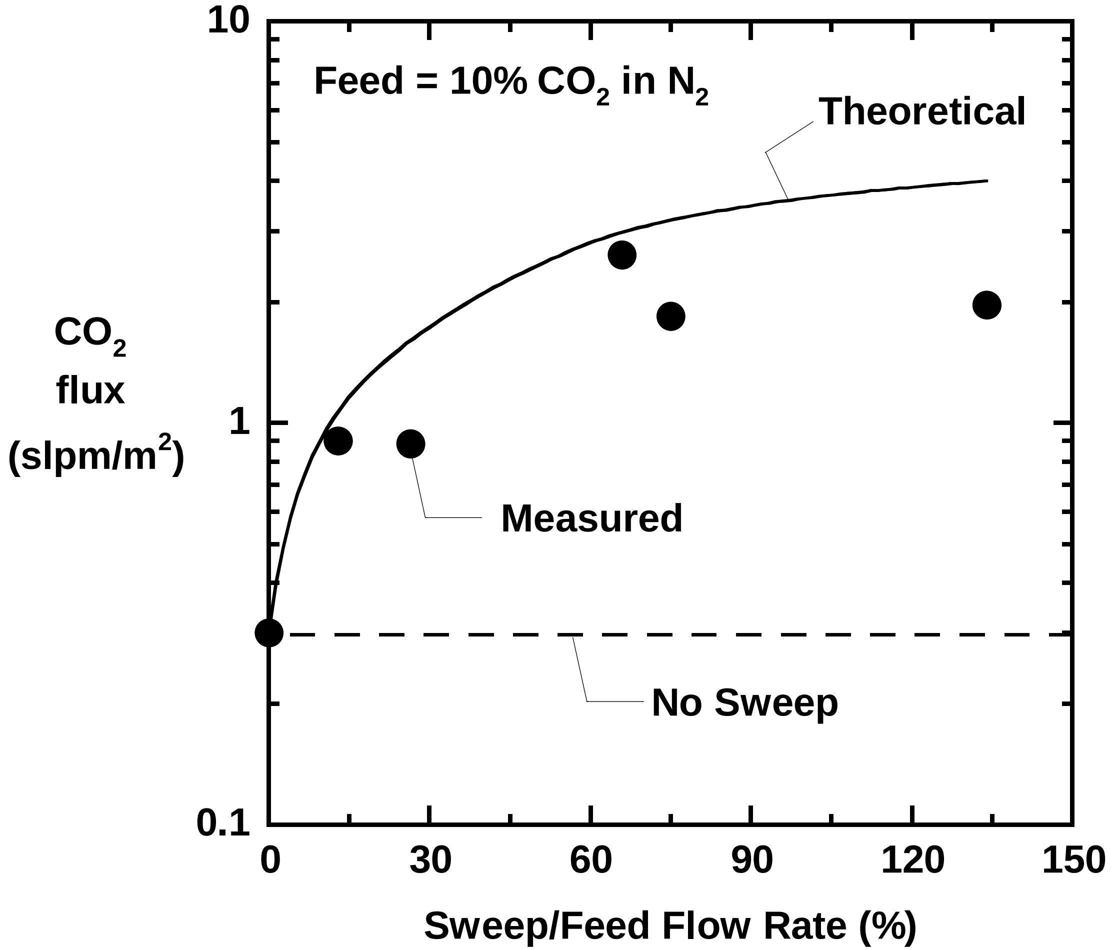


Selectivity



Mixed-gas selectivity is lower than pure-gas and decreases with increasing temperature. At 50°C, module selectivity is still >20.

Spiral-wound countercurrent sweep modules work



The optimal capture process uses about 100% sweep/feed ratio. At this sweep rate, the module shows a 10-fold increase in CO_2 flux compared to no sweep.

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Polaris™ membrane systems have proven field experience

BP Pascagoula

- Conducted 3-month field test of 8-inch diameter Polaris™ membrane modules.
- Removed CO_2 and higher hydrocarbons from raw natural gas.

APS Red Hawk power plant

- Uses 8-inch diameter Polaris™ membrane modules.
- Captured CO_2 will be used for biofuels production.

