

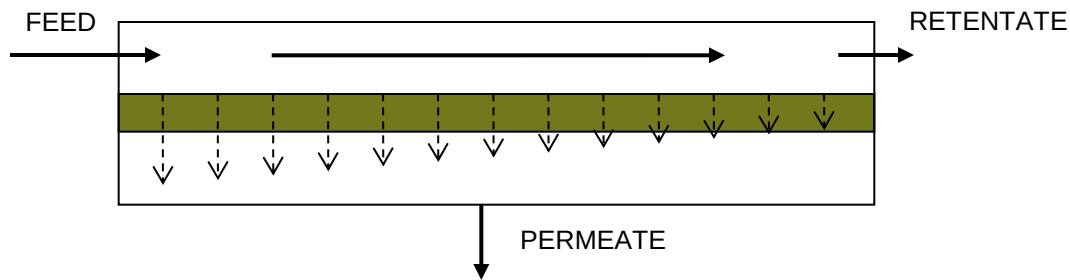


Membrane modules and configurations

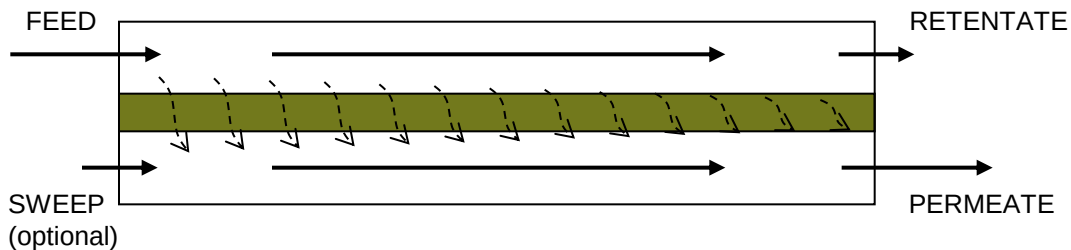
Gazzani Matteo, Separation Process Laboratory

Membrane Flow Patterns

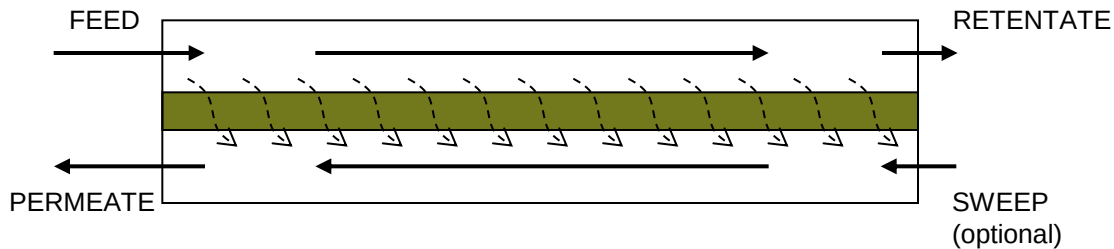
Flow patterns other than the well mixed case are more realistic but usually require numerical calculations



Cross – flow



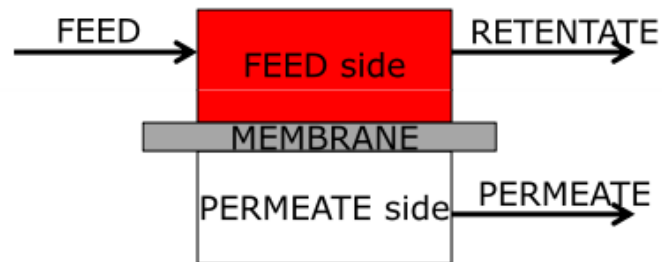
Co-current flow



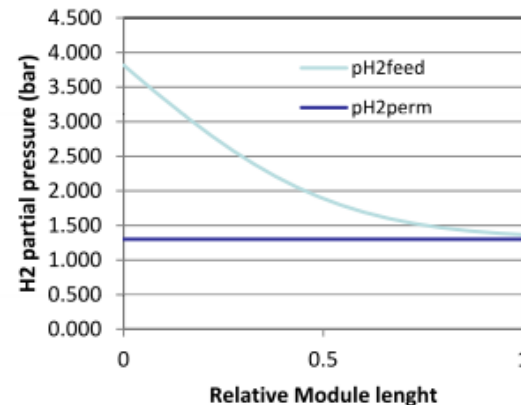
Counter-current flow

Acting on the operating conditions

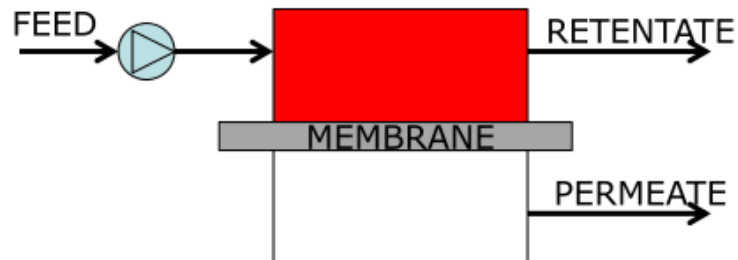
Necessity to increase the driving force across the membrane



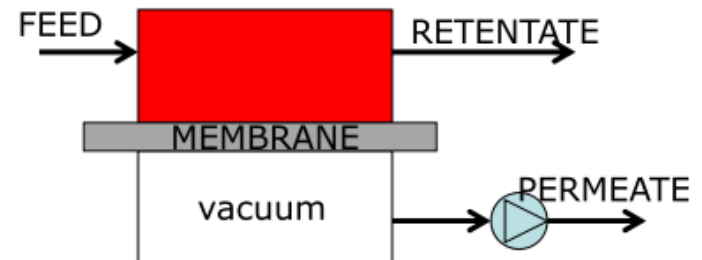
Without sweep gas



Membrane working efficiency decreases with increasing membrane area



Feed flow compression

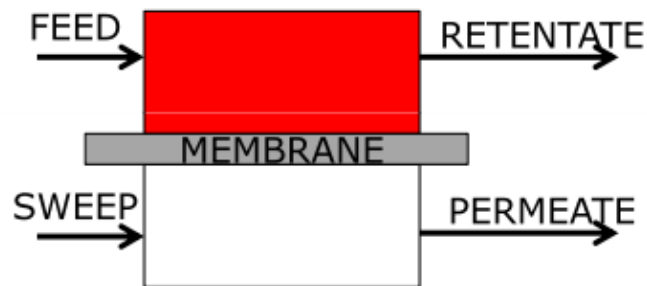


Permeate vacuum

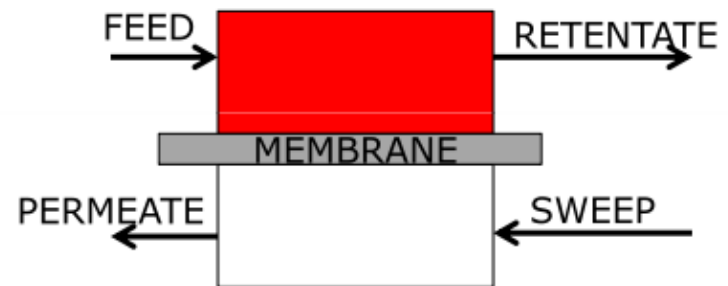
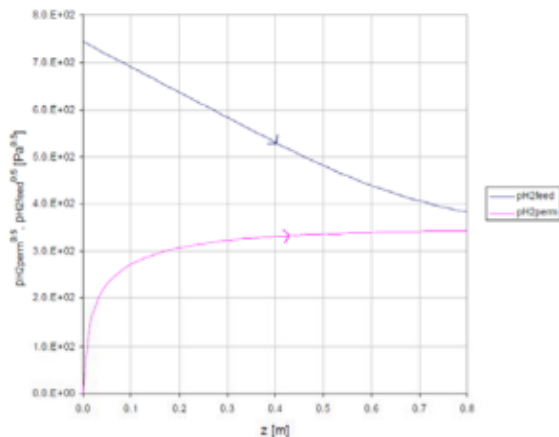
Compression in itself adds to total plant cost

