Industrial Membrane Processes

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Topics

1. definitions
2. from membrane to process
3. different membrane processes
4. membranes, modules and plant cosntruction
5. fundamentals
6. mass transfer at and in membranes
7. development and planning of membrane processes
8. plants and equipment (lab - industrial)
9. applications
10. cleaning and conservation of membranes

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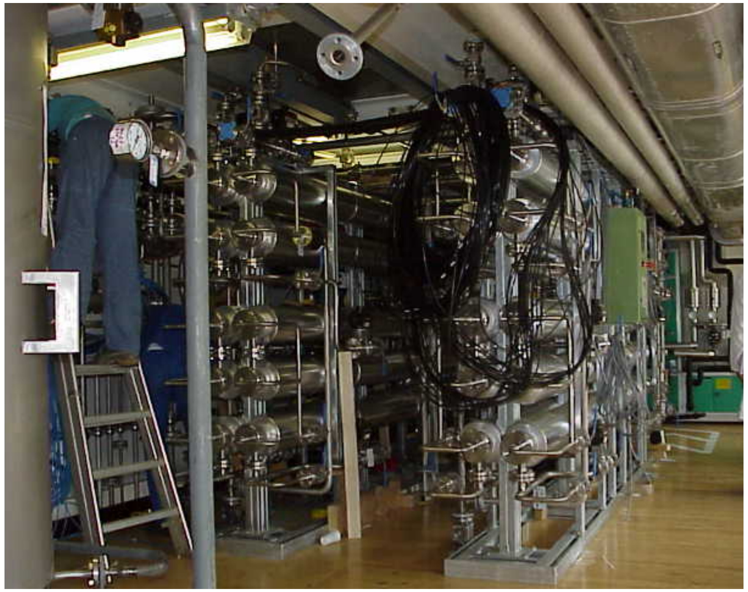
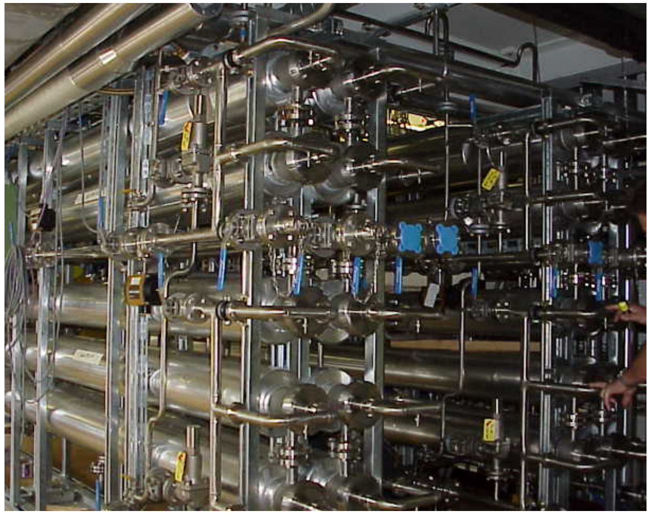
From Lab and Pilot........

to industrial scale





Membrane

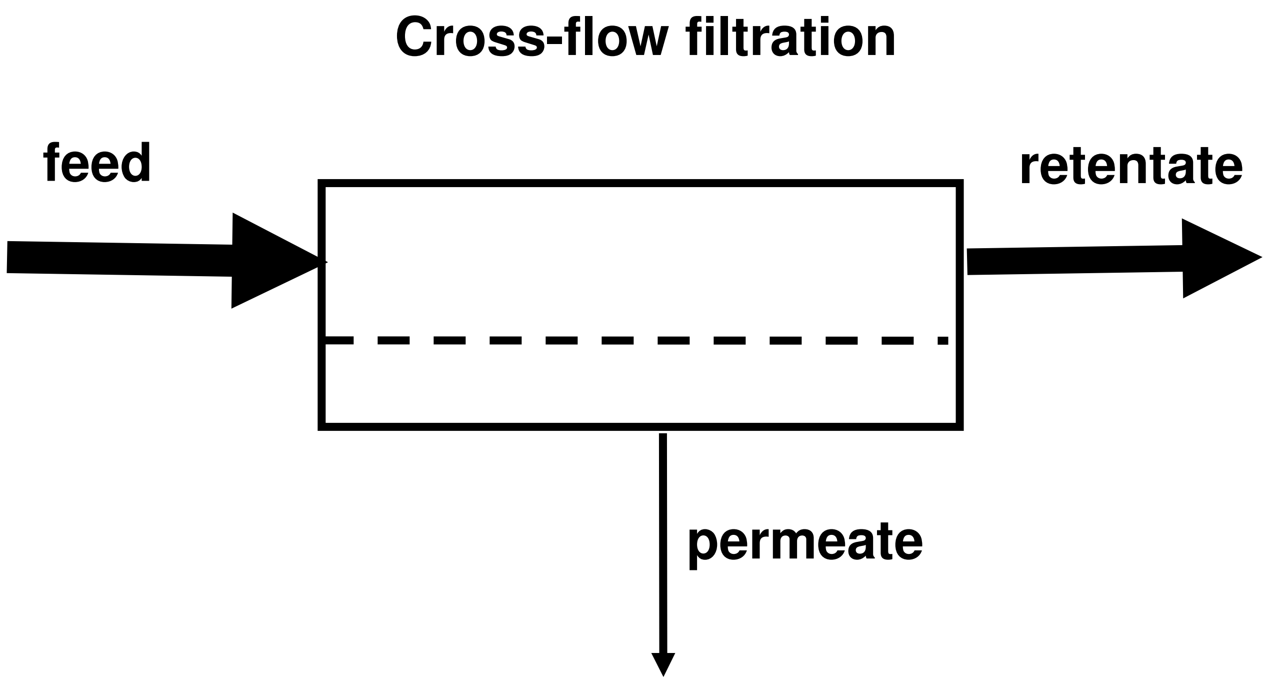
Definition:

„A membrane is a barrier that separates two phases and has different resistance for the transport of different components through it“

Qualities:

- high selectivity
- high permeability
- stability (mechanical, temperature, chemical)