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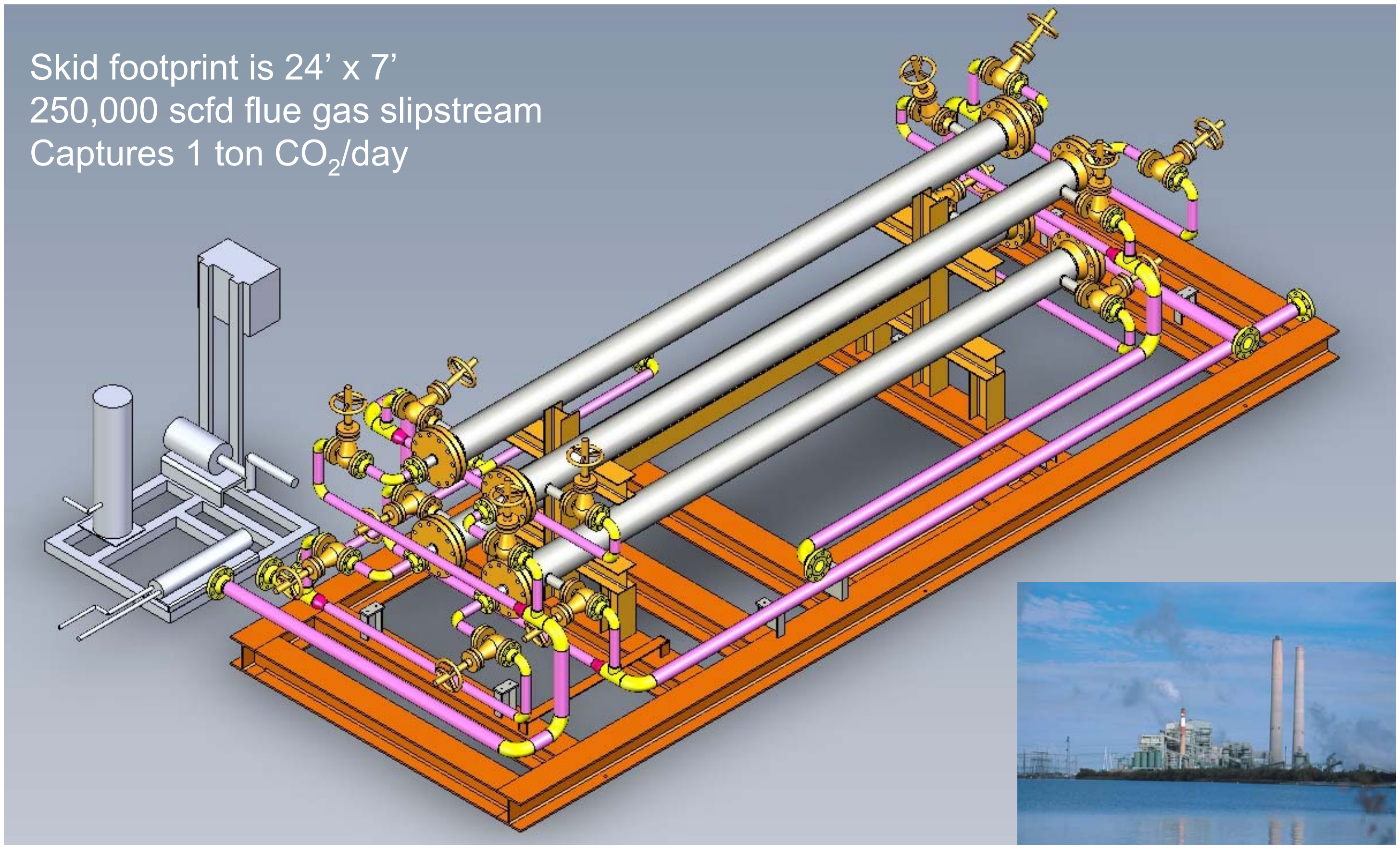
Cholla field test



- A 6-month field test of 8-inch diameter Polaris membrane modules at Cholla coal-fired plant is scheduled to begin in 4Q09.
- Key objectives are to demonstrate sweep operation in commercial-sized modules and to investigate membrane lifetime.