Acting on the operating conditions

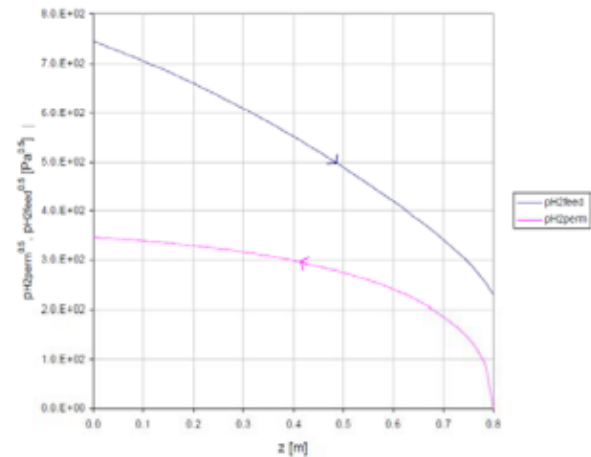
Necessity to increase the driving force across the membrane



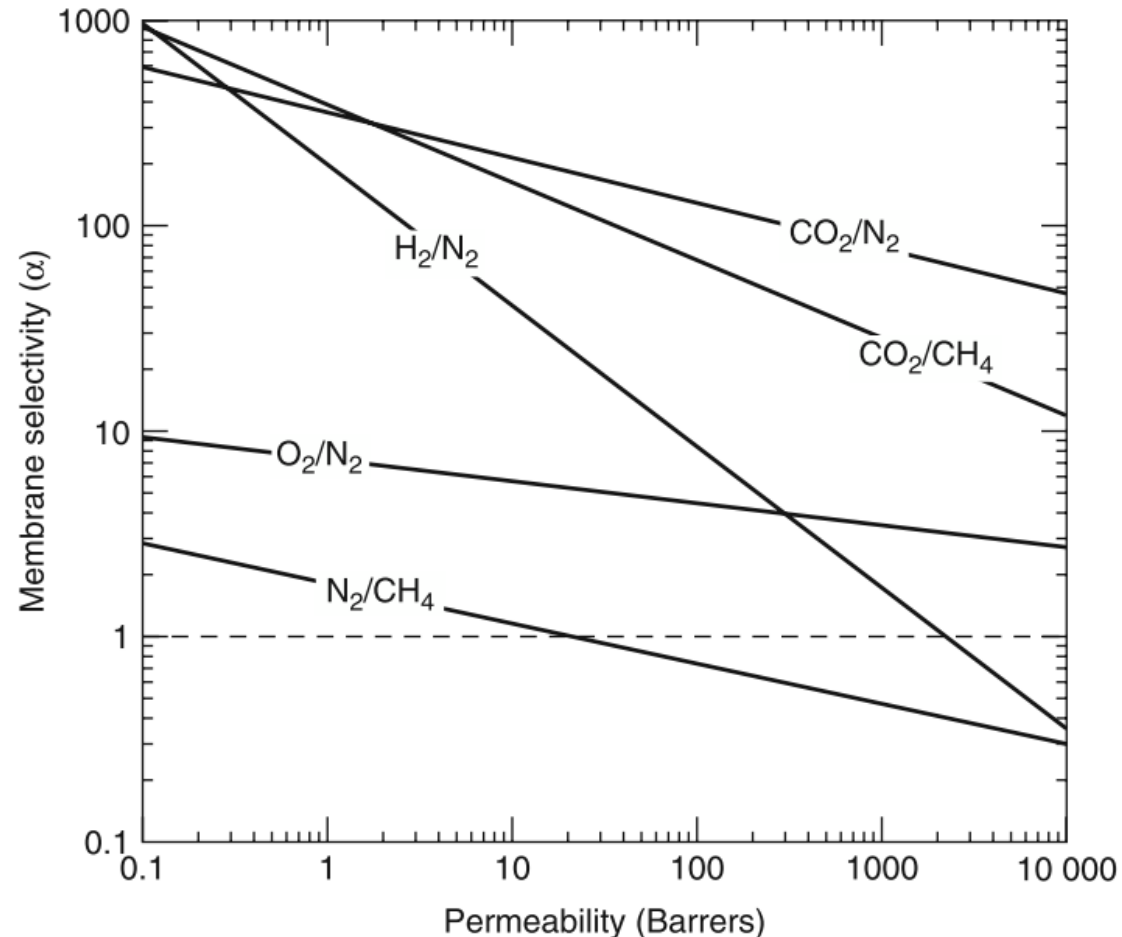
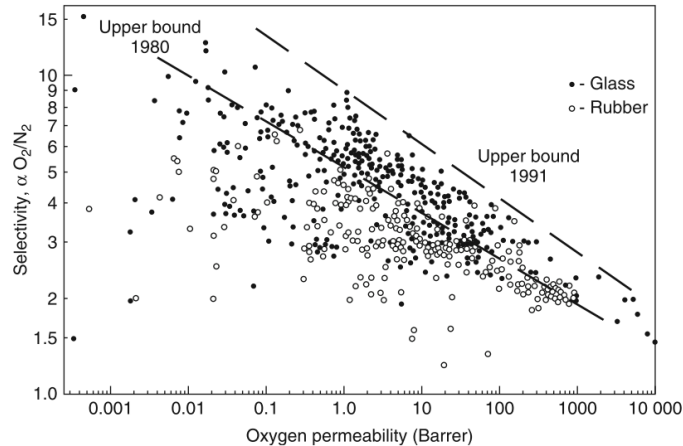
**Dilution by sweep flow
Co-Current set up**