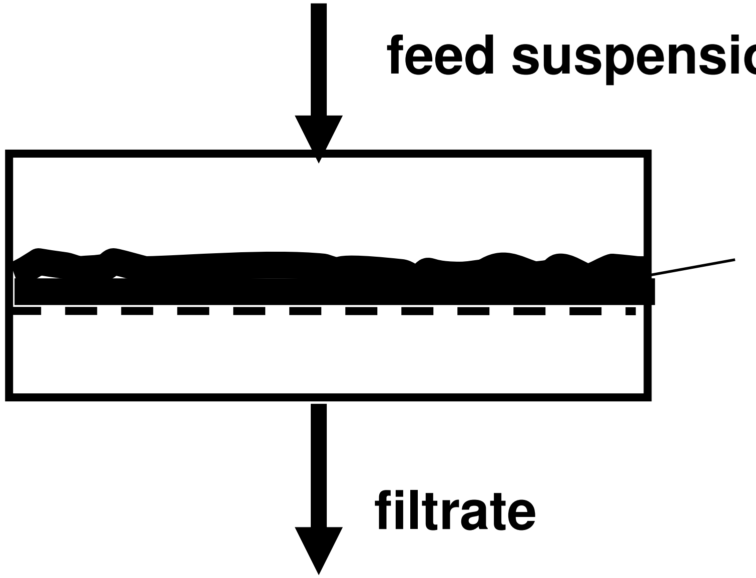
Cross-flow / dead end



- no cake formation
- feed to retentate flow >> permeate flow

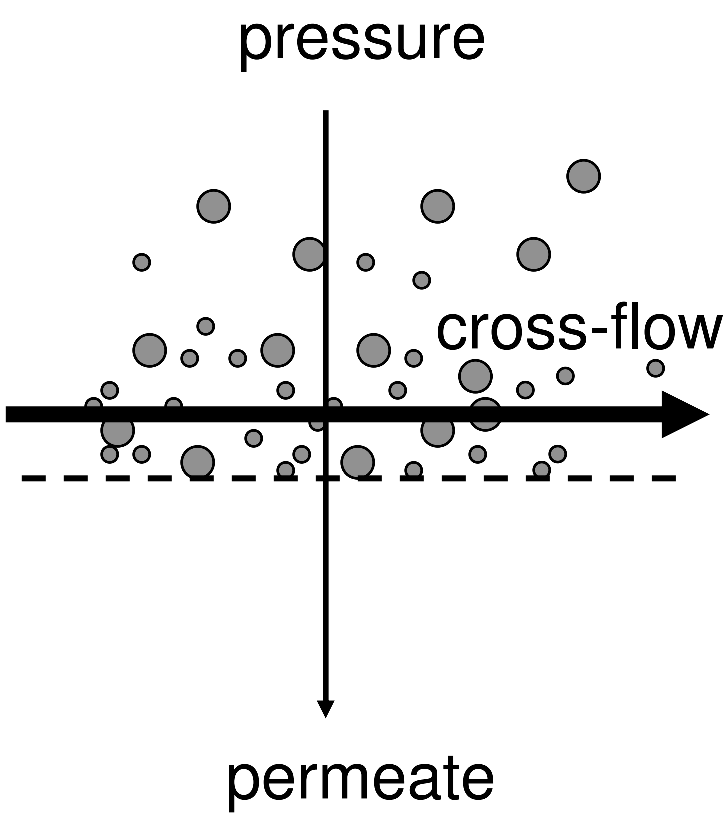
Cross-flow / dead end

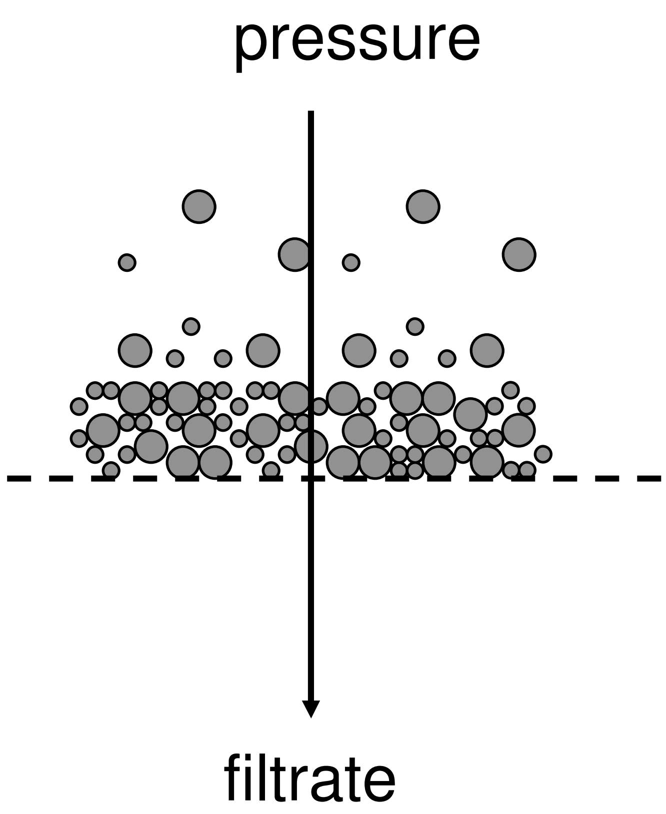
classical dead-end filtration



- cake formation limits filtrate flow
- only for big suspended material

Cross-flow / dead-end

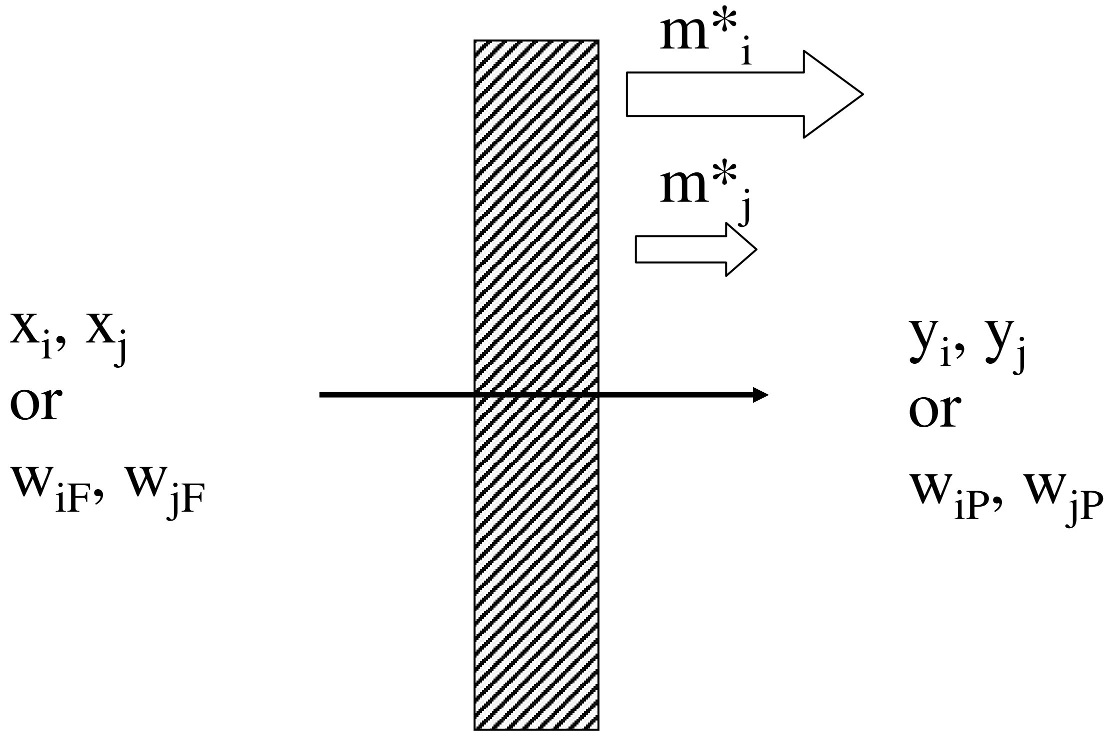




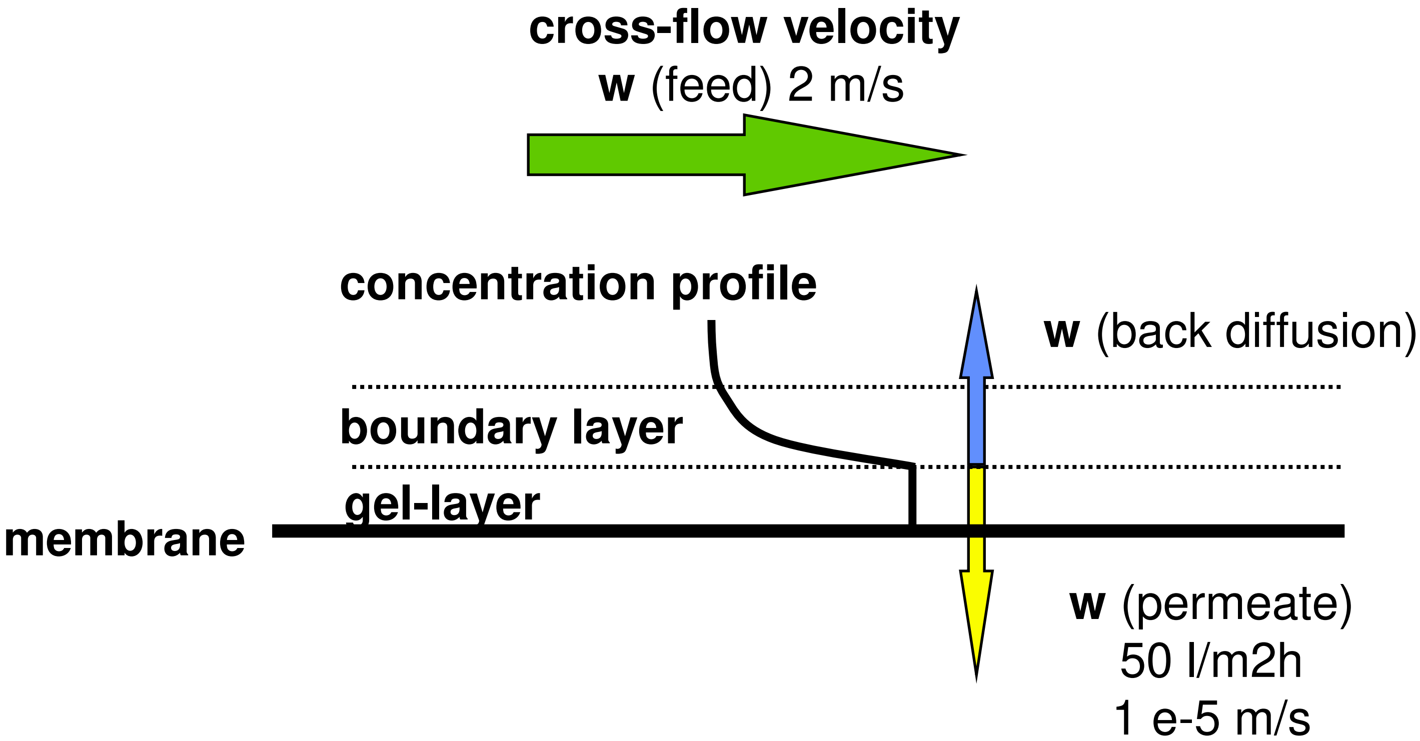
Zoom out - from membrane element to integrated process

- mass transfer through a membrane element
- mass transfer close to the membrane
- membrane module
- basic membrane process
- module combination and membrane plant stages
- integrated membrane process

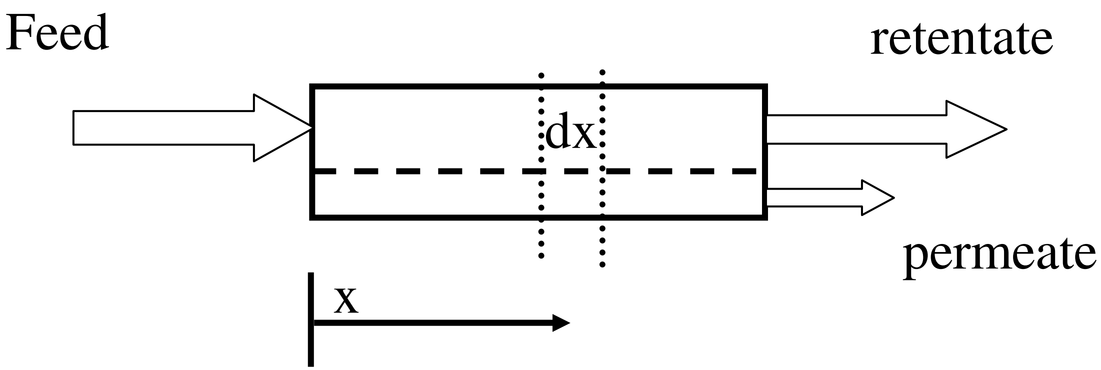
Mass transfer through a small membrane element

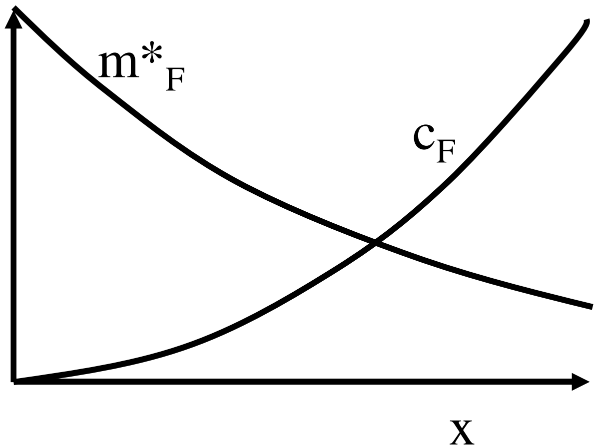


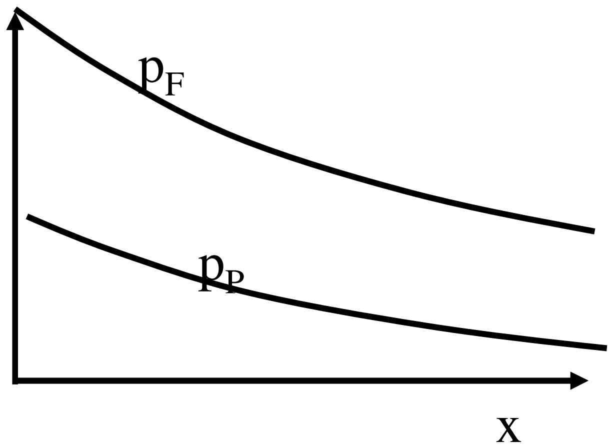
Mass transfer close to the membrane



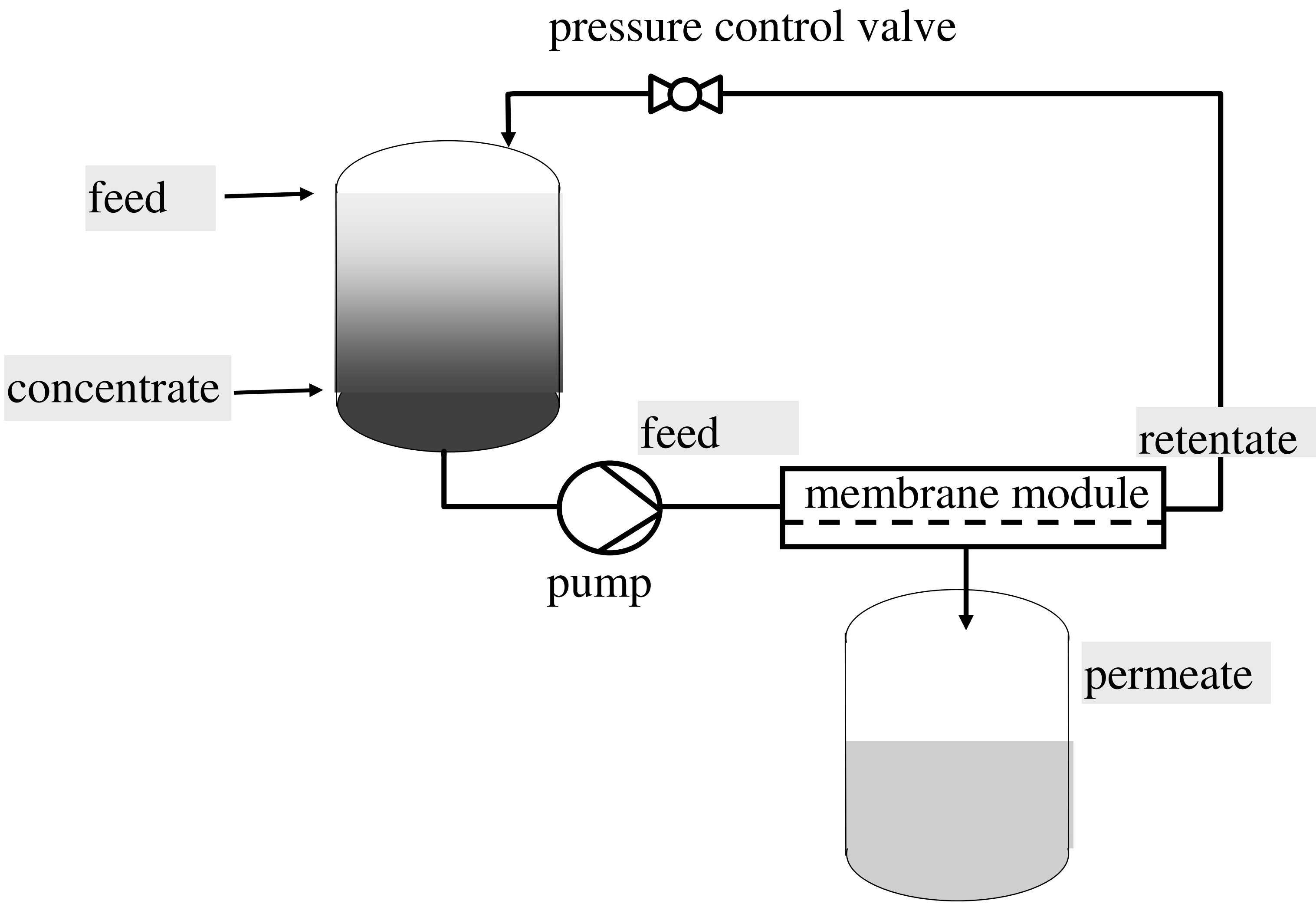
Membrane module



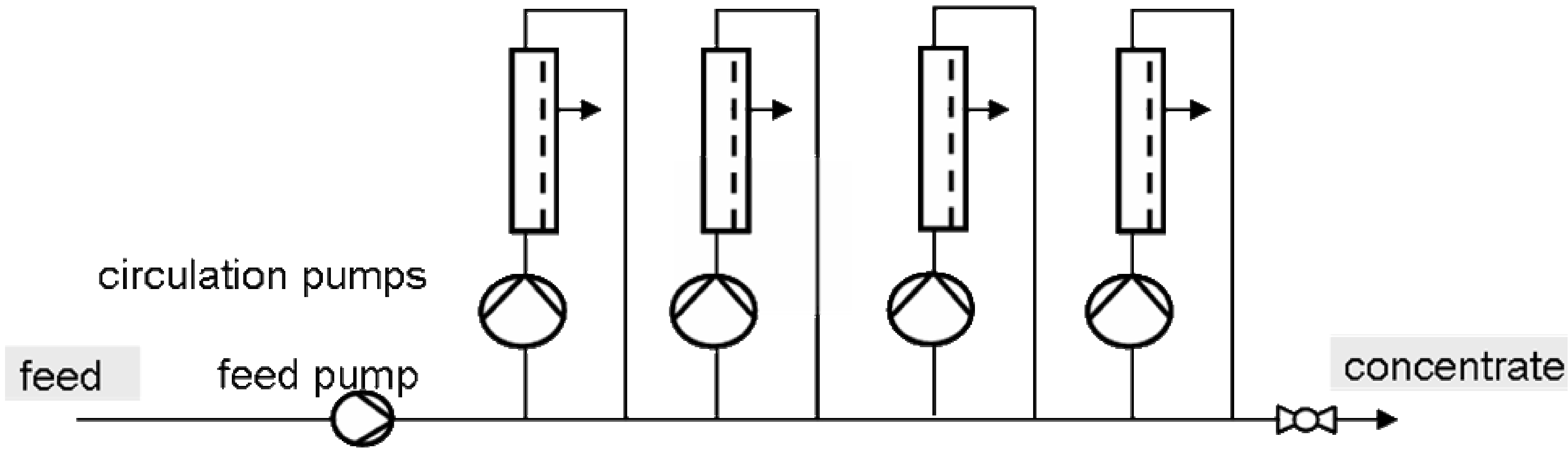




Basic membrane process (batch)



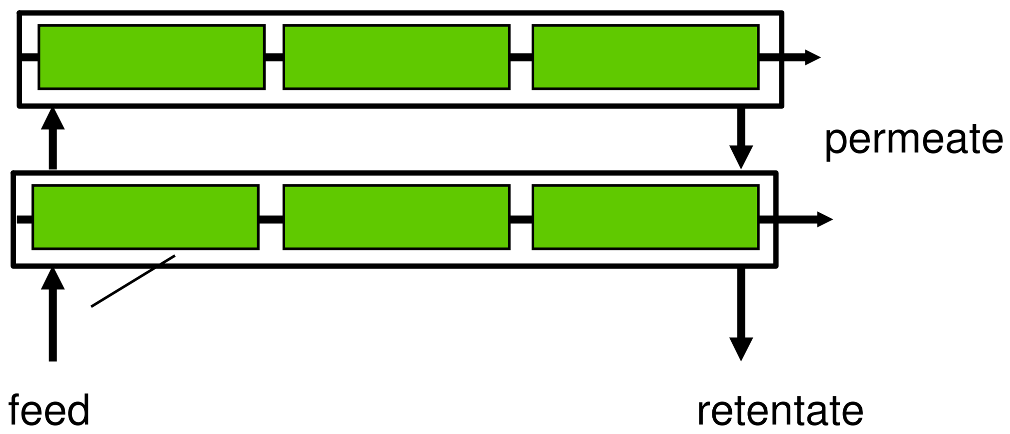
Basic membrane process (continuous)