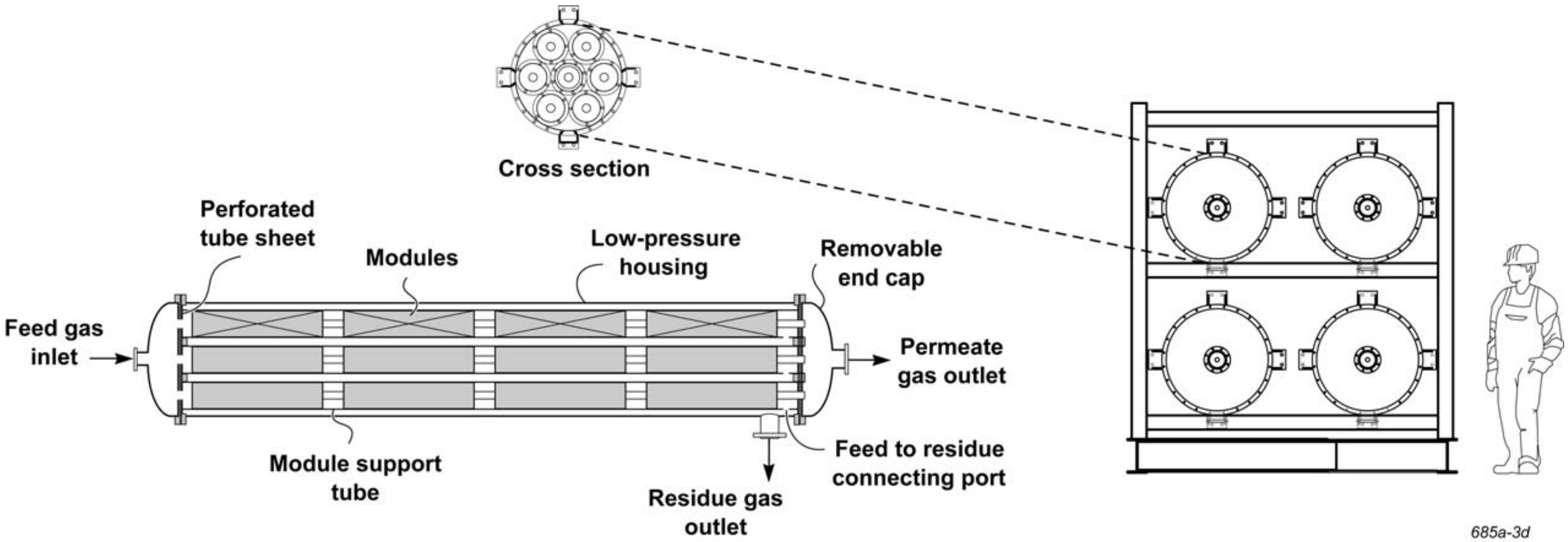
Membrane plants of the required size exist today

Ashkelon desalination plant

- 40,000 spiral-wound RO membrane modules
- 1.5 million m^2 membrane area

- Total energy use in plant is 56 MW; uses 5.5 MW water pumps.
- Plant produces 100 million m^3/yr of fresh water.

Efficient module packing and low-cost components reduce installed cost



Type of unit	Typical cost ($\$/m^2$)	
	High-pressure gas separation (steel vessels)	Reverse osmosis (plastic vessels)
Membrane	20	5
Membrane modules	100	10-15
Installed modules in a skid	570	20-50

About 130 mega-module skids would be required for a 600 MW_e power plant.