**Dilution by sweep flow
Counter-Current set up**



Overview of the membrane performance

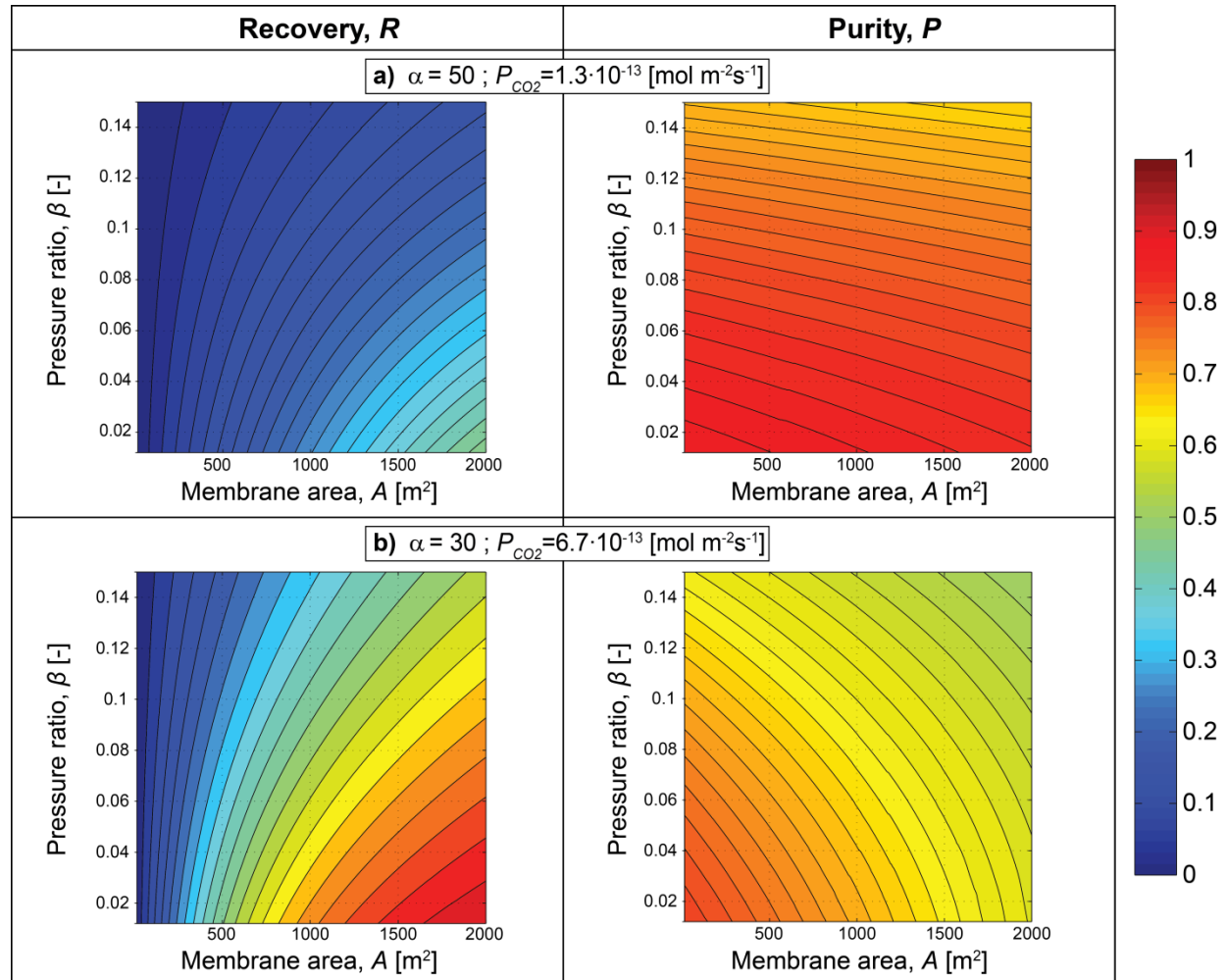


Only the most permeable polymers at a particular selectivity are of interest

Recovery-Purity trade off

As the recovery increases, purity decreases: the less permeable component permeates more

$$\beta = 1/\lambda$$



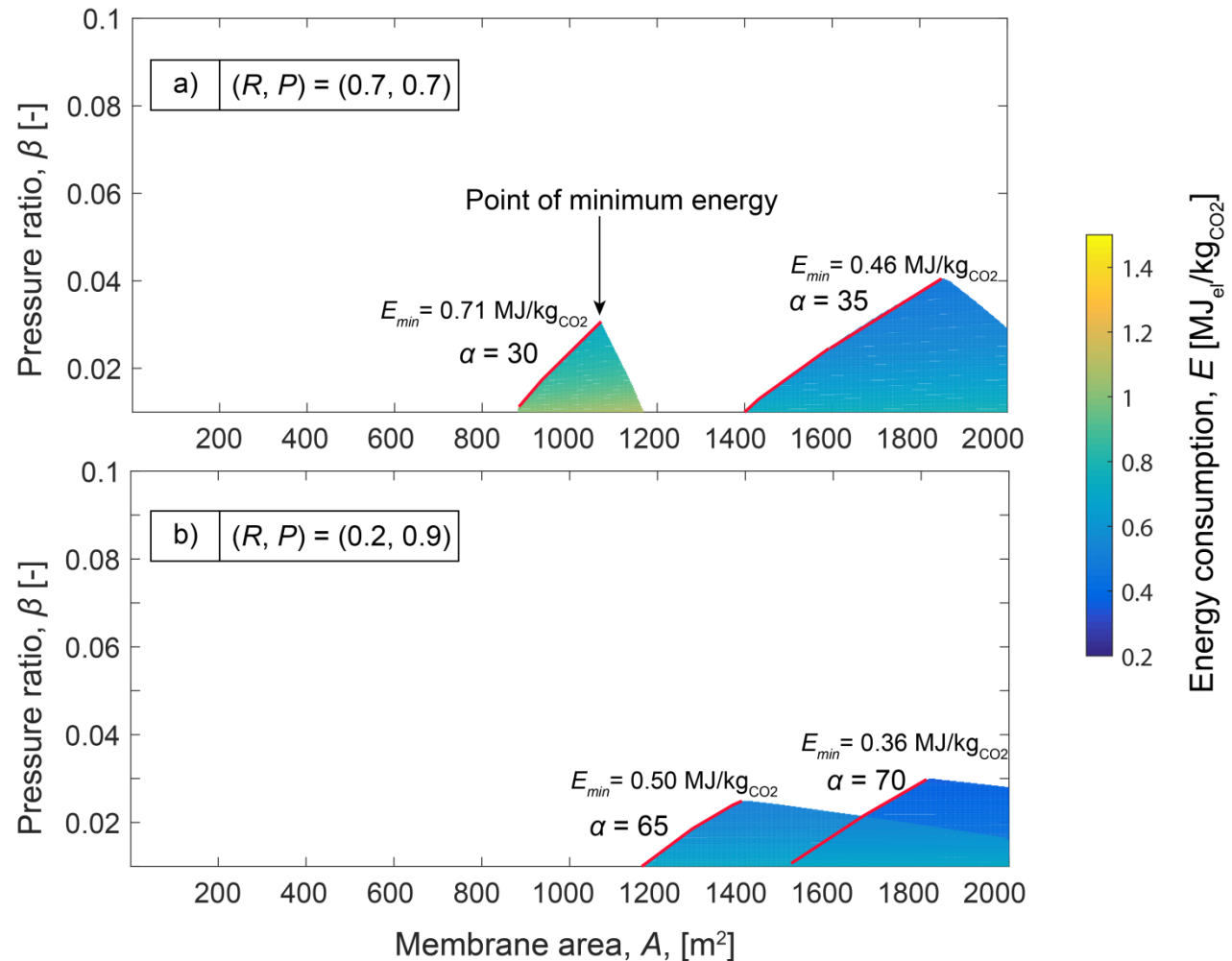
Energy-Area trade off

Purity and recovery maps can be superimposed to identify the regions where a certain separation target (R,P) is satisfied.