Module combination and membrane plant stages I

membrane elements serial in pressure vessels

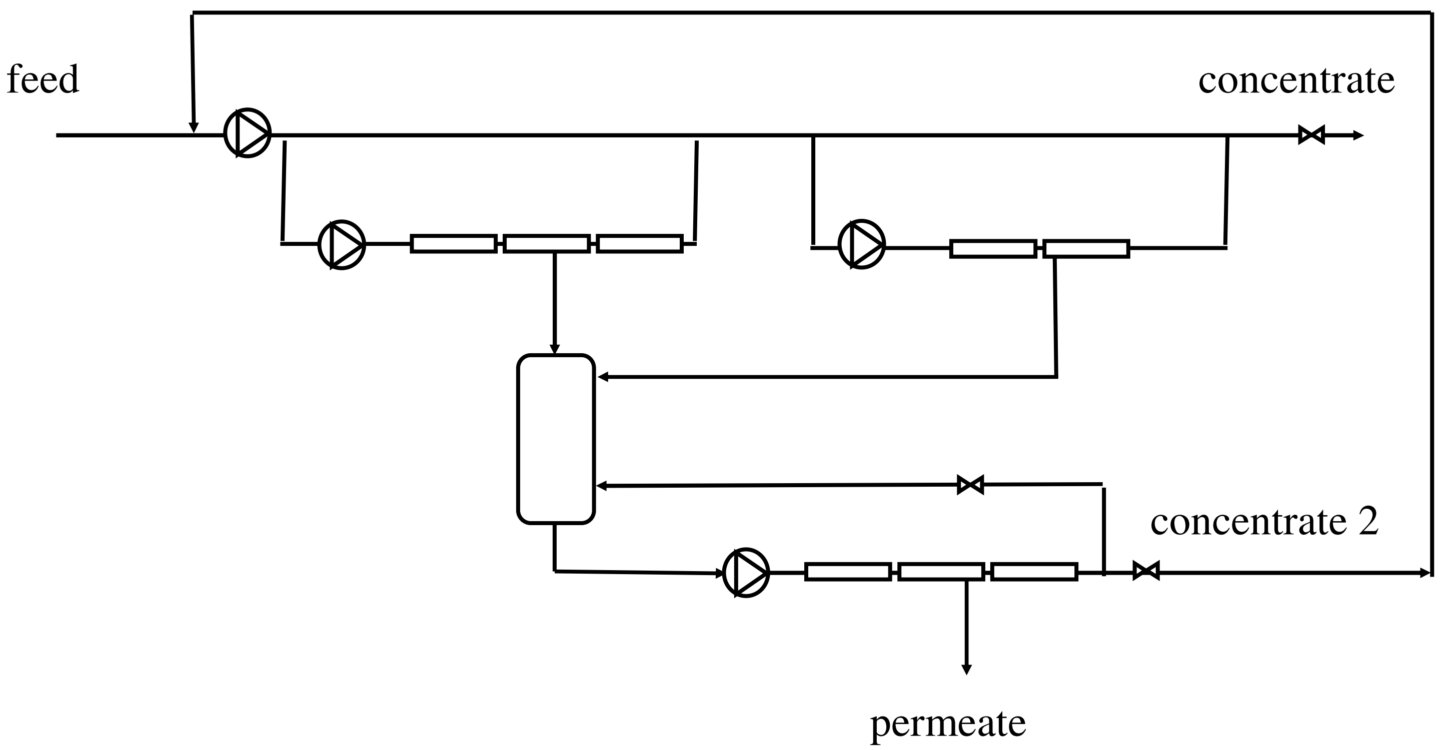
pressure vessels serial / parallel



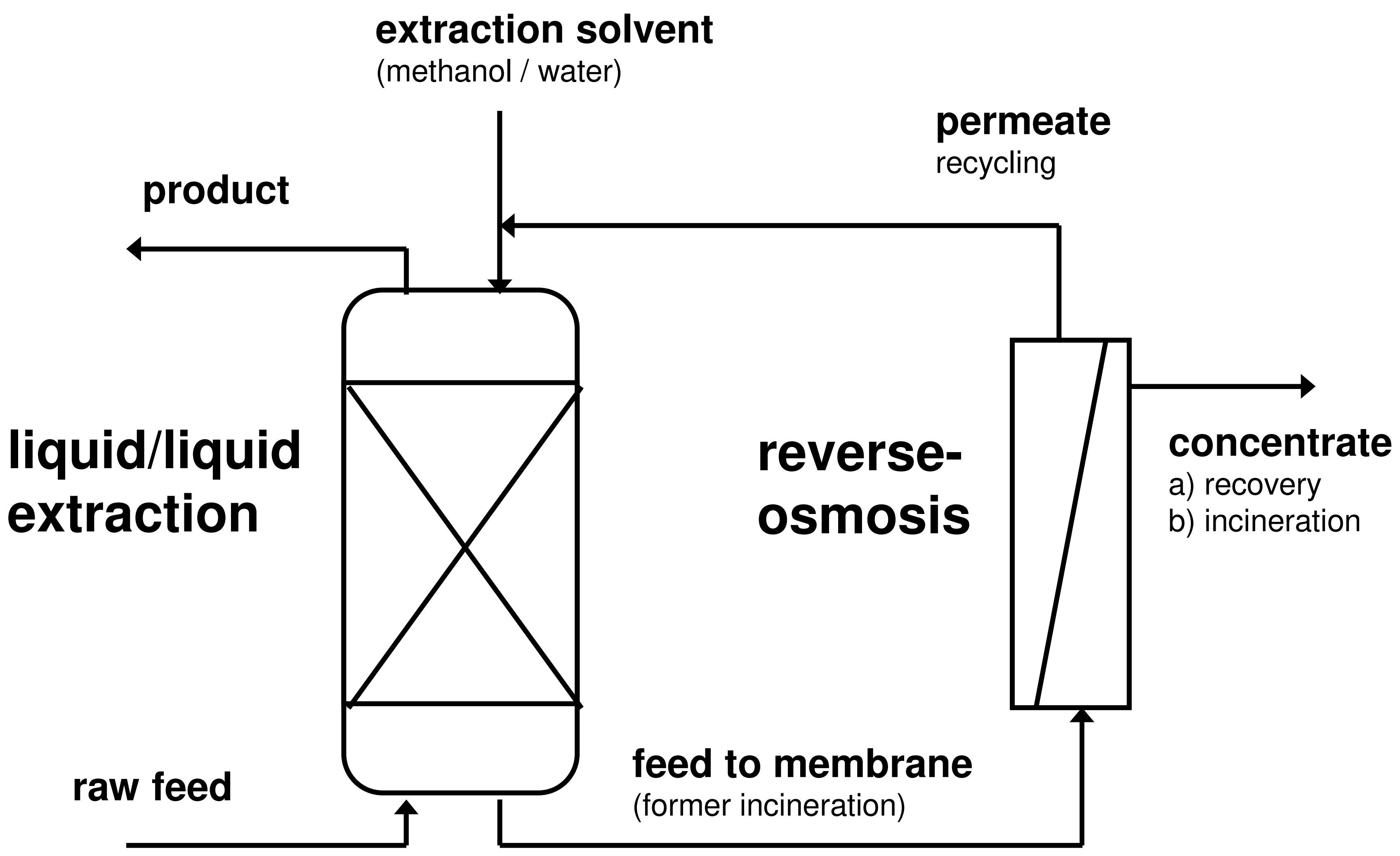
Module combination and membrane plant stages II

multiple loops in one stage

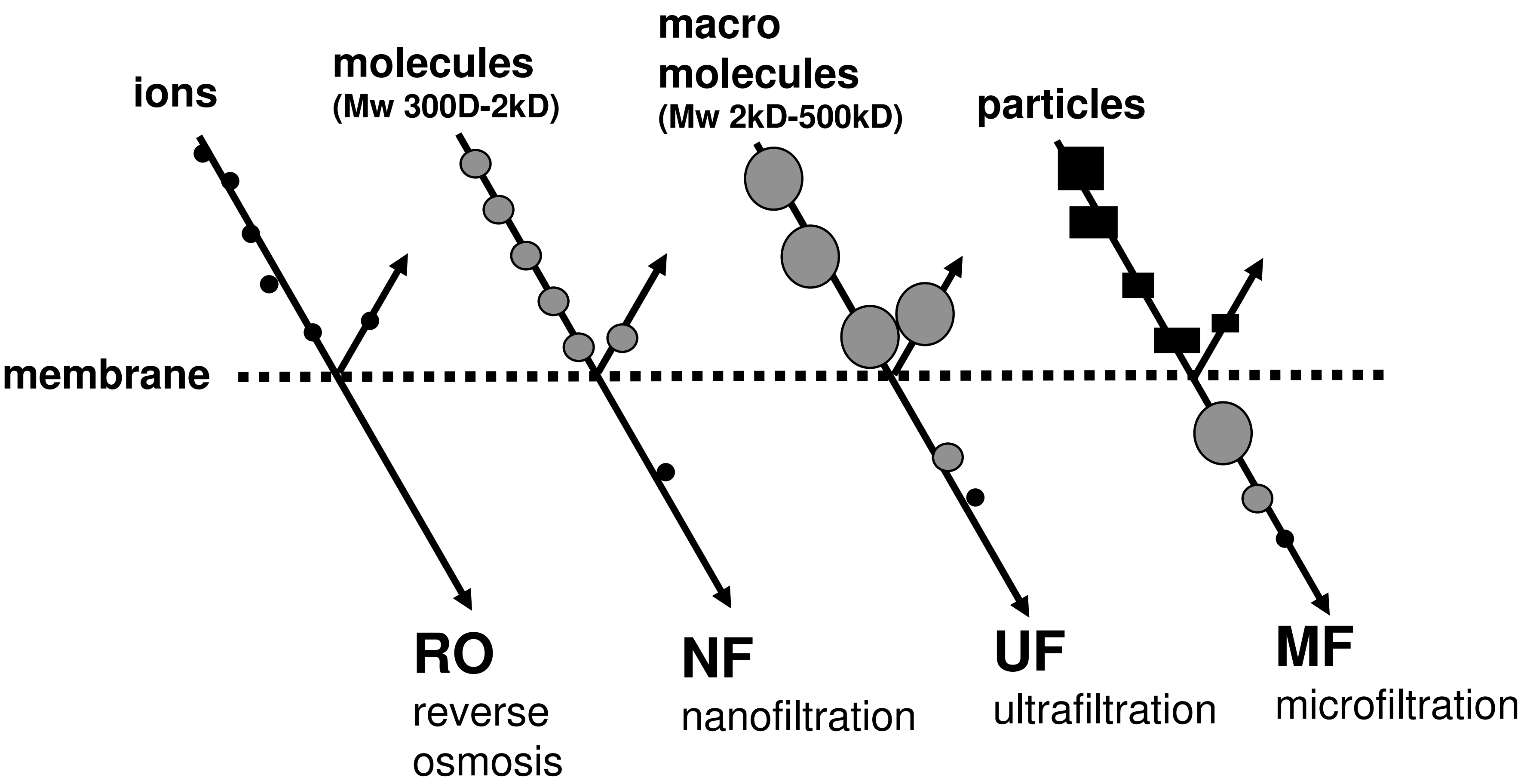
permeate stages



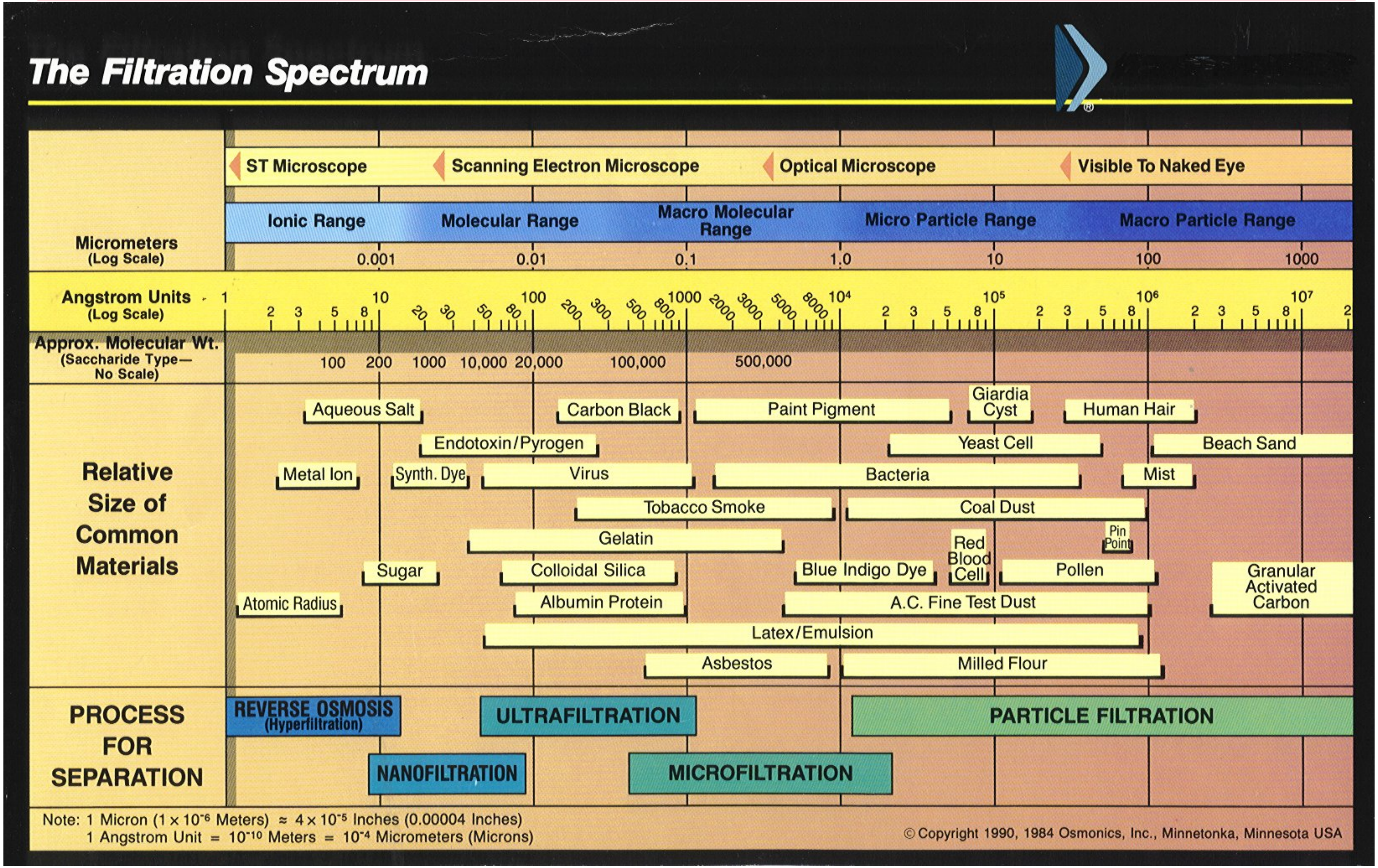
Integrated membrane process



Membrane processes I: pressure driven

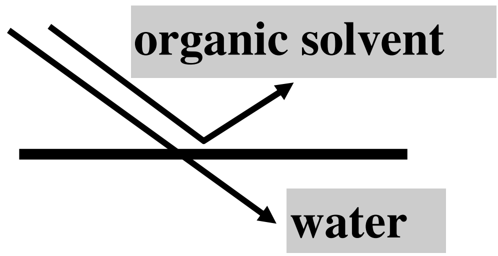


Membrane processes I: pressure driven



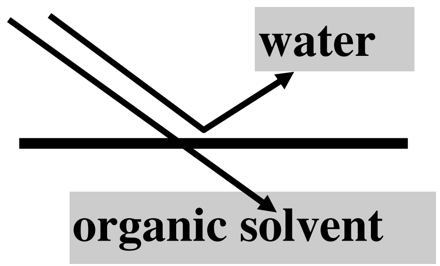
Membrane processes II: others

PV: pervaporation a) hydrophilic



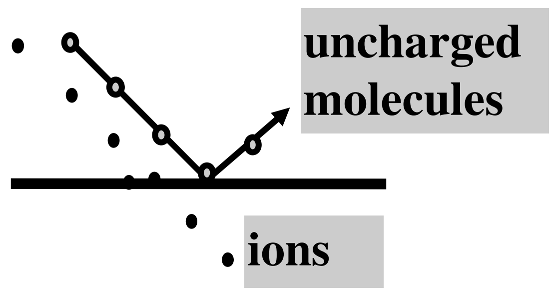
driving force:
partial pressure
difference