Advantages and challenges

Advantages:

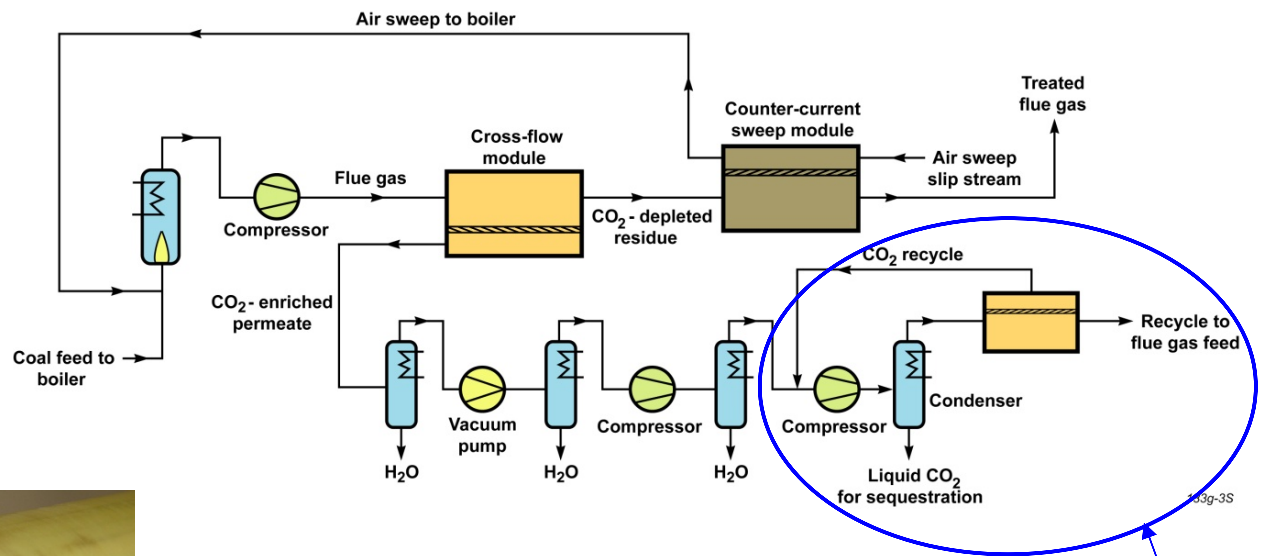
- Simple operation; no chemical reactions, no moving parts
- Tolerance to high levels of wet acid gases; inert to oxygen
- Compact and modular with a small footprint
- Low energy use; no additional water used (recovers water from flue gas)
- Builds on existing, low-cost technology already used at a similar scale

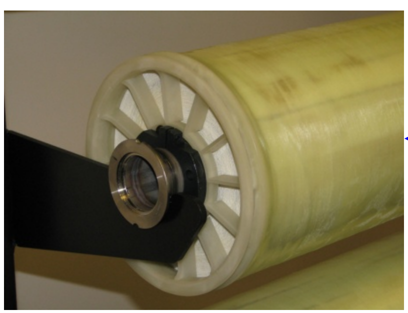
Challenges:

- Particulate matter and its potential impact on membrane lifetime
- Energy losses due to feed and permeate side pressure drops
- Cost reduction and device scale-up issues
- Integration with power plants and effect of recycle on boiler
- Lack of operating experience in the power industry

Future plans beyond the current project

① Develop plans for a 50-100 ton CO_2/day system





② Incorporate low-cost components (target $150/m²)

③ Include CO_2 liquefaction section

④ Explore options for testing air recycle to boiler

Summary

- Earlier project demonstrated the potential of high permeance membranes and a novel process design to cost-effectively capture CO_2 from coal-fired flue gas.
- Operating experience with real flue gas is critical. The upcoming field test at Cholla will be a key test of the membrane approach.
- The scale-up and cost reduction roadmap can be modeled on existing membrane technology.
- Next step is a 10-fold larger system that demonstrates low-cost components and CO_2 liquefaction.