Energy consumption can be computed for this area.

$$E = \sum_{k=1}^M \frac{1}{\eta} \frac{\gamma R T}{\gamma - 1} \left[\left(\frac{1}{\beta_k} \right)^{\frac{(\gamma-1)}{\gamma}} - 1 \right]$$

$$\beta = 1/\lambda$$



Task in membrane development

Key points for membrane developments

Membrane technology

To produce a selective, high flux, defect free membrane

- Material science: $\mathcal{P}, \delta$
- Manufacture: δ

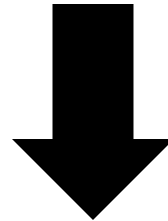
Membrane design

To assemble membranes into compact, high surface area, economical membrane modules

- Manufacture
- Process design

Factors for successful membrane fabrication

- Materials with appropriate chemical, mechanical and permeation properties
- Fabrication technology that provides a robust, thin, defect free membrane
- **Design of an efficient, high surface area and economical module**



Maximize the packing density

Why module?

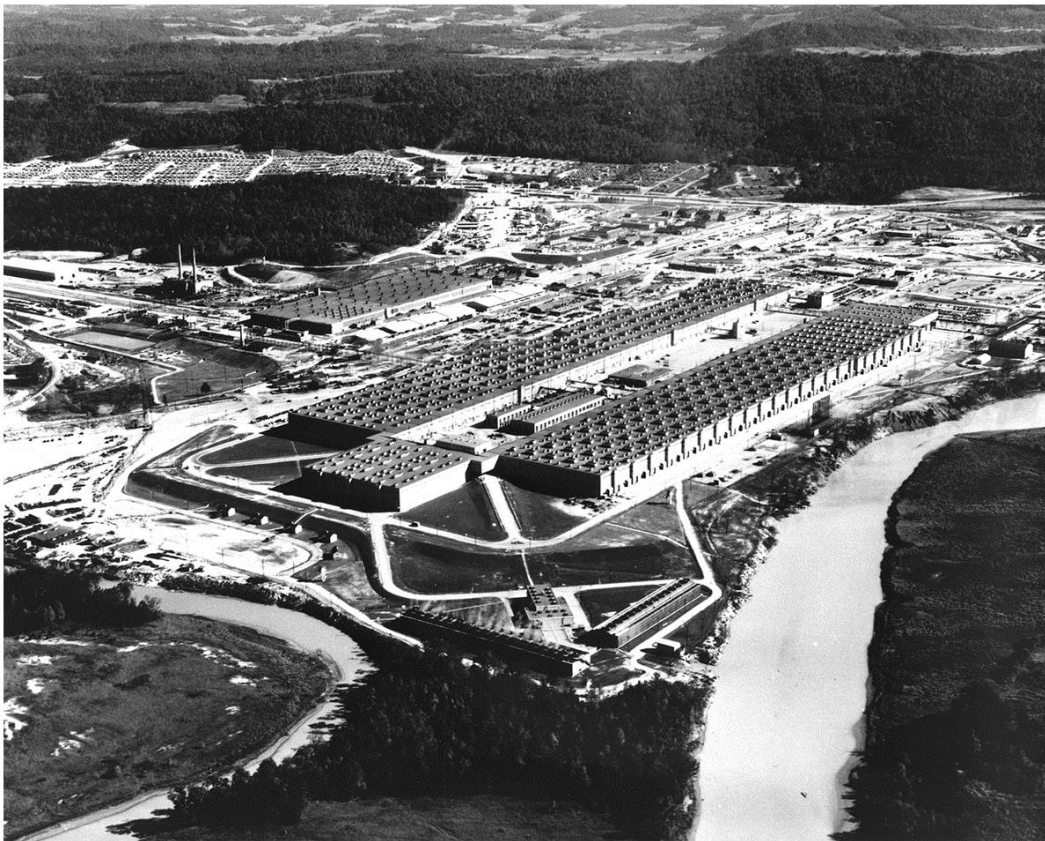
Industrial membrane plants often require membrane area in the range of hundreds to thousands square meters to perform the separation on a commercial scale.

Before a membrane separation can be performed industrially, therefore, methods of economically and efficiently packaging large areas of membrane are required.

These packages are called membrane modules

Historical background

The first large scale use of gas separation: uranium enrichment
separation of U^{235}F_6 from U^{238}F_6 (uranium hexafluoride)



The molecular weight of UF_6 depends entirely on the uranium isotope.

$^{235}\text{UF}_6$ was enriched using a cascade of finely micro-porous metal membranes

Plate and Frame Membrane Modules

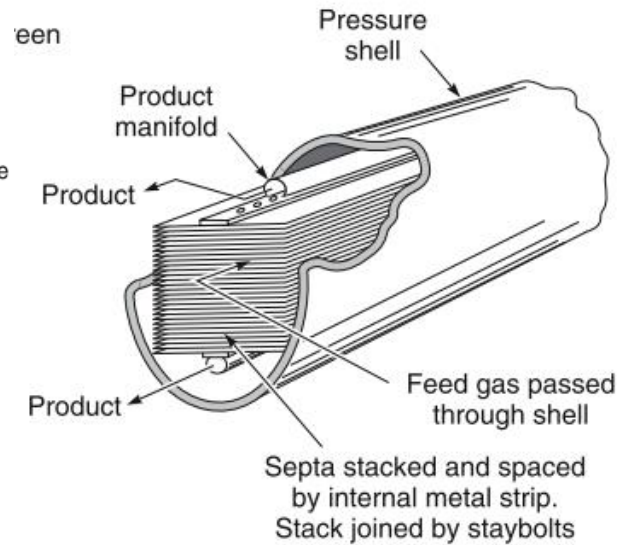
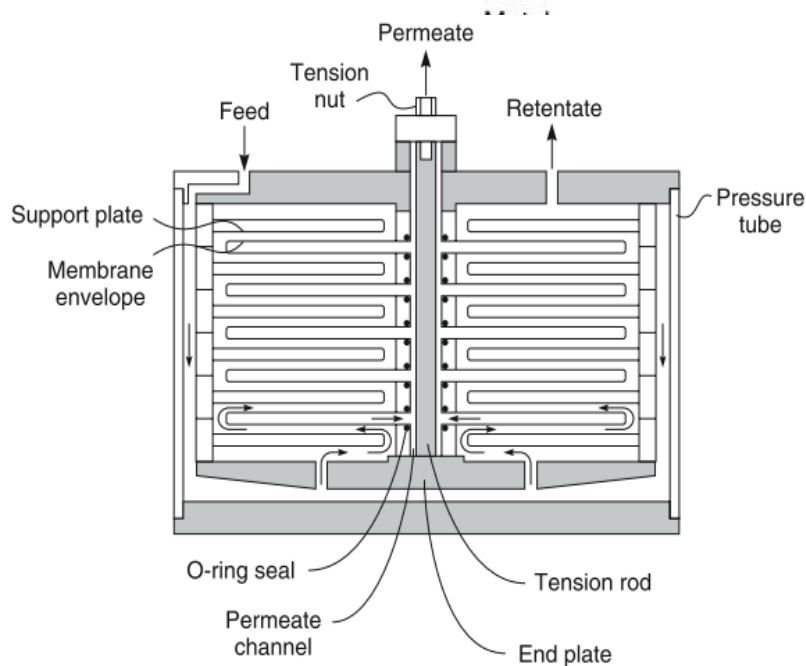
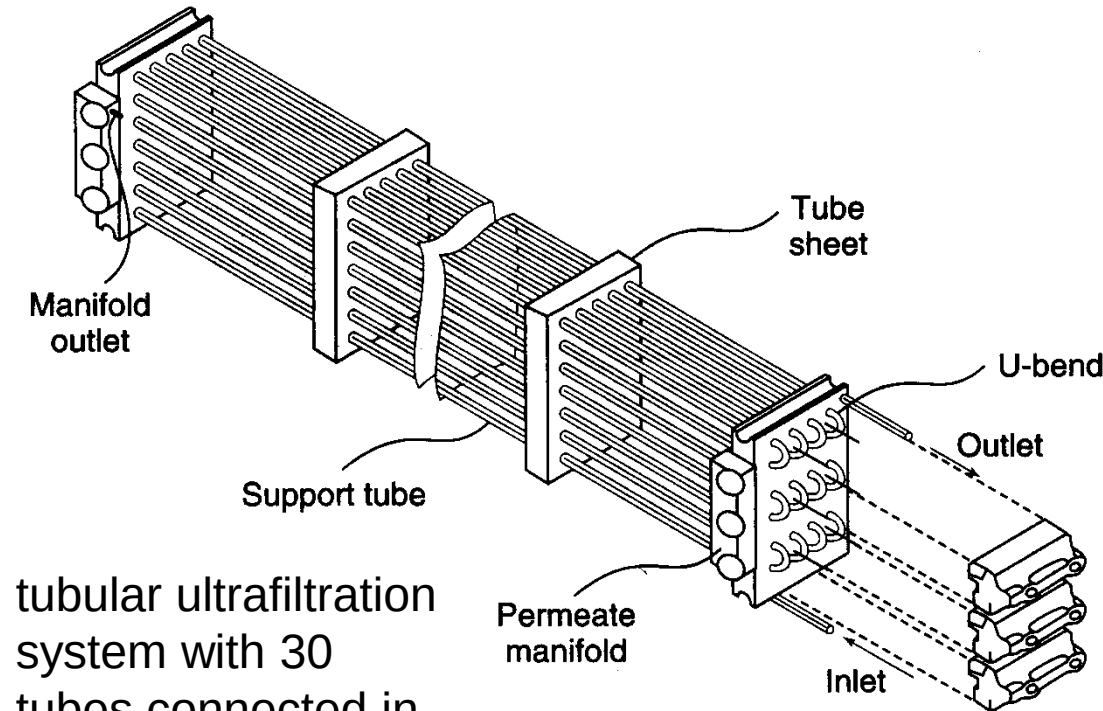