PV: pervaporation a) organophilic



driving force:
partial pressure
difference

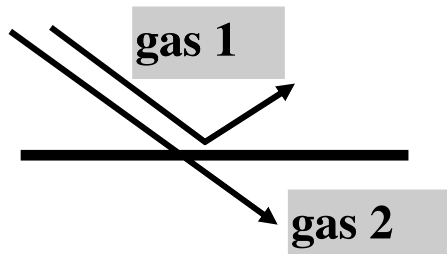
ED: electrodialysis



driving force:
electric field

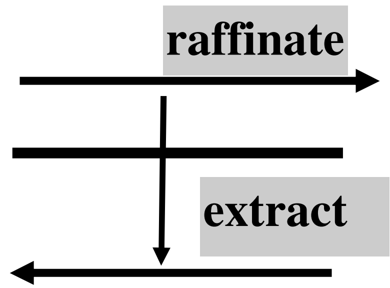
Membrane processes III: others

GS: gas separation



driving force: partial pressure difference

ME: membrane extraction

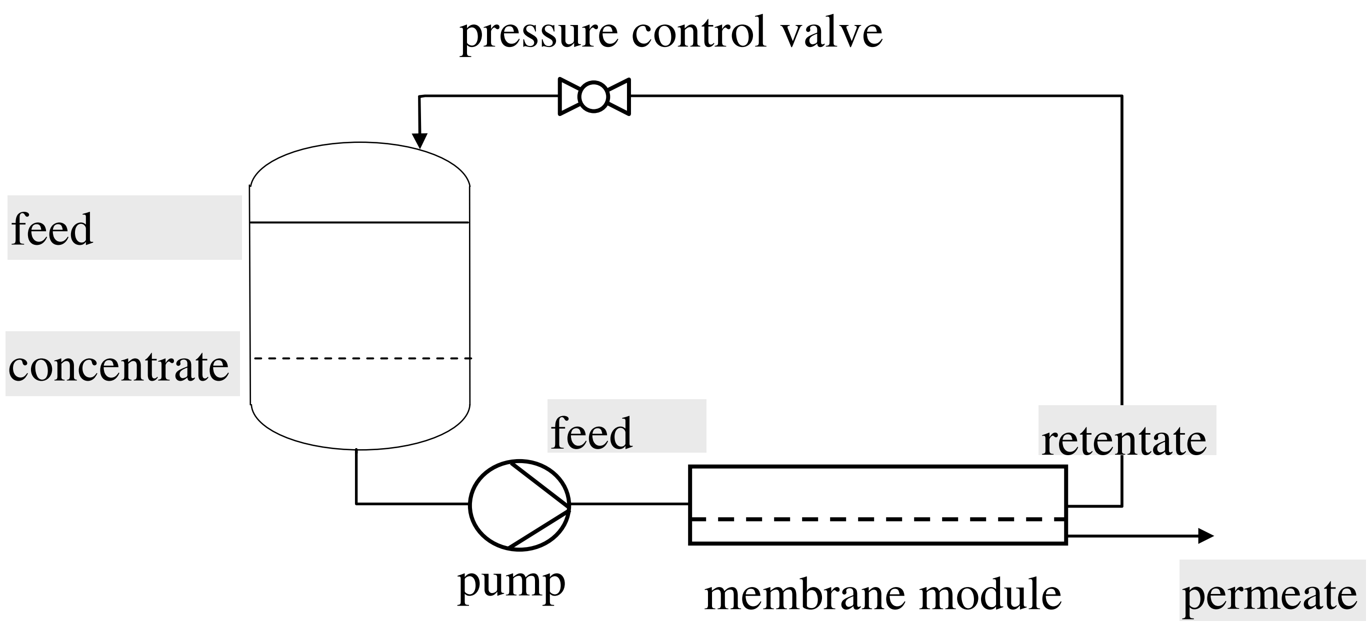


driving force: concentration difference

Membrane processes

process	pressure [bar]	retained component	Application examples
MF	1	microparticles > 0.1µm	particle removal, concentration or washing (e.g. pigments, fermentation broths) oil/water emulsion splitting
UF	5	macro molecules > 2 kD	concentration and cleaning of fermentation products, egg-white, gelatine, cheese-whey
NF	20	molecules > 300 D	concentration and desalting of chemical products (dye, optical brighteners, pharmaceuticals) or waste streams
RO	50 (200)	molecules > 150 D	sea water desalination, chemical product concentration, waste water concentration,
GS	10	different gases	N_2/O_2 separation solvent recovery from waste air
PV	Vakuum	org. solvent / water	(azeotrope-) dehydration e.g. alcohols, ketones, esters, organic acids // organic solvent removal from wastewater
ED	electric field	uncharged molecules	desalting, eletrochemical reactions, acid/base recovery from salts
ME	conc. difference		hämodialysis, membrane suported extraction

MF - RO in common / differences



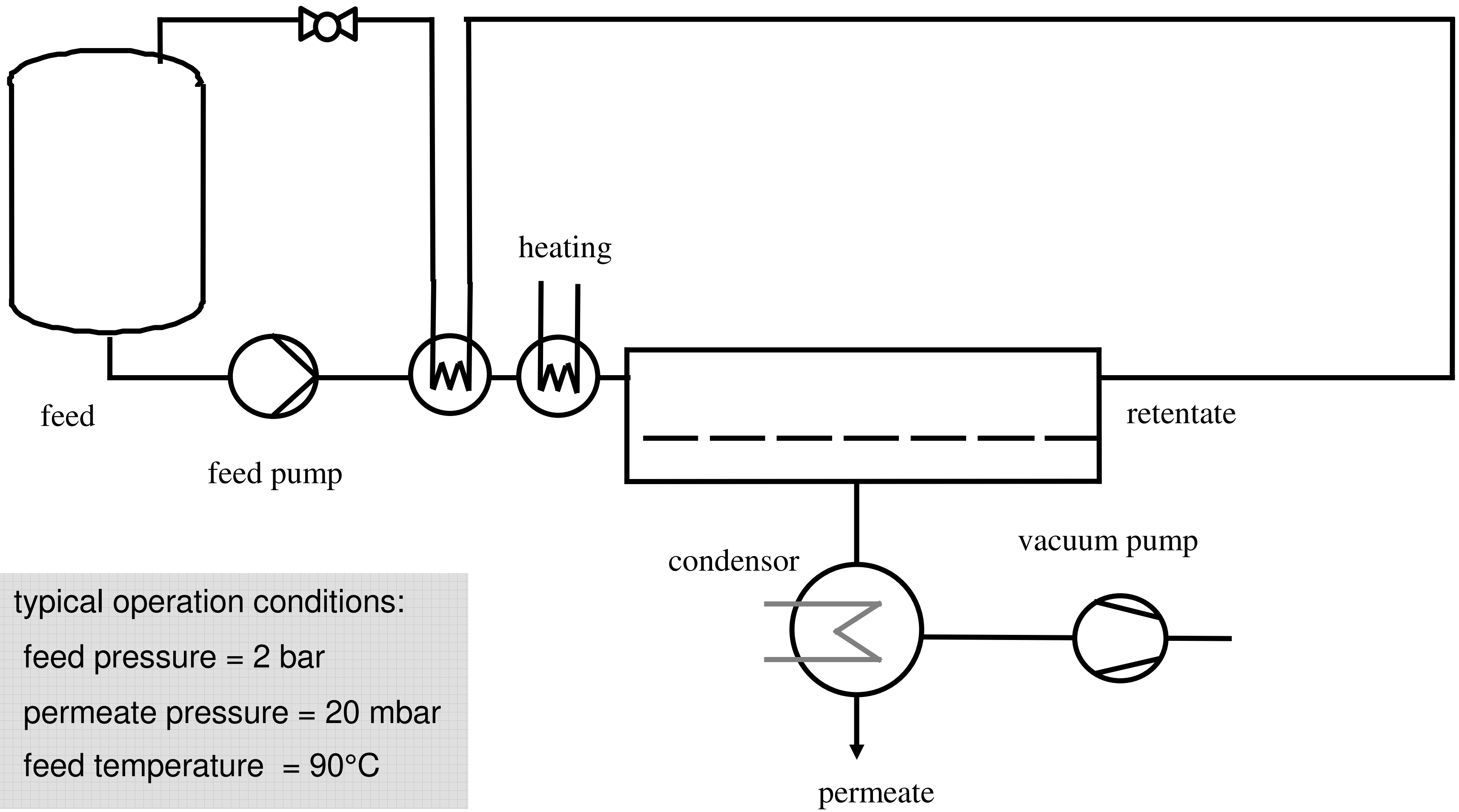
in common:

- pressure driven
- all streams liquid
- minimum components as above
- permeate flux
  from 20 to 100 l/m²h

differences:

- no osmotic pressure in MF
- MF has highest permeat flow
  needs highest cross flow velocity
- pressure drop in MF important
- driving pressure 0.5 bar MF to 200 bar RO

Pervaporation PV



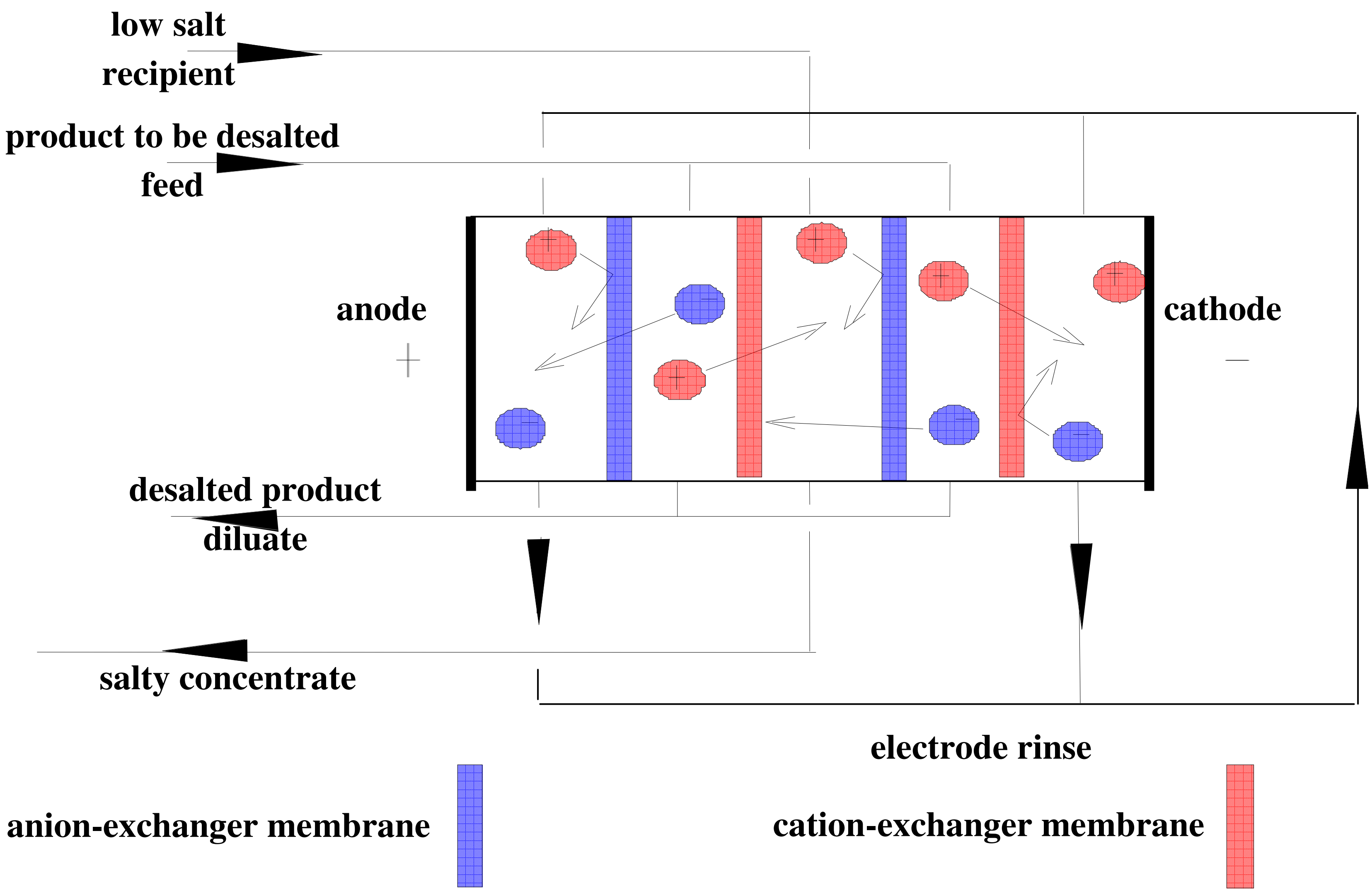
typical operation conditions:

feed pressure = 2 bar

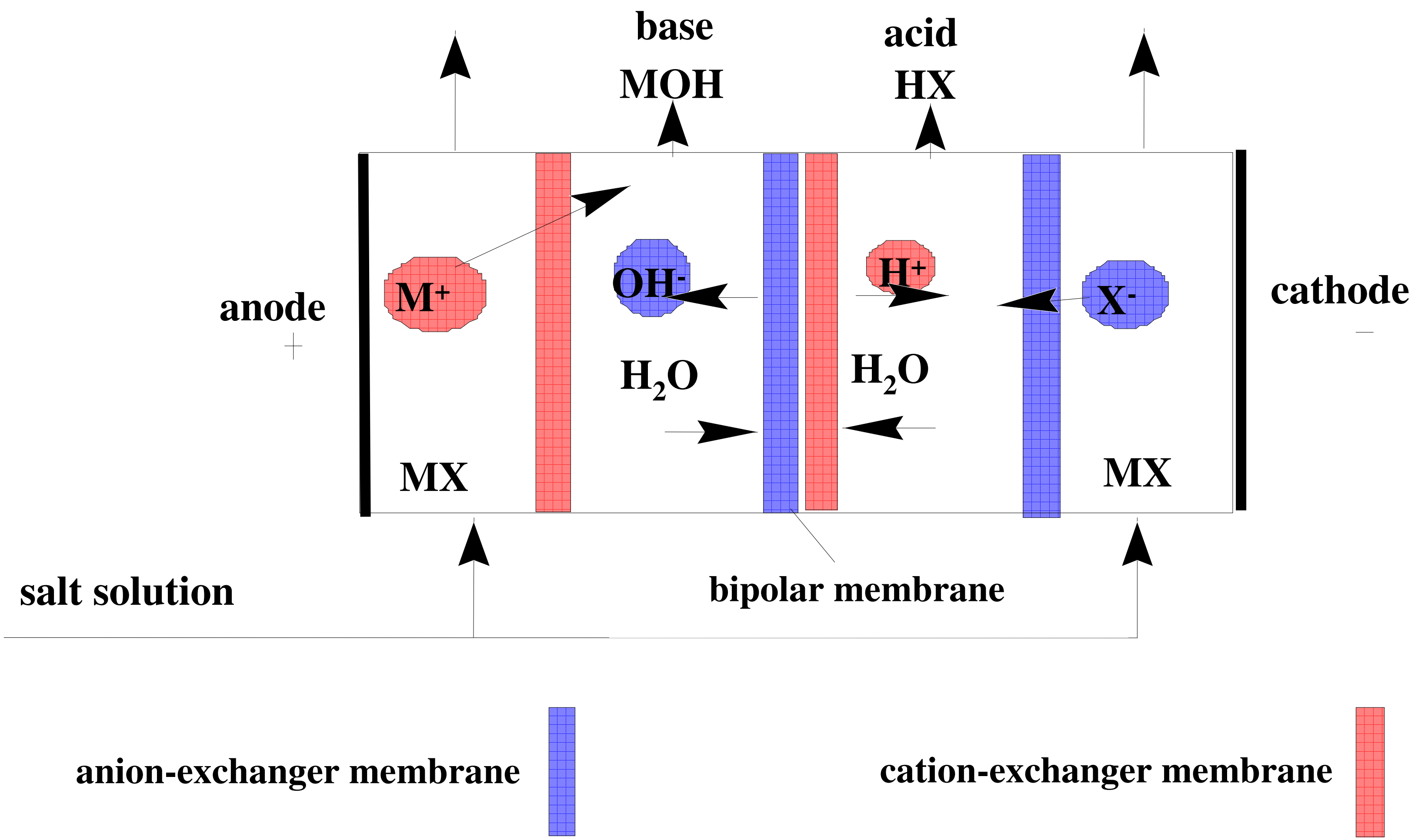
permeate pressure = 20 mbar

feed temperature = 90°C

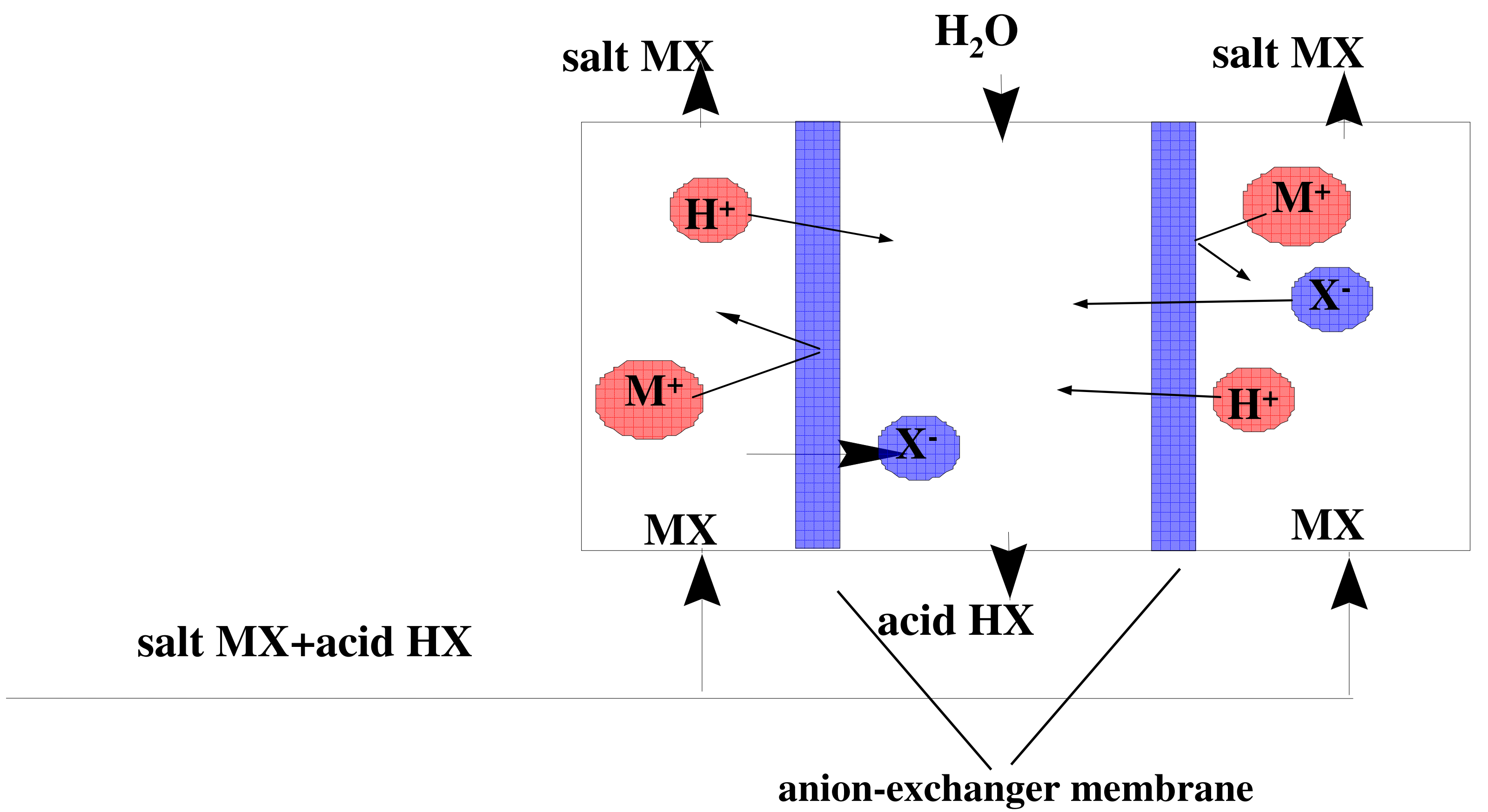
Electrodialysis ED



Electrodialysis with bipolar membranes



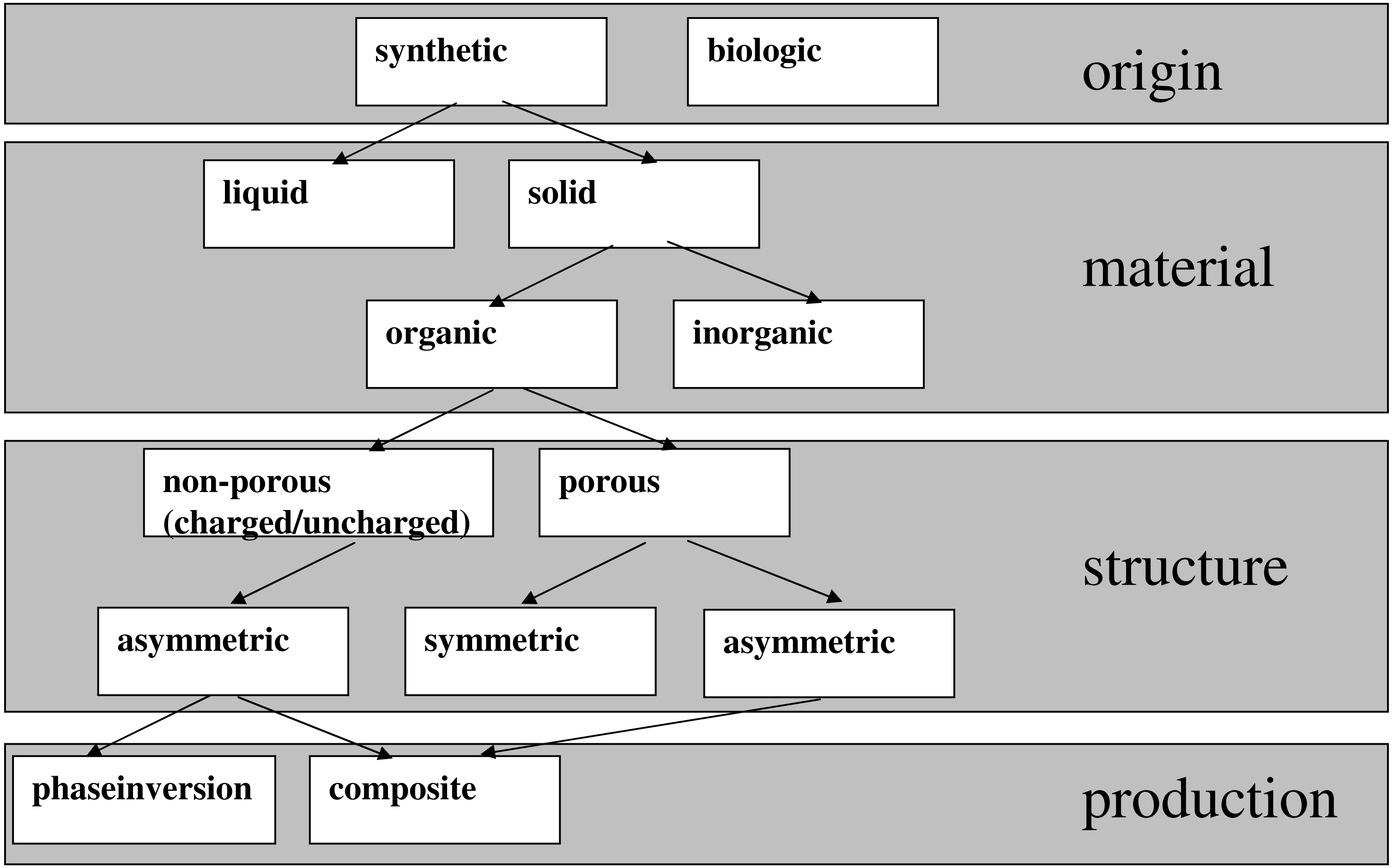
Acid dialysis (acid cleaning)



Other membrane processes

- variants of electrodialysis
- membrane extraction
- membrane distillation
- **gas separation**
- **dialysis**
- membrane reactor
- catalytic membrane
- liquid membranes
- ative transport

Membrane materials

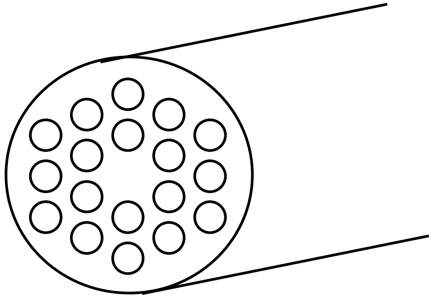


Membranes and modules

tubular	**flat**
tubular (Ø 6-25 mm)	plate and frame
capillary (Ø 0.5-6 mm)	spiral wound
hollow fibre (Ø 0.04-0.5 mm)	cushion type

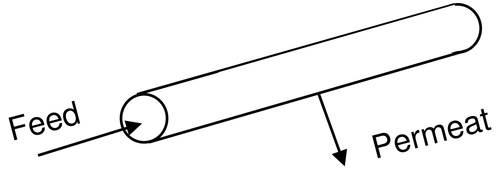
most common membrane module types

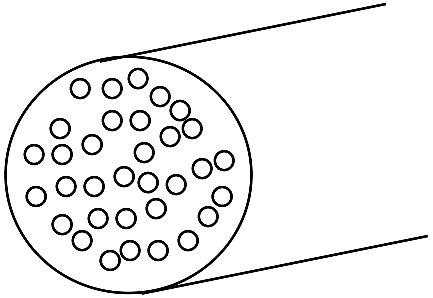
Module types I



tubular

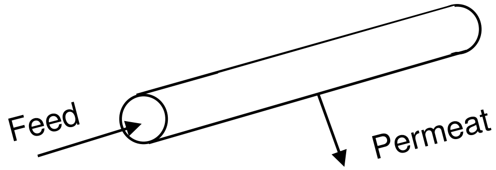
e.g. 18 tubes in series
12.5mm∅
2.4 m²
0.1m x 3.6m
1000 EUR