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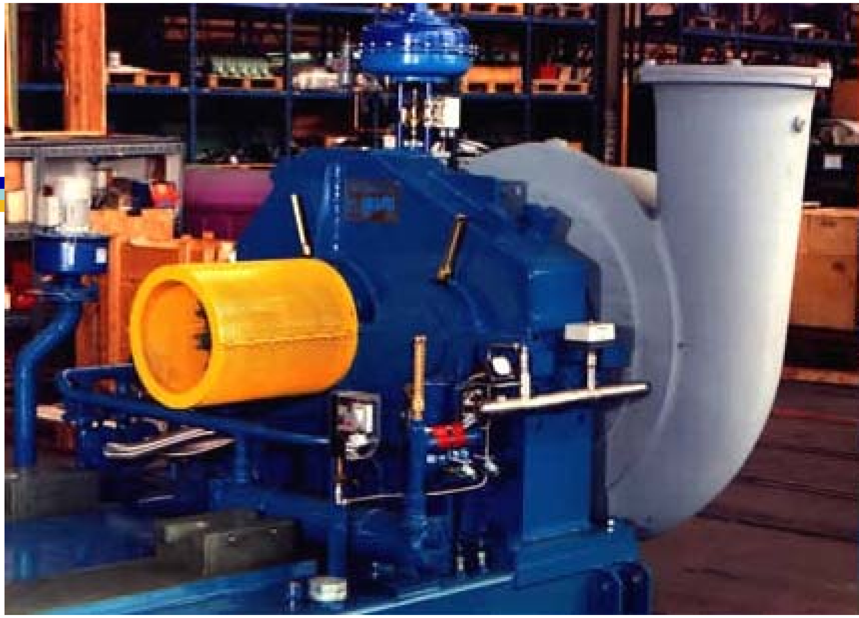
Acknowledgements

- DOE NETL – Heino Beckert, Jose Figueroa
- APS – Ray Hobbs, Xiaolei Sun
- EPRI – Abhoyjit Bhown, Brice Freeman, Dick Rudy, George Offen

Extras



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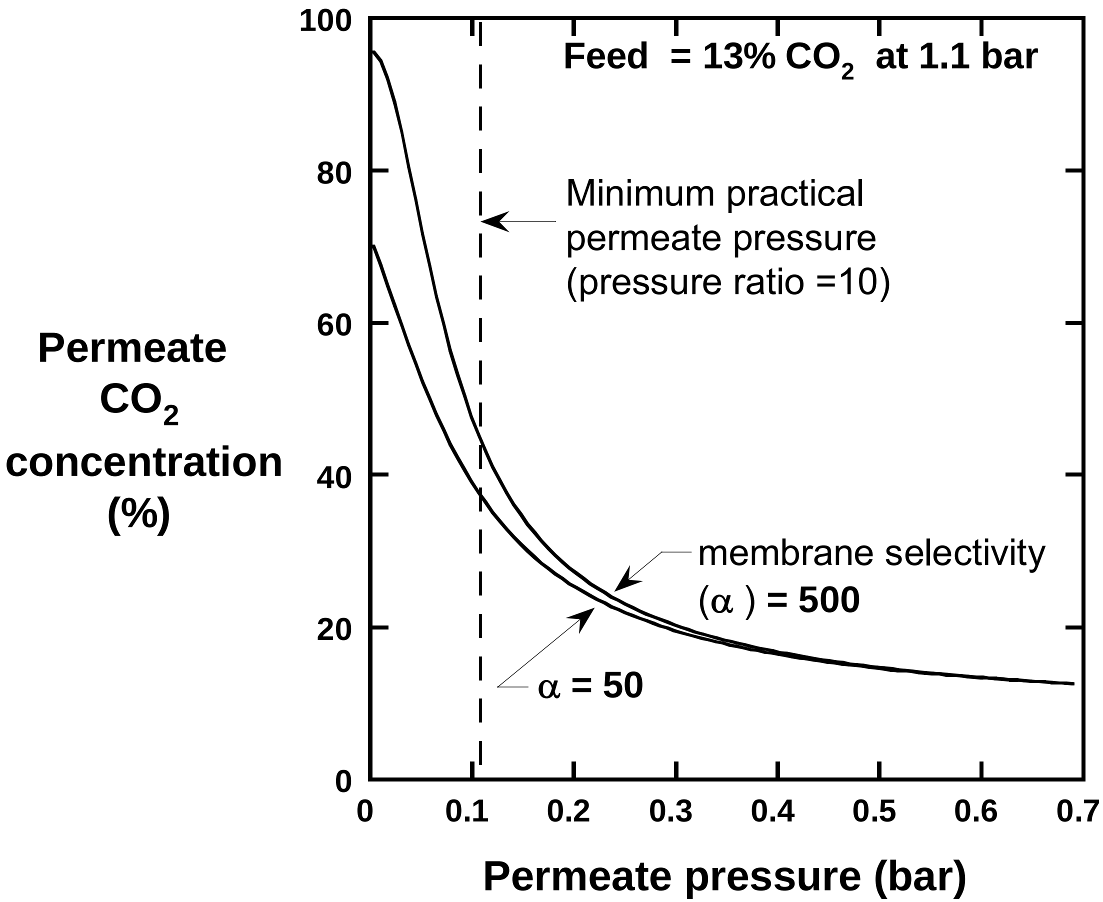
Why doesn't high membrane selectivity help?