Plate modules for He separation from natural gas

- One of the earlier approaches to module design.
- Some small scale applications (also filtration units)
- Expensive compared to other solutions
- Used only in electrodialysis and pervaporation
- Counter- and co-current flow



Tubular membrane modules



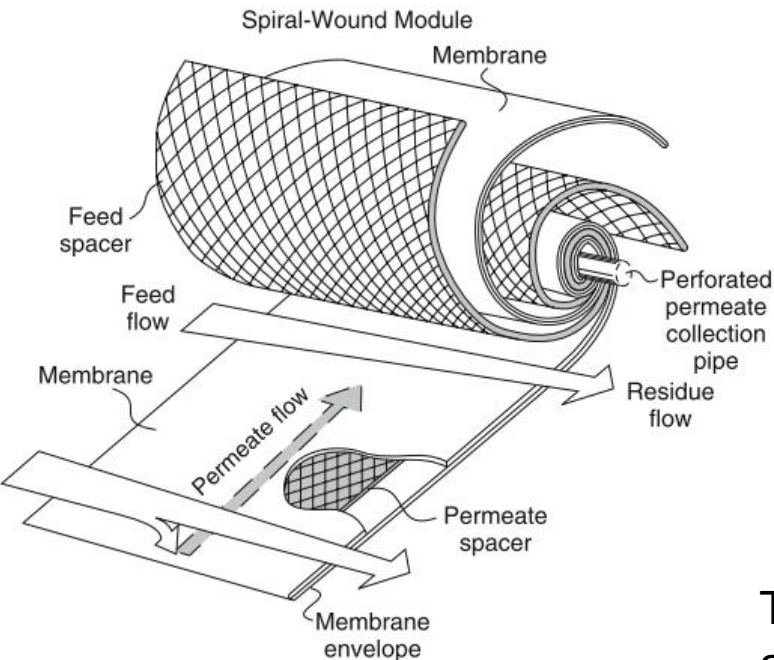
tubular ultrafiltration system with 30 tubes connected in series



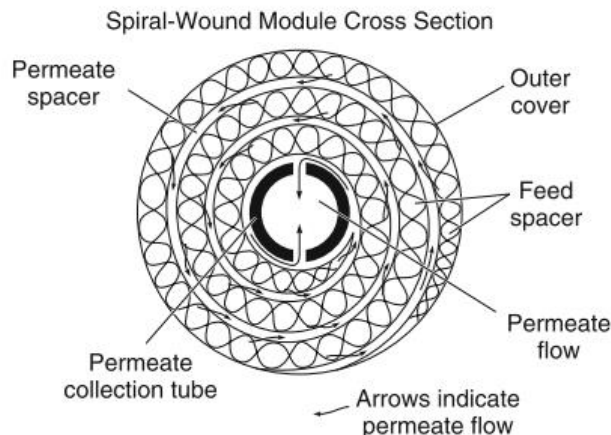
Typical tubular ultrafiltration module design (commercial modules).

- High cost (low surface / volume ratio)
- Turbulent flow → good resistance to fouling
- Application limited to ultrafiltration (in cases where polarization and fouling are problematic)

Spiral Wound Membrane Modules



- Used in artificial kidneys
- Generally applicable module type
- Fairly low manufacturing costs
- High surface to volume ratio
- Modules can be easily connected in series inside a tubular pressure vessel



The feed passes axially down the module across the membrane envelope. The permeate spirals toward the center and exits through the collection tube. Crosscurrent flow



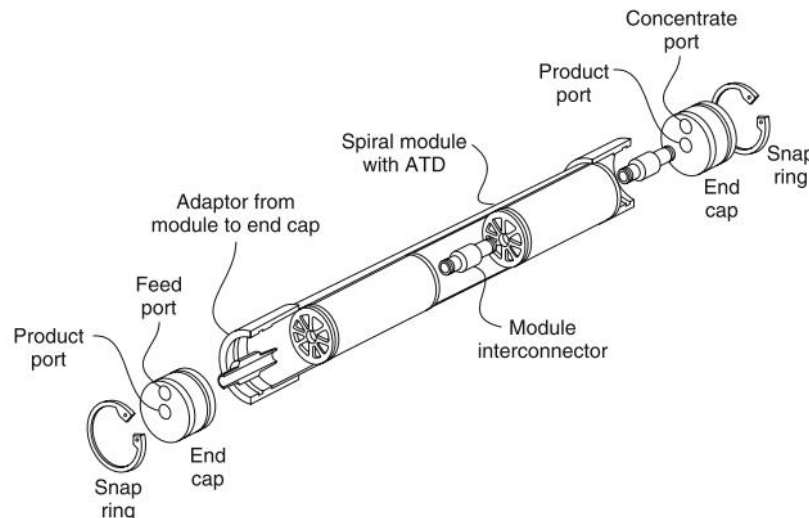
Spiral Wound Membrane Modules

Typical membrane area and number of membrane envelopes for 40-in.-long industrial spiral-wound modules

Module diameter (in.)	4	6	8	16
Number of membrane envelopes	4–6	6–10	15–30	50–100
Membrane area (m ²)	3–6	6–12	20–40	80–150

Four to six spiral-wound membrane modules are normally connected in series inside a single pressure vessel (tube).