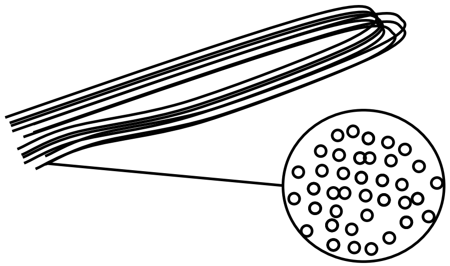




capillary

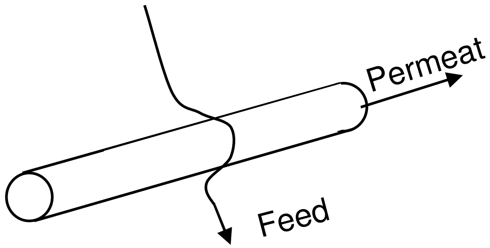
many tubes in parallel
1.5mm∅
12 m²
0.2m x 1.0m
4000 EUR





hollow-fibre

0.15mm ∅
24 m²
0.1m x 1m



Tubular

Capillary

Ceramic capillary

Module types II

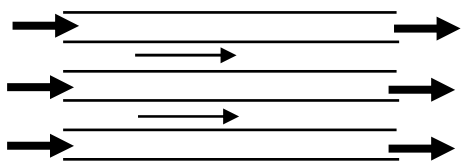
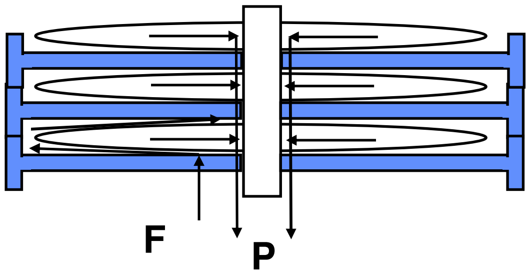


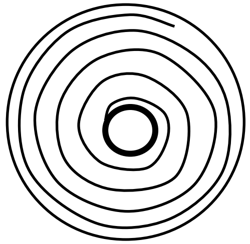
plate and frame

with seals / without seals
all sizes



cushion type

membranes welded
high pressure up to 200 bar



spiral

membrane pockets wrapped
8 / 32 m^2 Membranfläche
0.1m x 1m, 0.2 x 1m
500 EUR

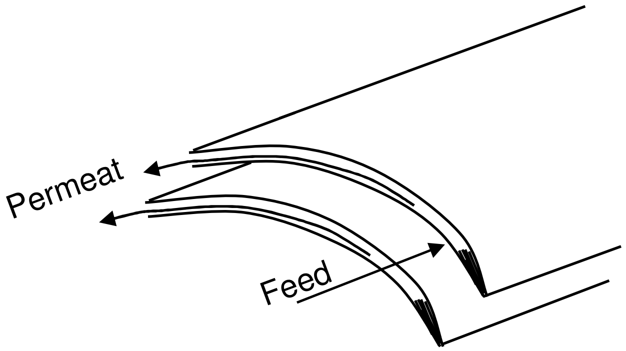


Plate-and-frame

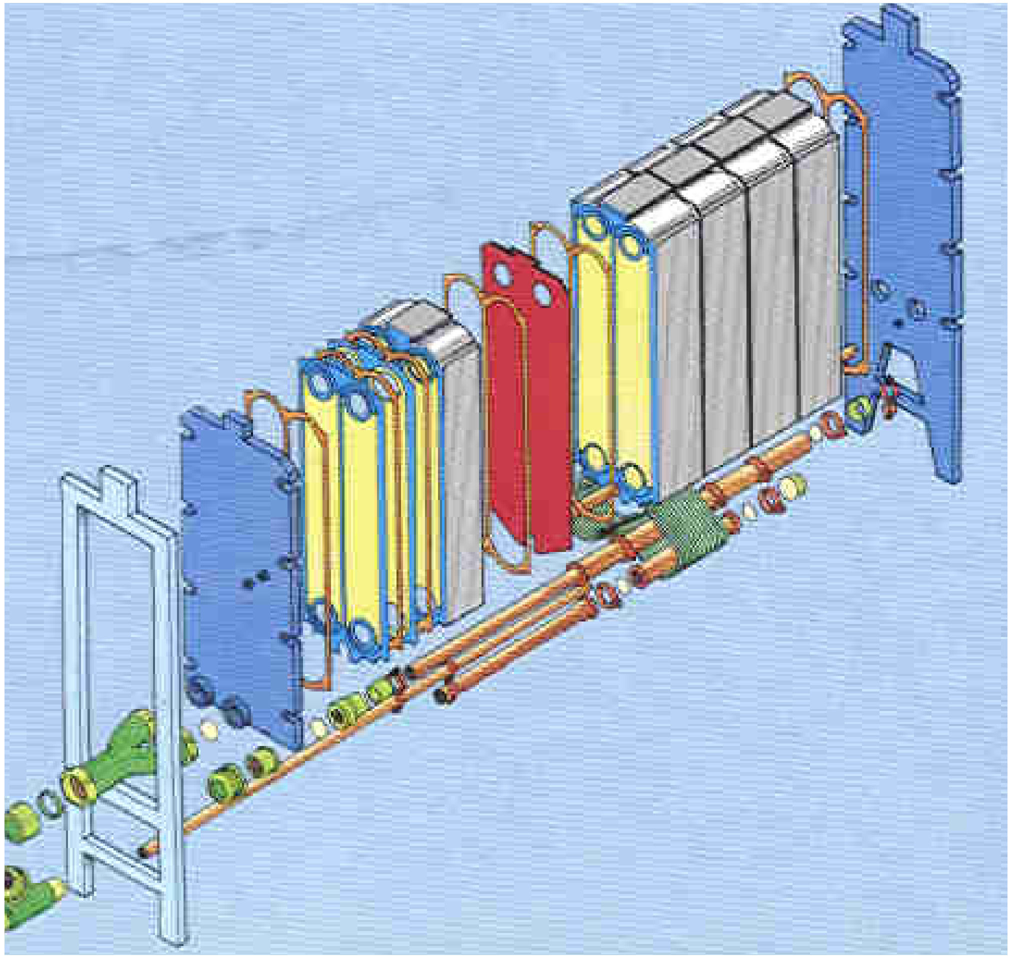
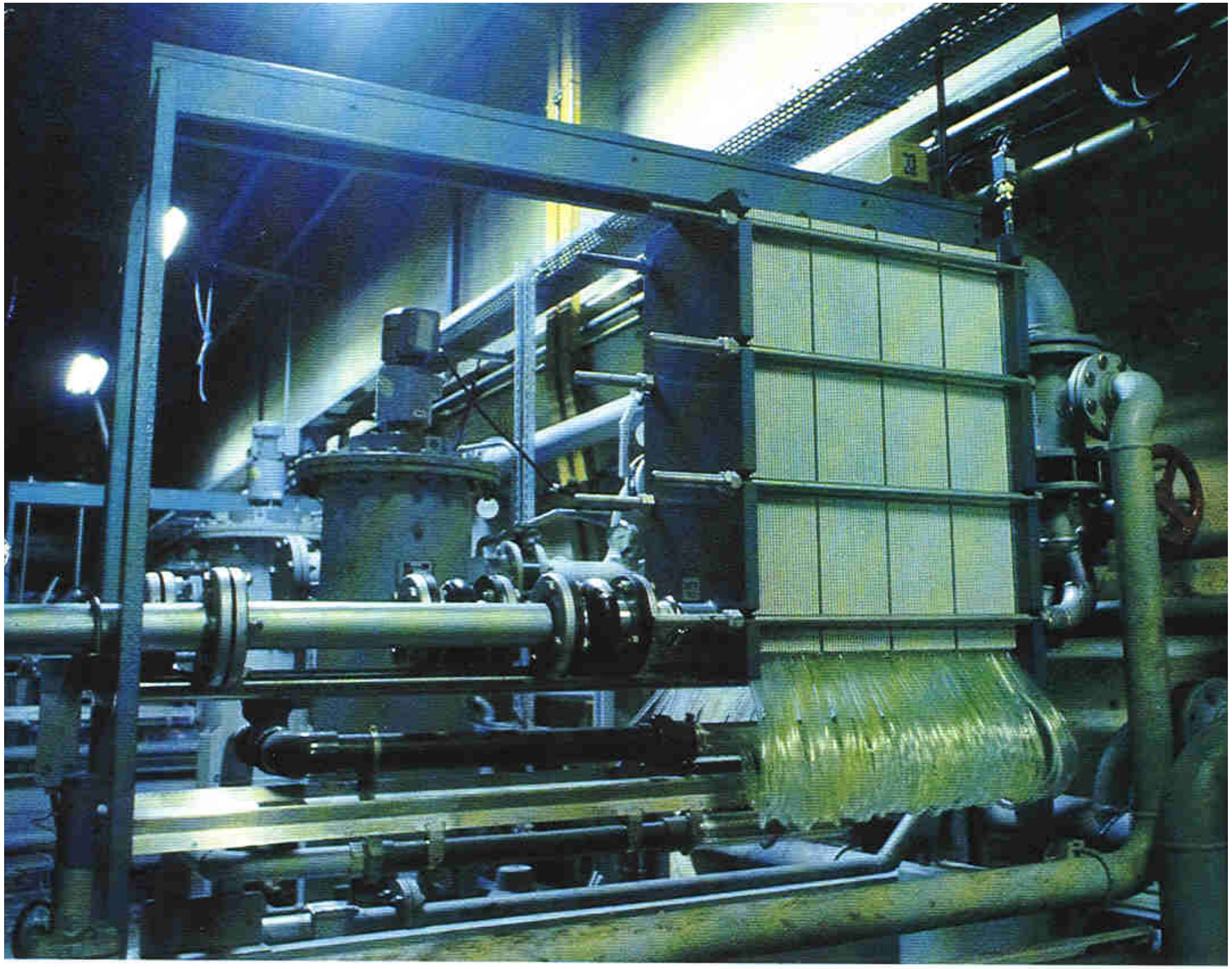
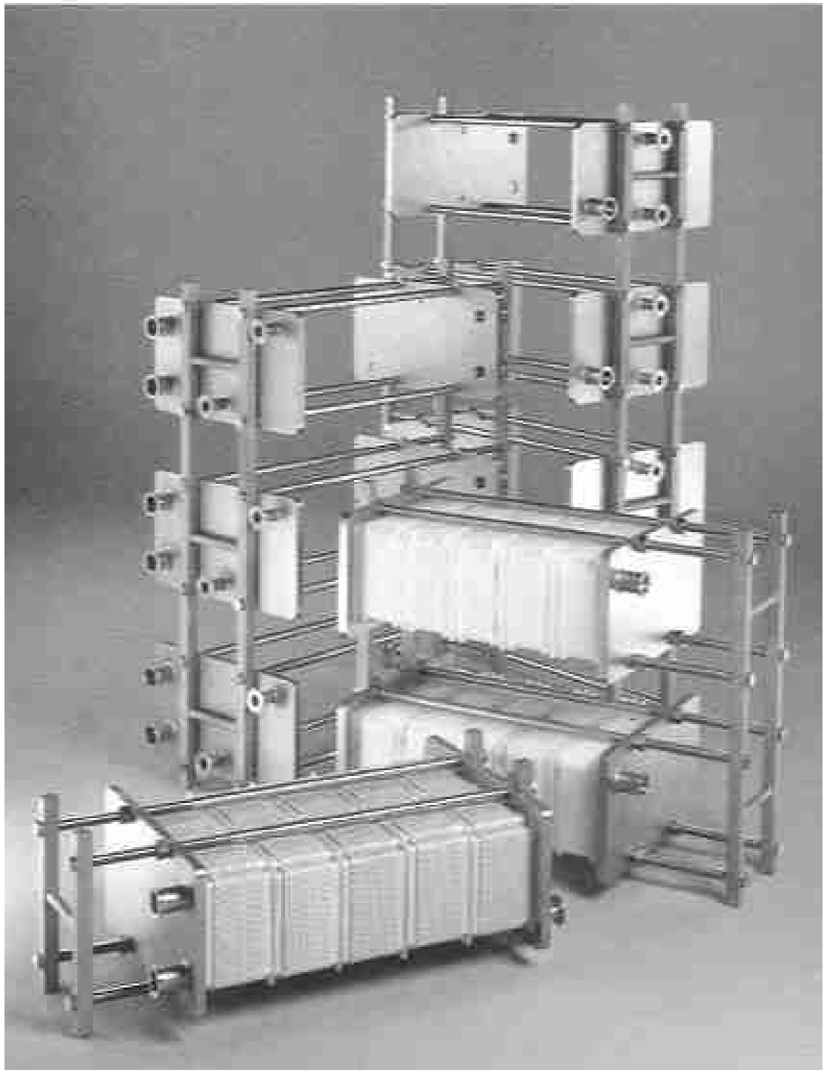