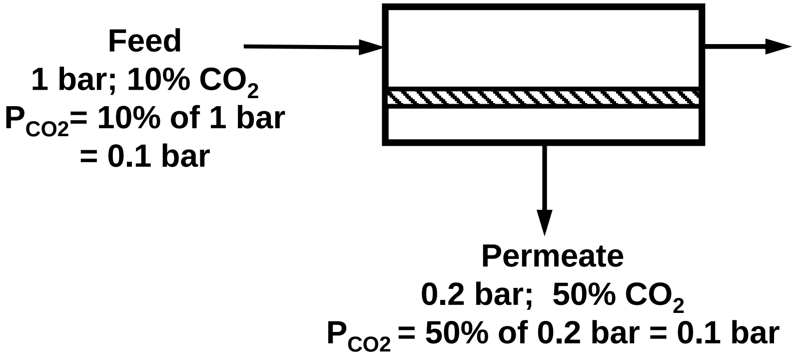


The separation is pressure ratio limited, and

- high selectivity demands high membrane area.
- increasing the pressure ratio is energy intensive.

Understanding membrane process design is important to direct materials development

The importance of pressure ratio



$$\text{Membrane enrichment} \leq \text{Pressure ratio}$$

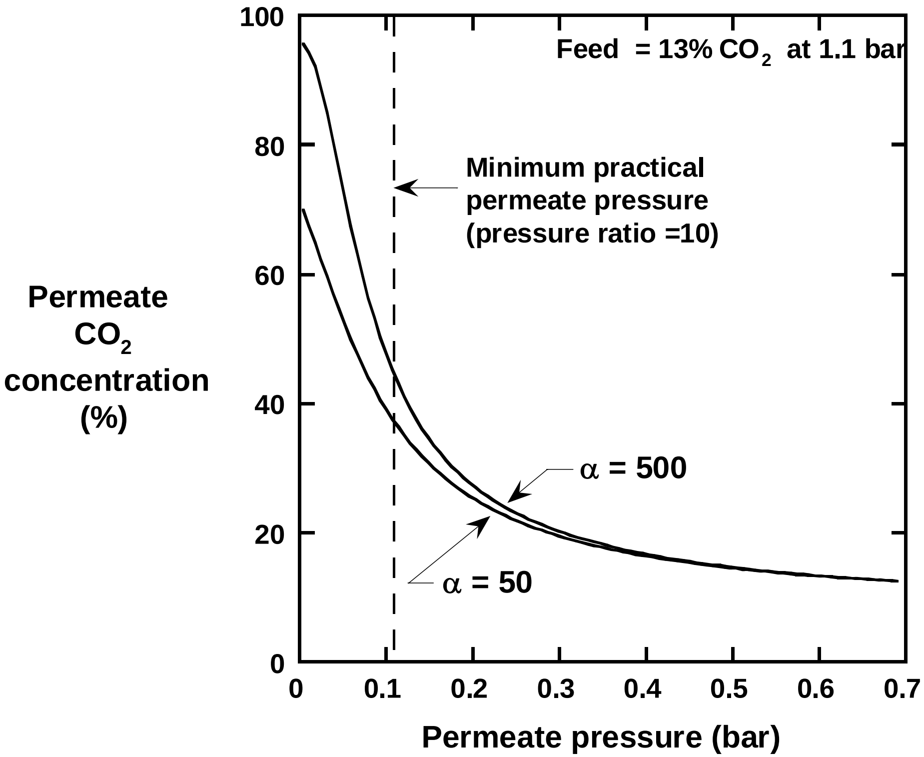
$$\left(\frac{\textit{permeate conc}}{\textit{feed conc}}\right) \leq \left(\frac{P_{feed}}{P_{permeate}}\right)$$