A typical 0.2m diameter tube containing six modules has 150–250 m² of membrane area



Hollow Fiber Membrane Modules

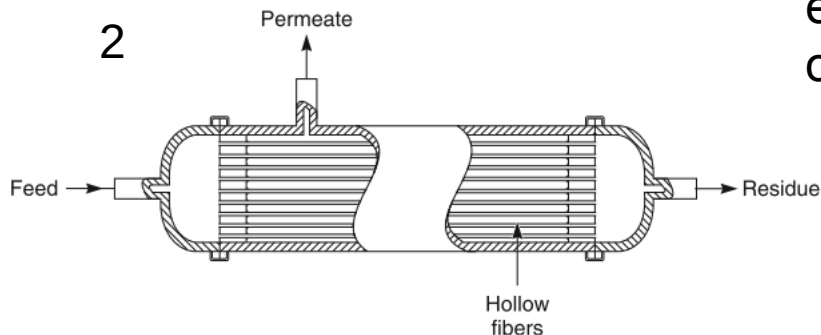
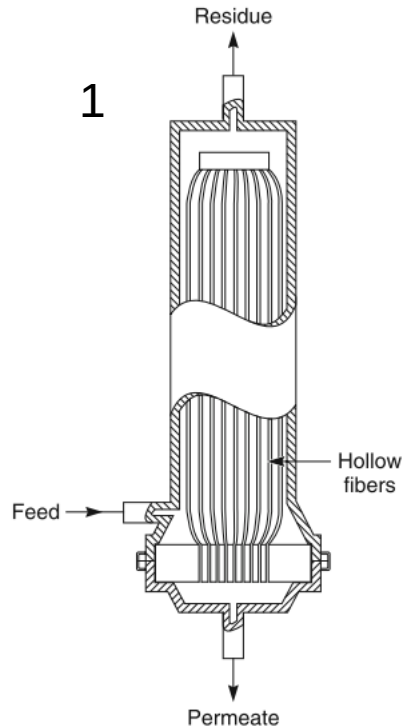
Two basic geometries.

1. The shell side feed design: a loop of fibers is contained in a pressure vessel. The system is pressurized from the shell side, permeate passes through the fiber wall and exits through the open fiber ends.

- easy to make
- very large membrane areas
- Thick wall and small diameter to stand the pressure
- Used in gas separation and reverse osmosis
- Counter-current flow

2. The bore-side feed type: fibers are open at both ends the feed fluid is circulated through the bore of the fibers. Large diameter to minimize Δp .

- Used in ultrafiltration and pervaporation
- $p < 10$ bar
- Co-current flow



Hollow Fiber Membrane Modules

- Highest surface to volume ratio of all membrane modules
- Used e.g. in hemodialysis (see below „one way artificial kidneys“ for 15 \$ → 1.3 billion \$ market)
- Shell side feed for high pressure applications (e.g. gas separation), bore side feed to avoid concentration polarization (no stagnant volumes).



Module use	High-pressure reverse osmosis and gas separation	Low-pressure gas separation		Ultrafiltration	
Fiber diameter (μm)	100	250	500	1000	2000
Number of fibers/module (thousands)	1000	250	40	10	2.5
Membrane area (m^2)	315	155	65	32	16
Packing density (cm^2/cm^3)	100	50	20	10	5

Membrane technology: effects on the process design

- Flux: $J_i = \frac{D_i K_i (p_{i0} - p_{il})}{\delta}$
- Permeability: $P_i = D_i K_i$
- Selectivity: $\alpha_{ij} = \frac{P_i}{P_j} = \frac{D_i K_i}{D_j K_j}$

$\frac{D_i}{D_j} \rightarrow$ mobility selectivity $\rightarrow$ size of the molecule

$\frac{K_i}{K_j} \rightarrow$ solubility selectivity $\rightarrow$ relative solubility of the two gases

TABLE 22-24 Gas-Permeation Units

Quantity	Engineering units	Literature units	SI units
Permeation rate	Standard cubic feet/minute		kmol/s
Permeation flux	ft ³ /ft ² ·day	cm/sec (STP)	kmol/m ² ·s
Permeability	ft ³ ·ft/ft ² ·day·psi	Barrers	kmol/m·s·Pa
Permeance	ft ³ /ft ² ·day·psi	Barrers/cm	kmol/m ² ·s·Pa

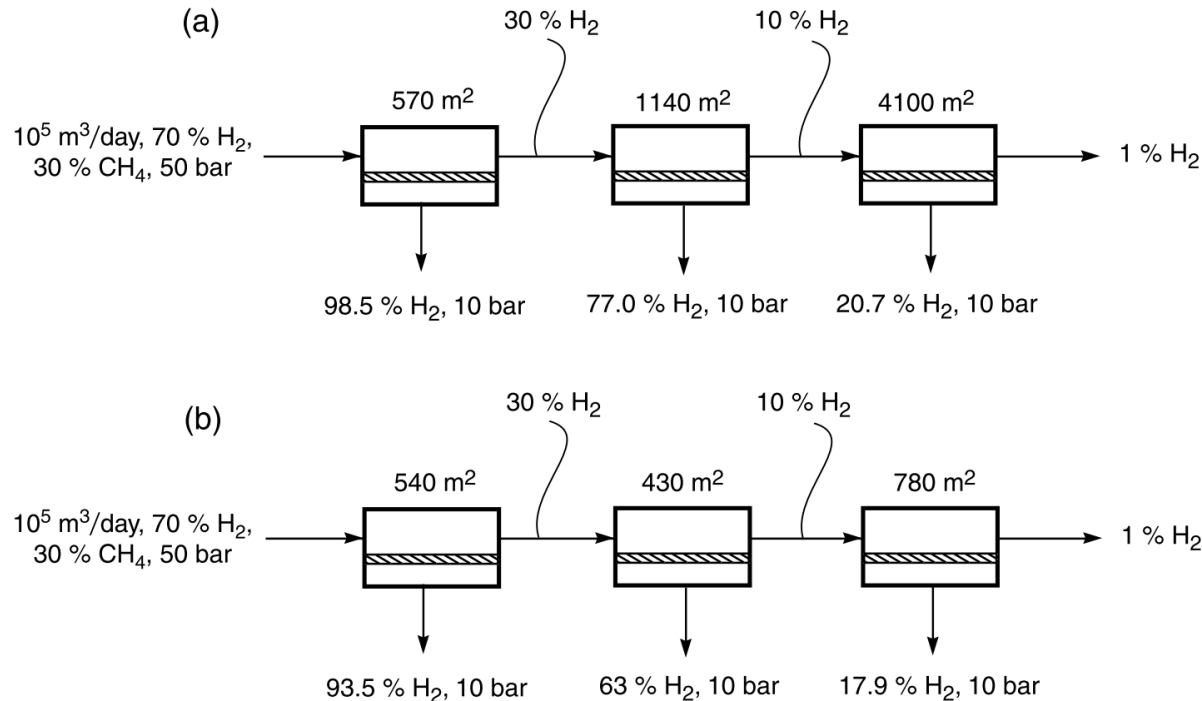
TABLE 22-25 Barrer Conversion Factors

Quantity	Multiply	By	To get
Permeability	Barrers	3.348×10^{-19}	kmol/m·s·Pa
Permeability	Barrers	4.810×10^{-8}	ft ³ (STP)/ft·psi·day
Permeance	Barrers/cm	3.348×10^{-17}	kmol/m ² ·s·Pa
Permeance	Barrers/cm	1.466×10^{-6}	ft ³ (STP)/ft ² ·psi·day