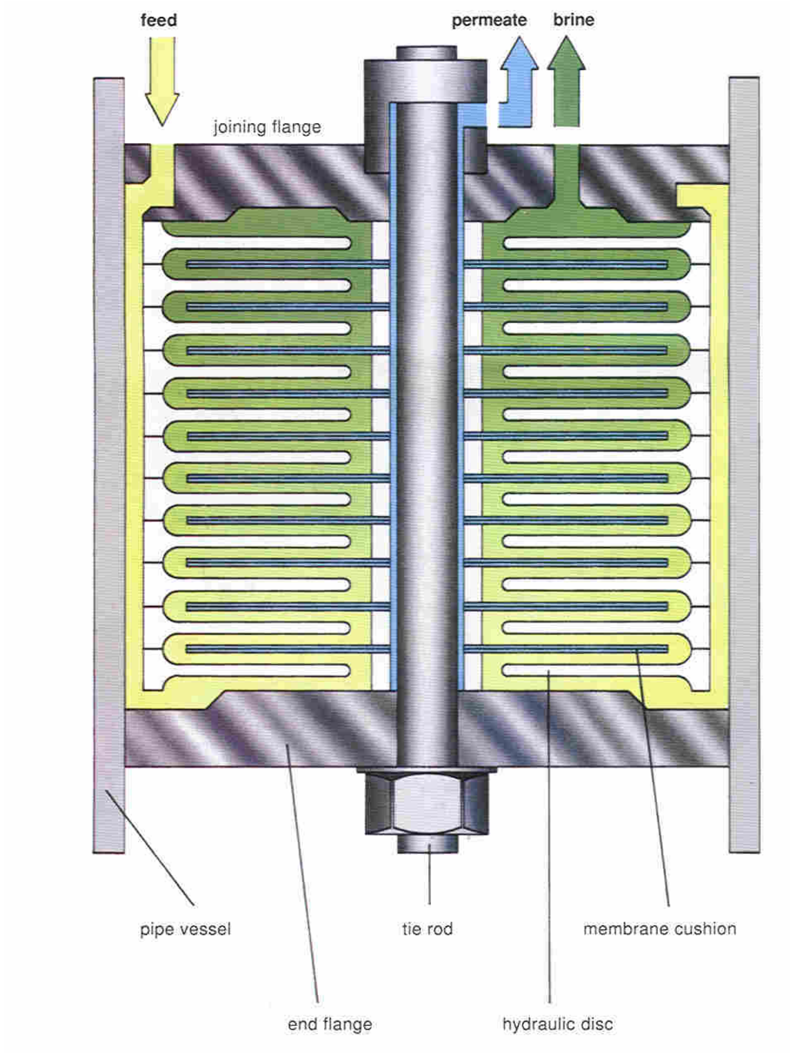
Plate-and-frame



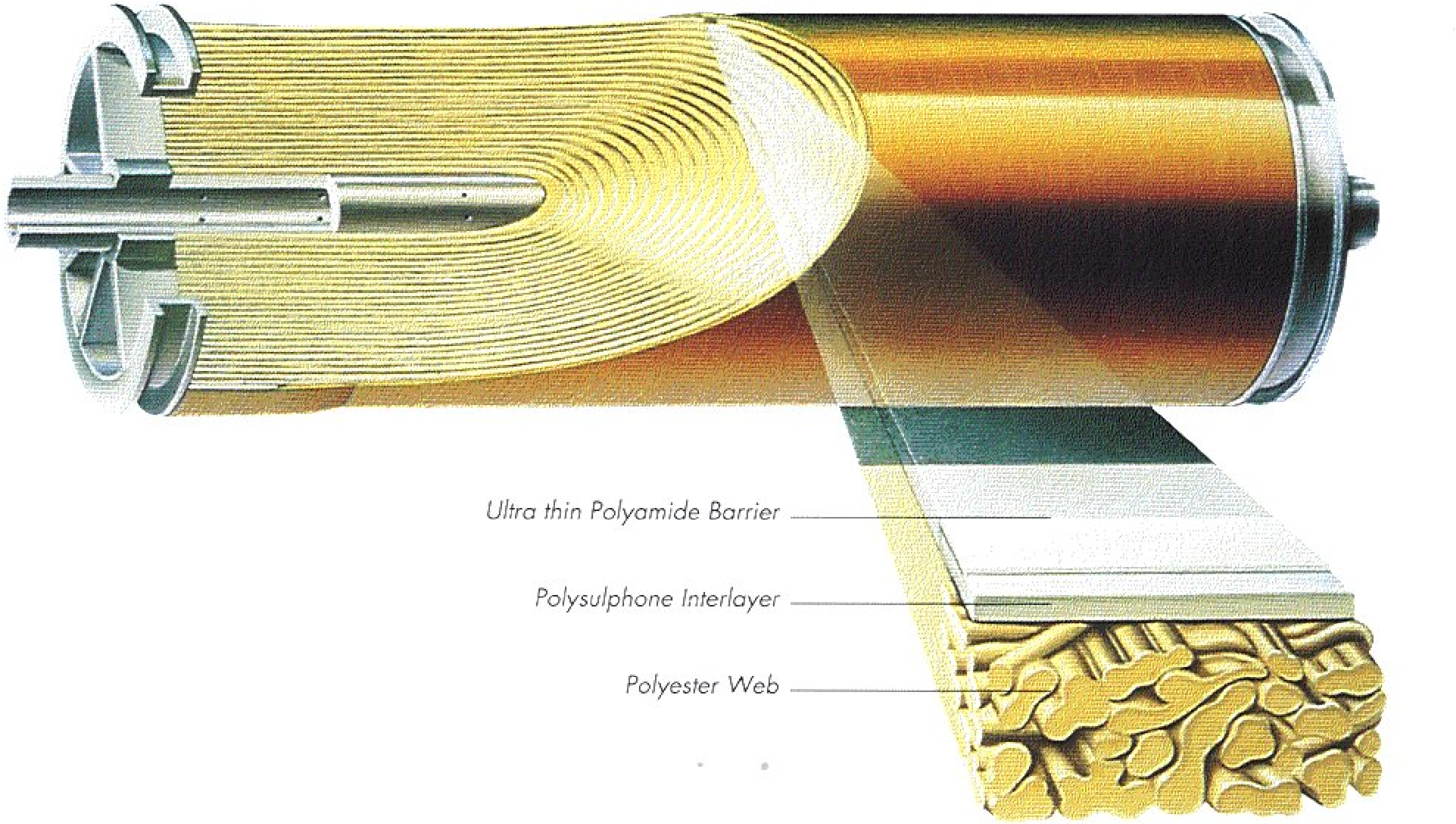
Cassette modules



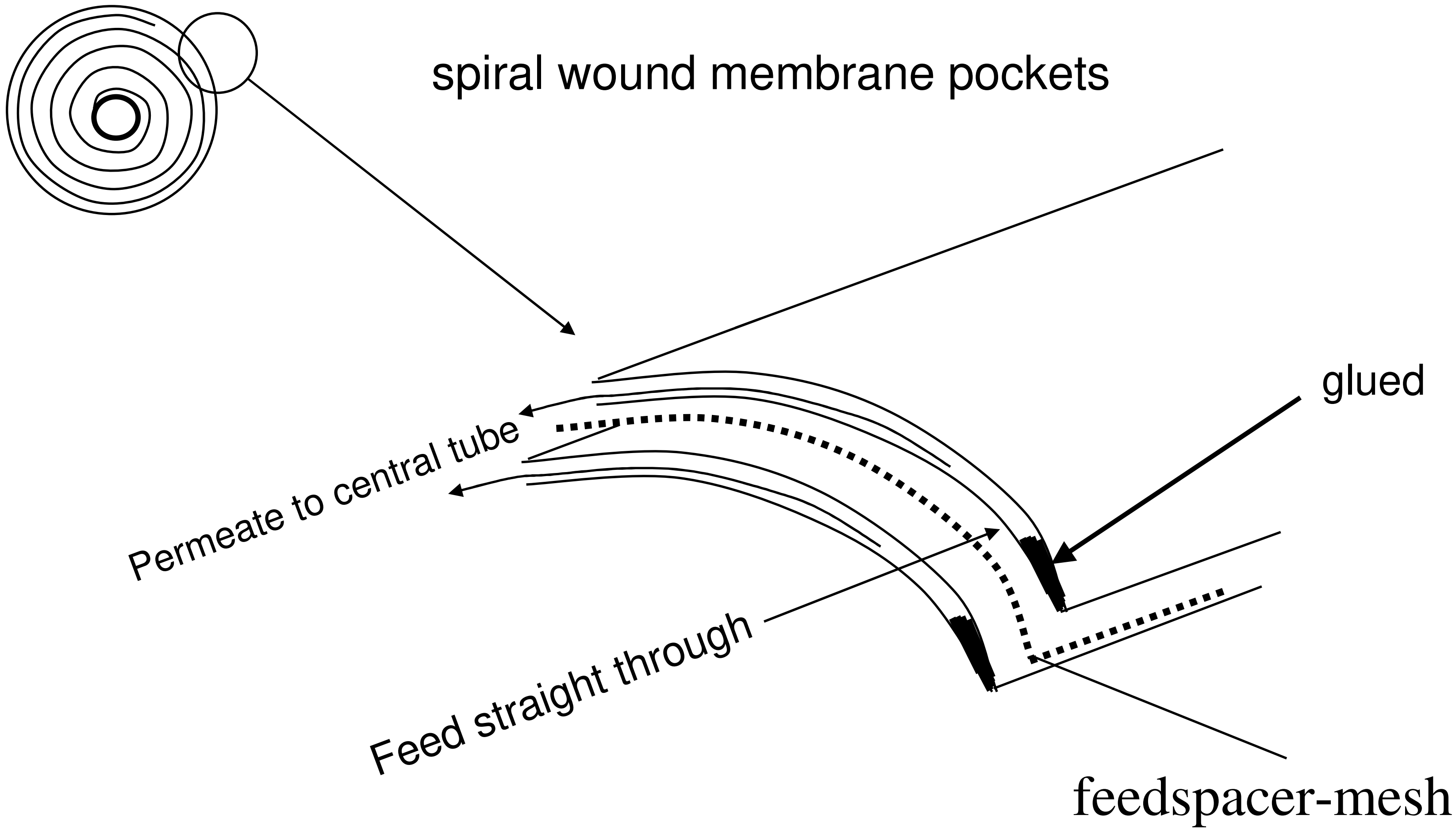
Cushion module



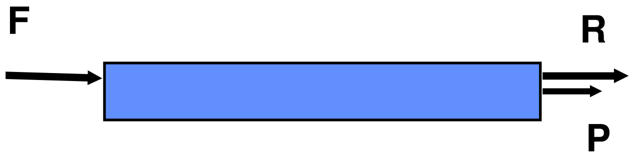
Spiral-wound

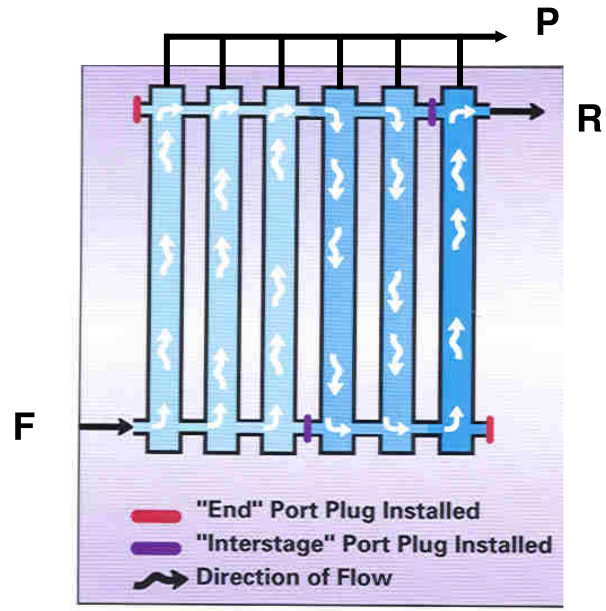


Spiral-wound

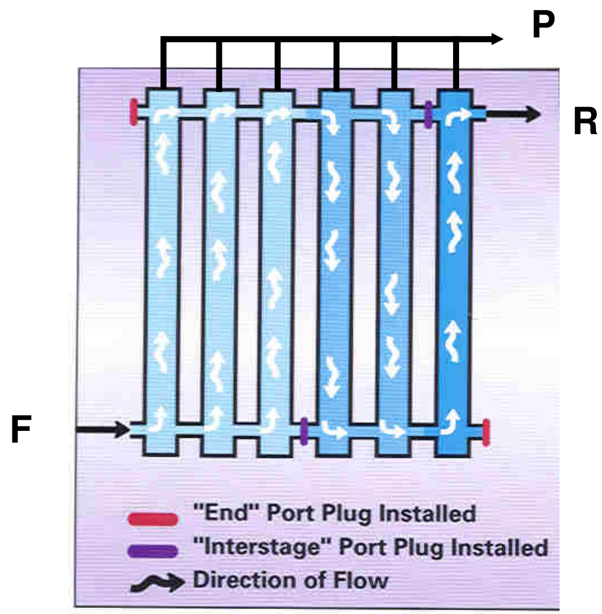


Pressure vessels for spiral elements





Side-port pressure vessels for spiral elements

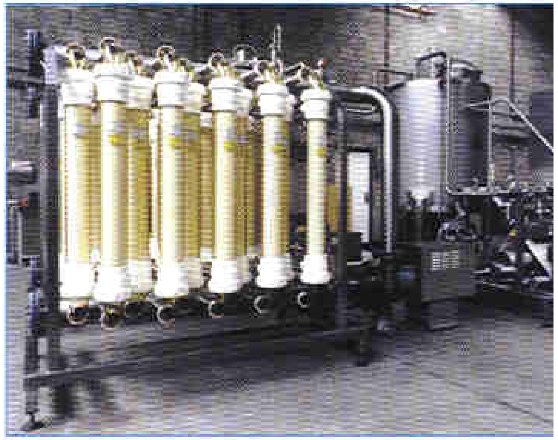


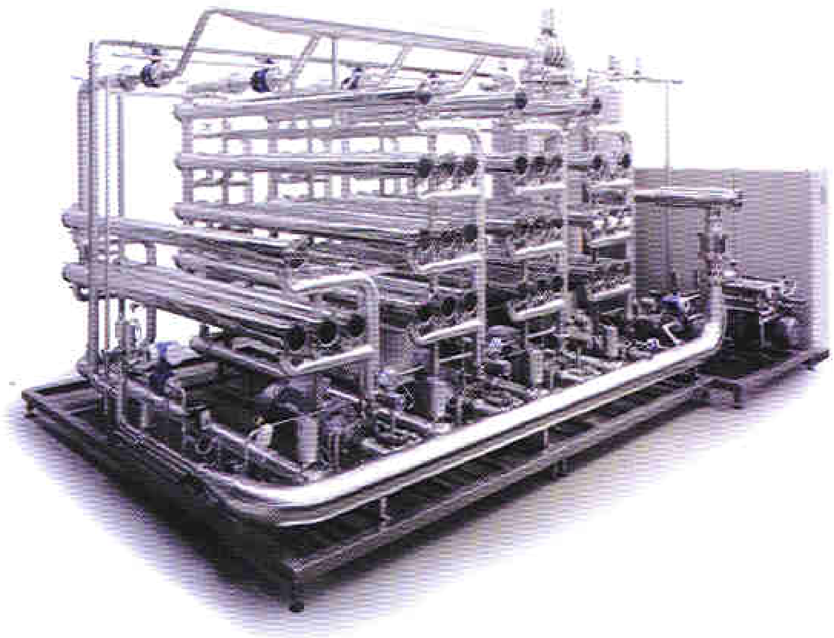
Membranes and modules

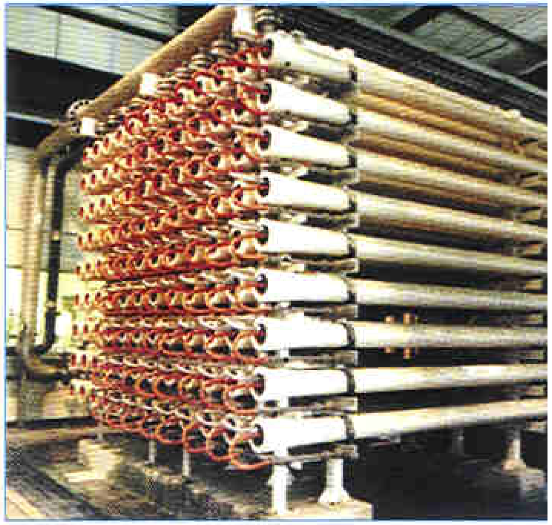
membrane material	module types	separations
ceramic	multitube	MF, UF, NF
carbon	tubular	MF
zeolithe	tubular	PV
metal	tubular	MF
cellulose aceate	plate, spiral	NF, RO
regenerated cellulose	plate, spiral	MF, UF
PA/PSU	plate, spiral	UF, NF, RO
PVDF	plate, spiral	MF
PVA/PAN	plate	PV
PES/PVP	plate, spiral, capillary	MF, UF, NF
PE, PP	capillary	MF