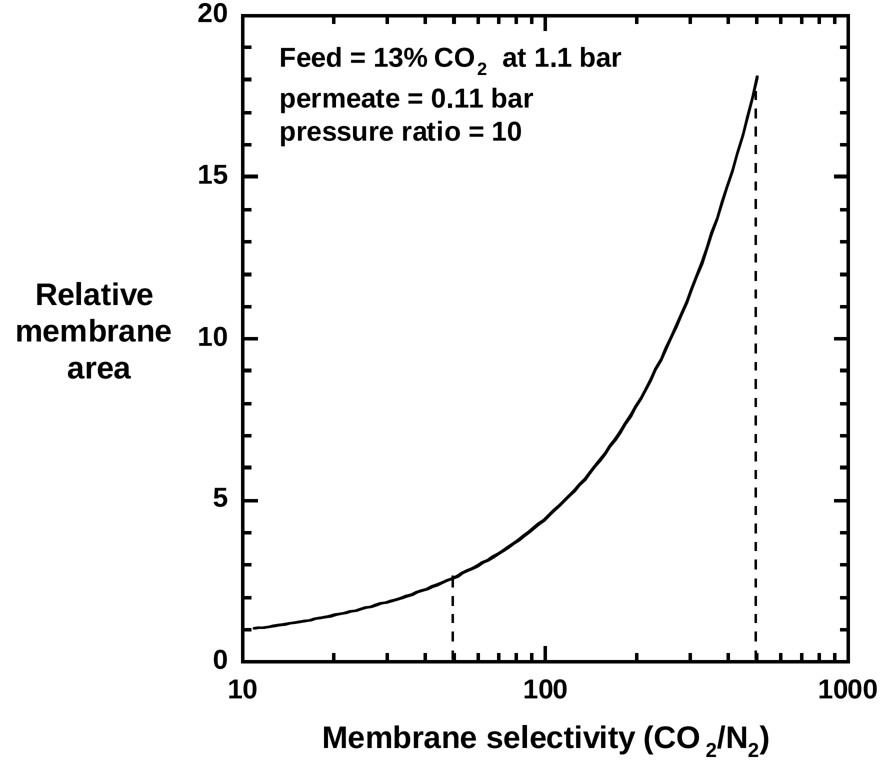
$$\left(\frac{50\%}{10\%}\right) \leq \left(\frac{1\,bar}{0.2\,bar}\right)$$

For this example,

- the concentration of CO_2 in the permeate can never exceed 50% no matter how selective the membrane
- At least half the permeate must be the slow component (N_2)
- Permeation of the slow component determines the membrane area
- Infinite selectivity = no slow component permeation = infinite membrane area