TABLE 22-26 Industry-Specific Gas Measures

Industry-unit	How measured	Cubic feet per pound mole	kmol per mscf
STP, Mscf	1000 ft ³ at 32°F	359.3	1.262
Gas industry, Mscf	1000 ft ³ at 60°F	379.8	1.194
Air industry, Mnsf	1000 ft ³ at 70°F	387.1	1.172

Selectivity-pressure ratio



The effect of membrane selectivity on separation performance in pressure-ratio-limited separations for

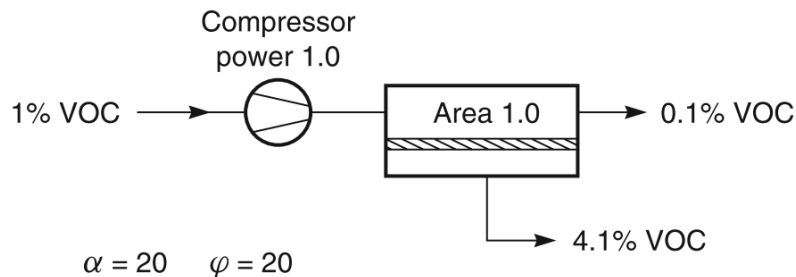
(a) high-selectivity (100) and (b) low-selectivity (20) membranes,

Both membranes have equal permeances for the more permeable gas (hydrogen).

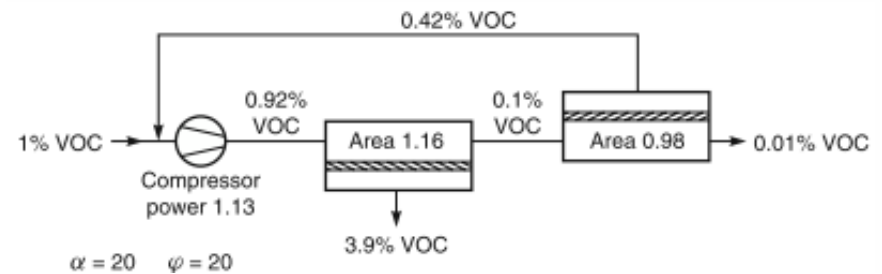
At high-feed-gas concentrations (first step), the highly selective membrane is preferred, while at low-feed-gas concentrations the less selective membrane is preferred (almost equivalent separation and a membrane area of 1/5).

Multi-step and multi-stage design

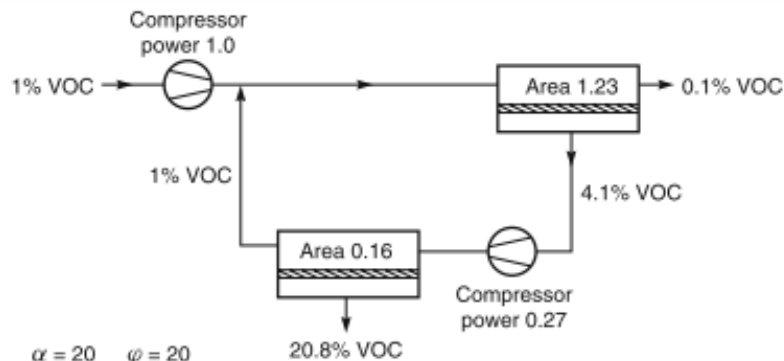
A one-stage membrane system may not provide the separation desired



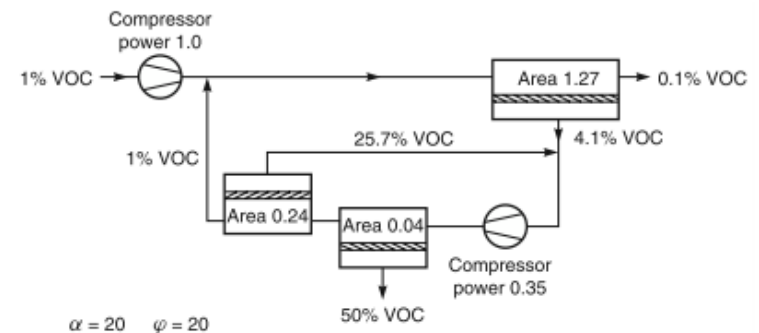
Two step system: lower concentration of the permeable gas in the retantate



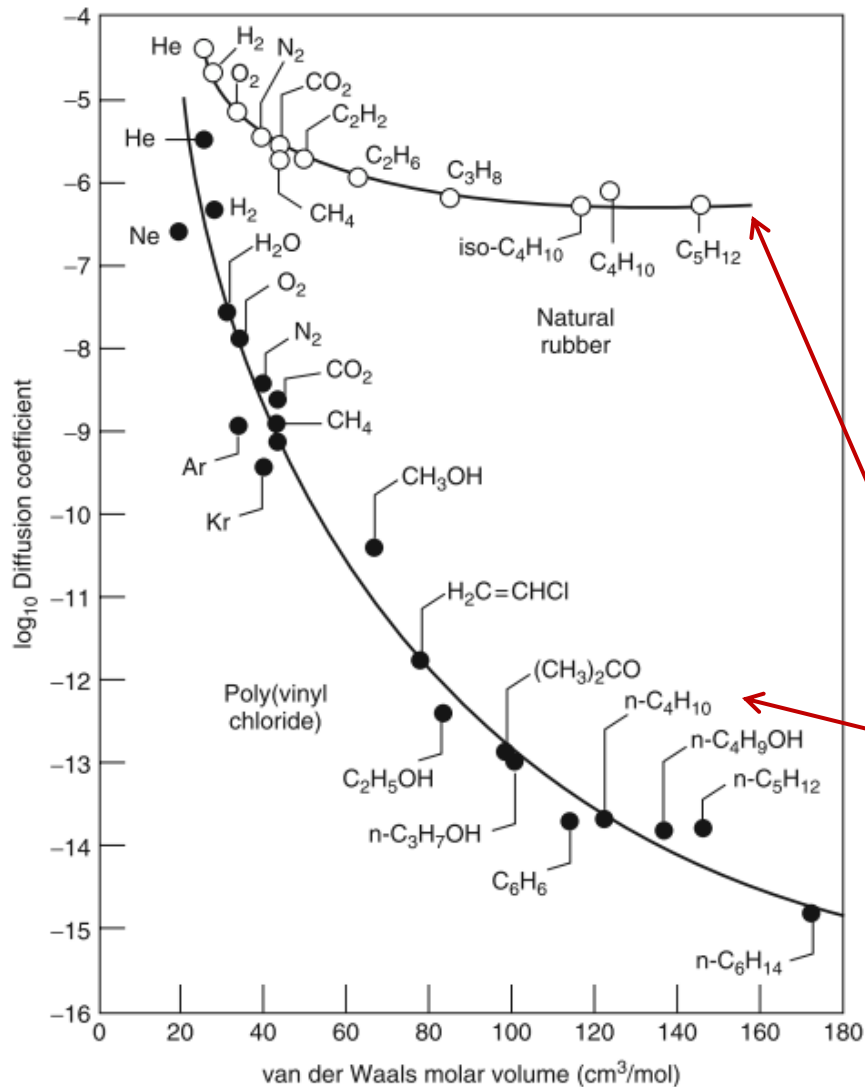
Two stage system: higher concentration of the permeable gas in the permeate



Two-and-one-half-stage system



Diffusion coefficient



In all polymers, the diffusion coefficient decreases with increasing permeant molecular size: large molecules interact with more segments of the polymer chain than do small molecules.

Big change if membrane material is above or below its glass transition

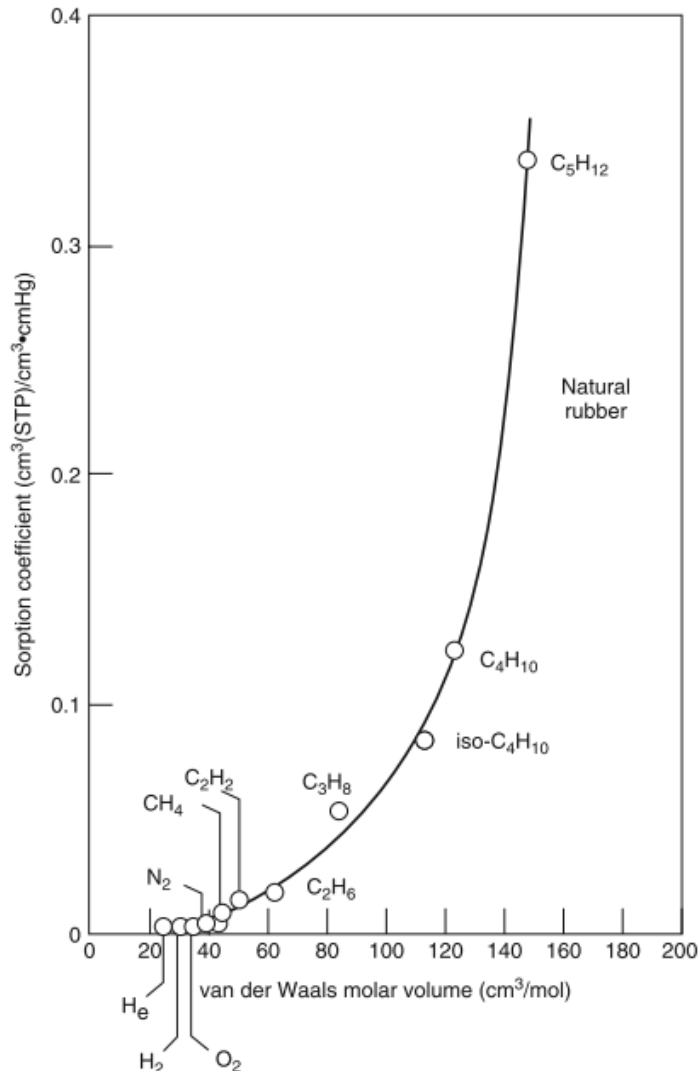
Diffusion coefficients in rubber material

Diffusion coefficients in glassy materials are small and decrease much more rapidly with increasing permeate size

TABLE 22-23 Kinetic Diameters for Important Gases

Penetrant	He	H_2	NO	CO_2	Ar	O_2	N_2	CO	CH_4	C_2H_4	Xe	C_3H_8
Kinetic dia, nm	0.26	0.289	0.317	0.33	0.34	0.346	0.364	0.376	0.38	0.39	0.396	0.43

Sorption coefficient

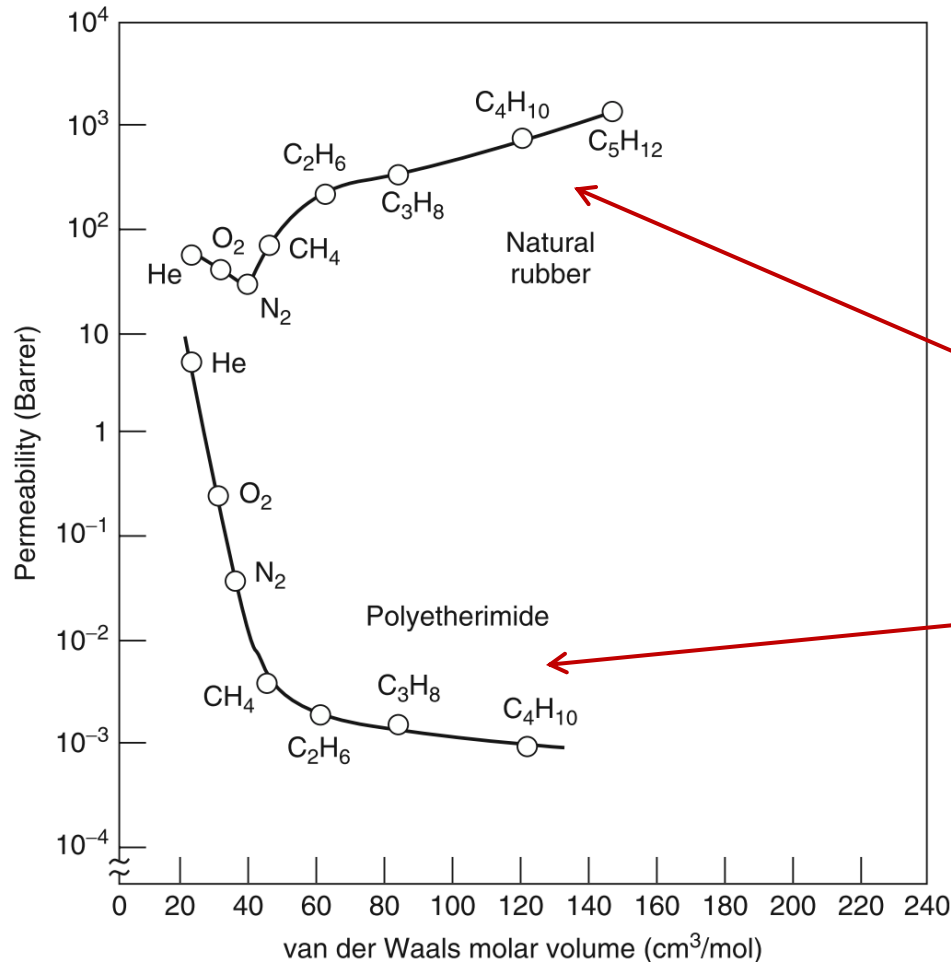


The sorption coefficient of gases and vapors increases with increasing condensability of the permeant. This means that the sorption coefficient increases with molecular diameter as large molecules are normally more condensable than smaller ones.

Sorption selectivity favors larger, more condensable molecules, over permanent gases, such as oxygen and nitrogen.

No change if membrane material is above or below its glass transition

Diffusion + sorption coefficient



In rubbery polymers the sorption selectivity term is usually dominant: permeability increases with increasing permeate size, and larger molecules permeate preferentially.

In glassy polymers the mobility term is usually dominant: permeability falls with increasing permeate size and small molecules permeate preferentially.