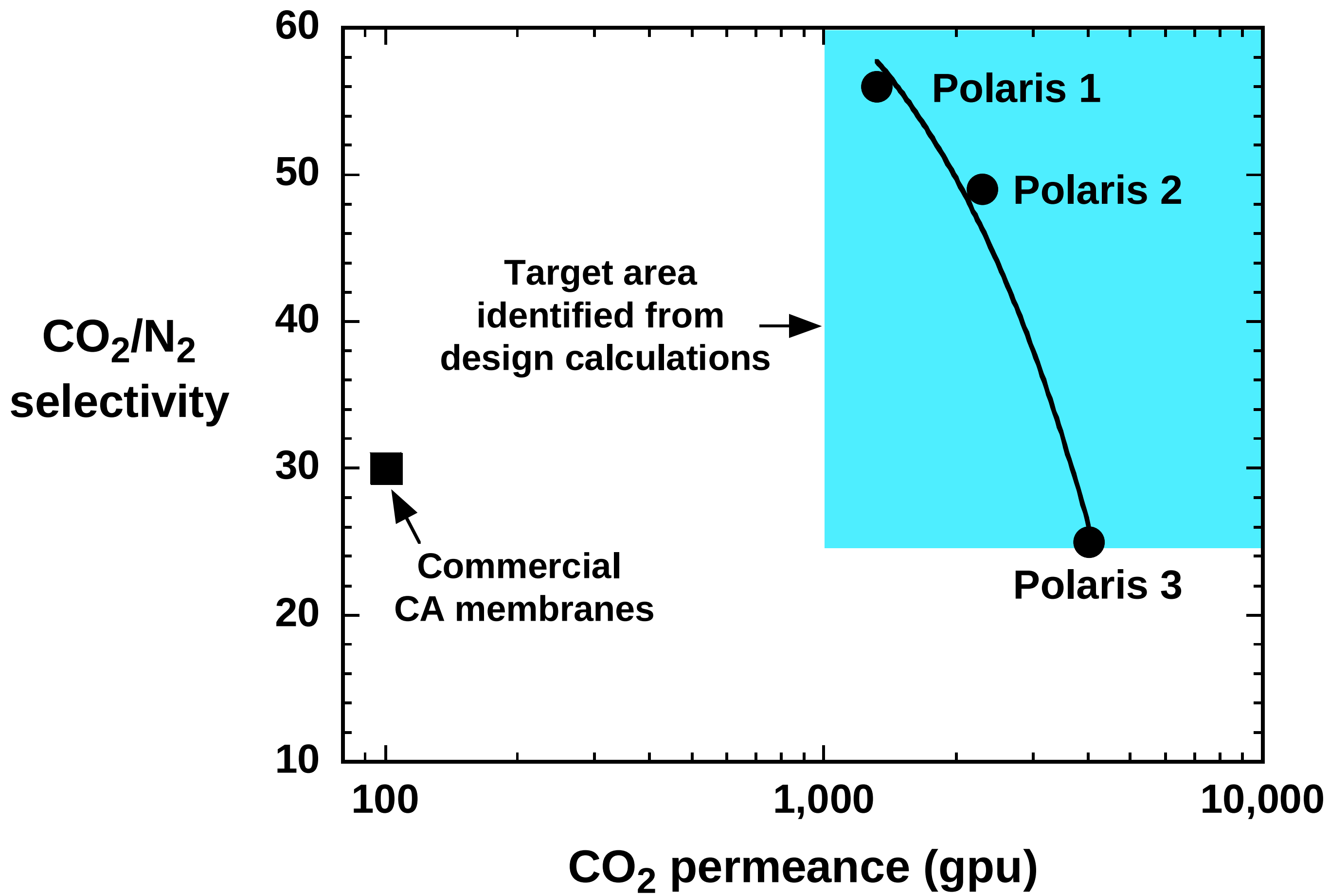
Would a membrane with higher selectivity help?





No! The separation is pressure ratio limited, and high selectivity demands high membrane area

Polaris™ membranes are extremely permeable to CO_2



Pure-gas data at 25°C and 50 psig feed pressure

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Project overview

- Initial 2-year project (4/1/07 to 3/31/09) investigated the feasibility of new polymer membranes to cost-effectively capture CO_2 from flue gas.
- All objectives were met within time and budget; key findings include:
  - Membranes can be fabricated into commercial modules; membrane permeance is 10x higher than existing materials and stability in acid gases looks good.
  - For a real-world membrane system, membrane permeance is much more important than selectivity.
  - Novel design shows promise to capture 90% CO_2 using <15% of plant energy.
- New 2-year, $4.4 million project (10/1/08-9/30/10) with EPRI and APS will field demonstrate the membrane process with commercial-sized components; key objectives are:
  - Run a 6-month field test at APS's Cholla coal-fired power plant.
  - With EPRI, conduct a comparative economic analysis of the proposed process.
  - Develop low-cost component prototypes and a cost reduction roadmap.
  - Investigate scale-up issues and begin plans for next-stage, 10x larger demonstration.

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Key remaining challenges to be addressed in the current project

- Particulate matter and its potential impact on membrane lifetime
- Energy losses due to feed and permeate side pressure drops
- Cost reduction and device scale-up issues
- Lack of operating experience

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