Membrane racks

oben links: *Rohrmodulanlage zur Abwasseraufbereitung*
oben rechts: *Mikrofiltrationsanlage zur Weinklärung*
unten links: *Mehrstufige Spiralmodul-Anlage zur Proteinkonzentrierung/-fraktionierung*
unten rechts: *Mehrstufige Umkehrosmoseanlage zur Aufbereitung von Wasser/ Abwasser*







Other plant components: piping

- material (stainless steel, PVC, PP)
- pressure rating, cost relevant, also for instrumentation, espec. >40bar
- connectors (lab units: Swagelok, sanitary: Tri-Clamp, high pressure: flanges

Other plant components: pumps

- centrifugal: high volumes, limited pressure (max. 20-40 bar)
- side channel: smaller volume, higher pressure
- piston: small volume, high pressure (<10m3/h, >100 bar) no solids
- membrane: similar to piston, max. 100 bar, solids allowed

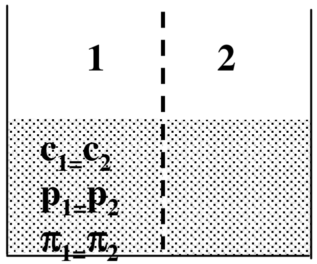
Other plant components: instrumentation

- pressure gauge: piezo-resistive or classical, with diaphragm
- flowmeter: magnetic, rotary, (rarely corriolis)
- pressure controll valve: critical size choice, needle (no solids), ball valve (solids broad flow range)
- pump flow: frequency converters are cheap today !

Osmosis

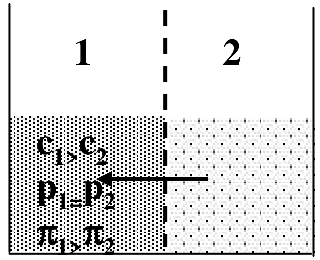
natural equilibrium

$c_1=c_2$ same concentration (so $\pi_1=\pi_2$)
$p_1=p_2$ same pressure
no solvent flux



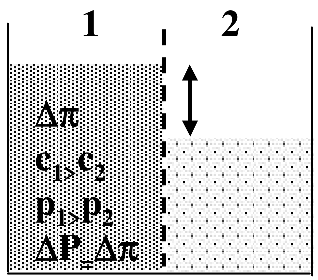
osmosis

$c_1>c_2$ concentration difference (so $\pi_1>\pi_2$)
$p_1=p_2$ same pressure
solvent flux from 2 to 1



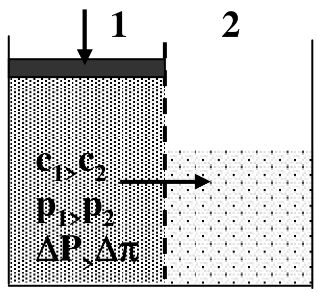
osmotic equilibrium

$c_1>c_2$ same concentration (so $\pi_1>\pi_2$)
$p_1>p_2$ pressure difference ($\Delta p=\Delta\pi$)
no solvent flux



reverse osmosis

$c_1>c_2$ same concentration (so $\pi_1>\pi_2$)
$p_1>p_2$ pressure difference ($\Delta p>\Delta\pi$)
solvent flux from 1 to 2



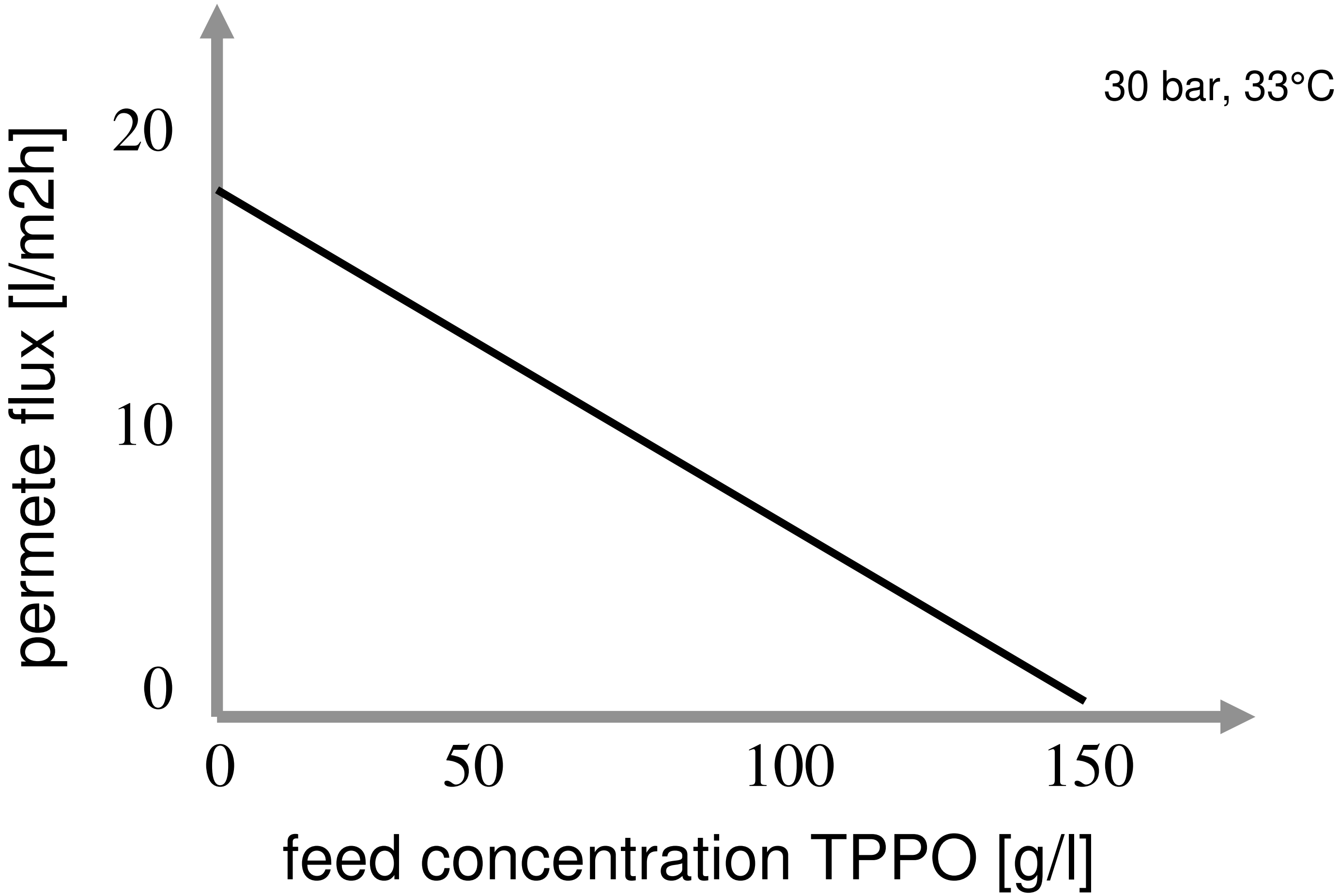
Osmotic pressure and reverse osmosis

osmotic pressure difference: $$\Delta \pi = \beta \Delta cRT$$

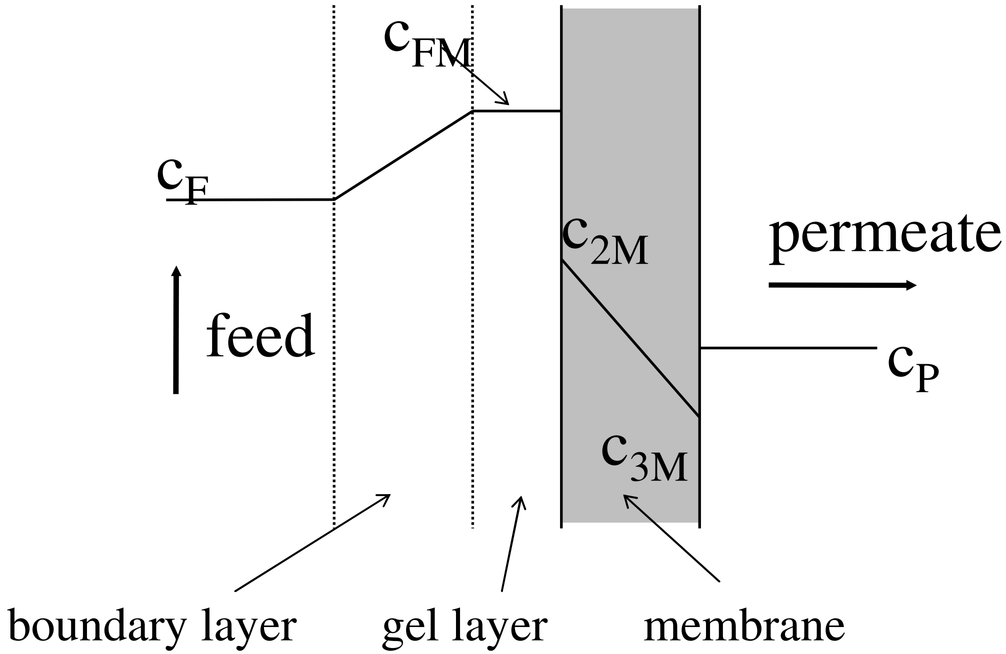
dissoziation of ions: $$\beta = 1 + \alpha(\nu - 1)$$

reverse osmosis flux: $$J_{LSM} = A(\Delta p - \Delta \pi)$$

Influence of feed concentration



Membrane retention: definitions



true membrane retention:

$$R_W = 1 - \frac{c_P}{c_{FM}}$$

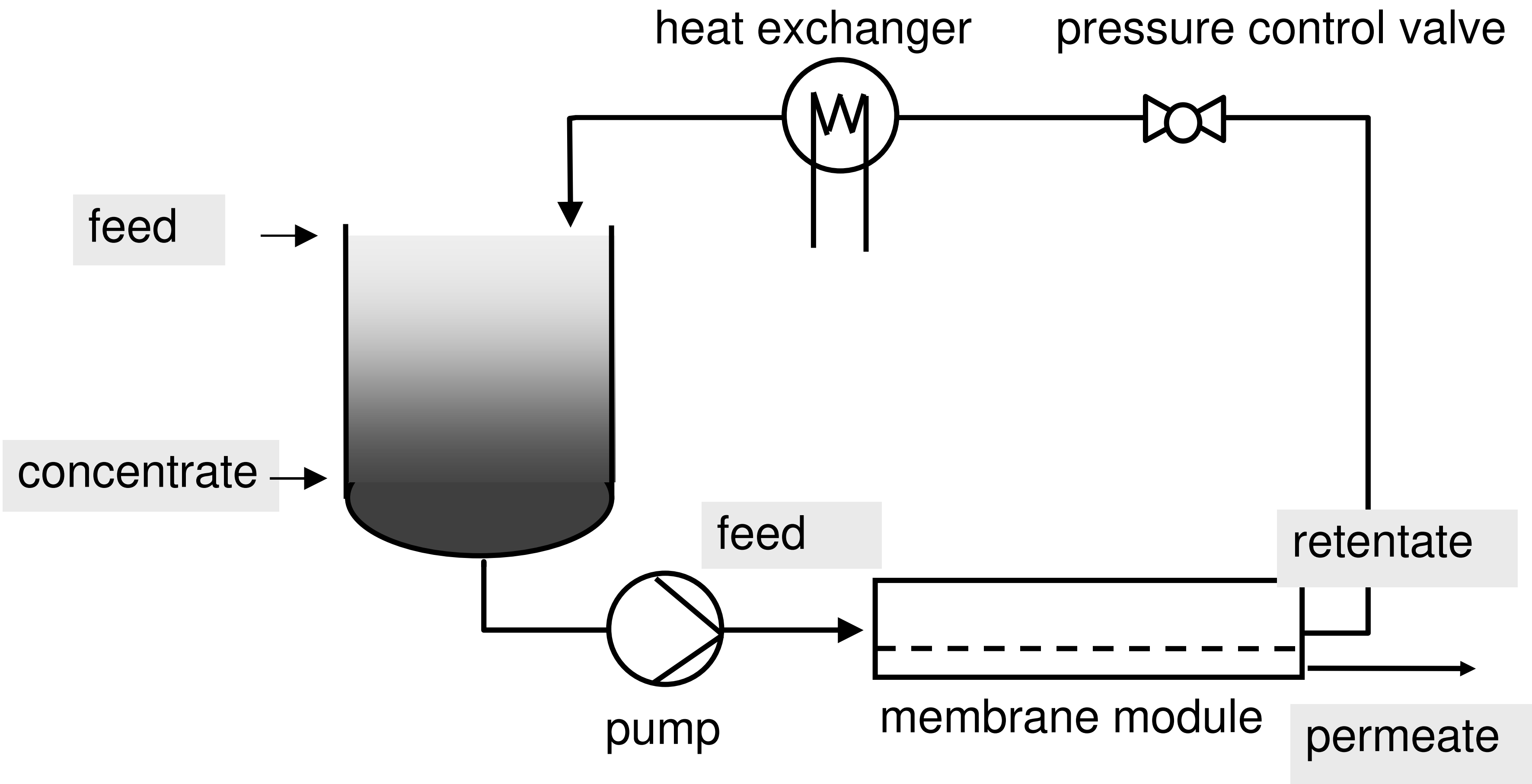
apparent retention:

$$R_S = 1 - \frac{c_P}{c_F}$$

mass balance retention (yield):

$$R_{mb} = \frac{V_R c_K}{V_F c_0} = 1 - \frac{V_P c_{\sum P}}{V_F c_0}$$

Batch process



Batch process: concentrating

volumetric concentrating factor:

$$X = \frac{V_0}{V_K}$$

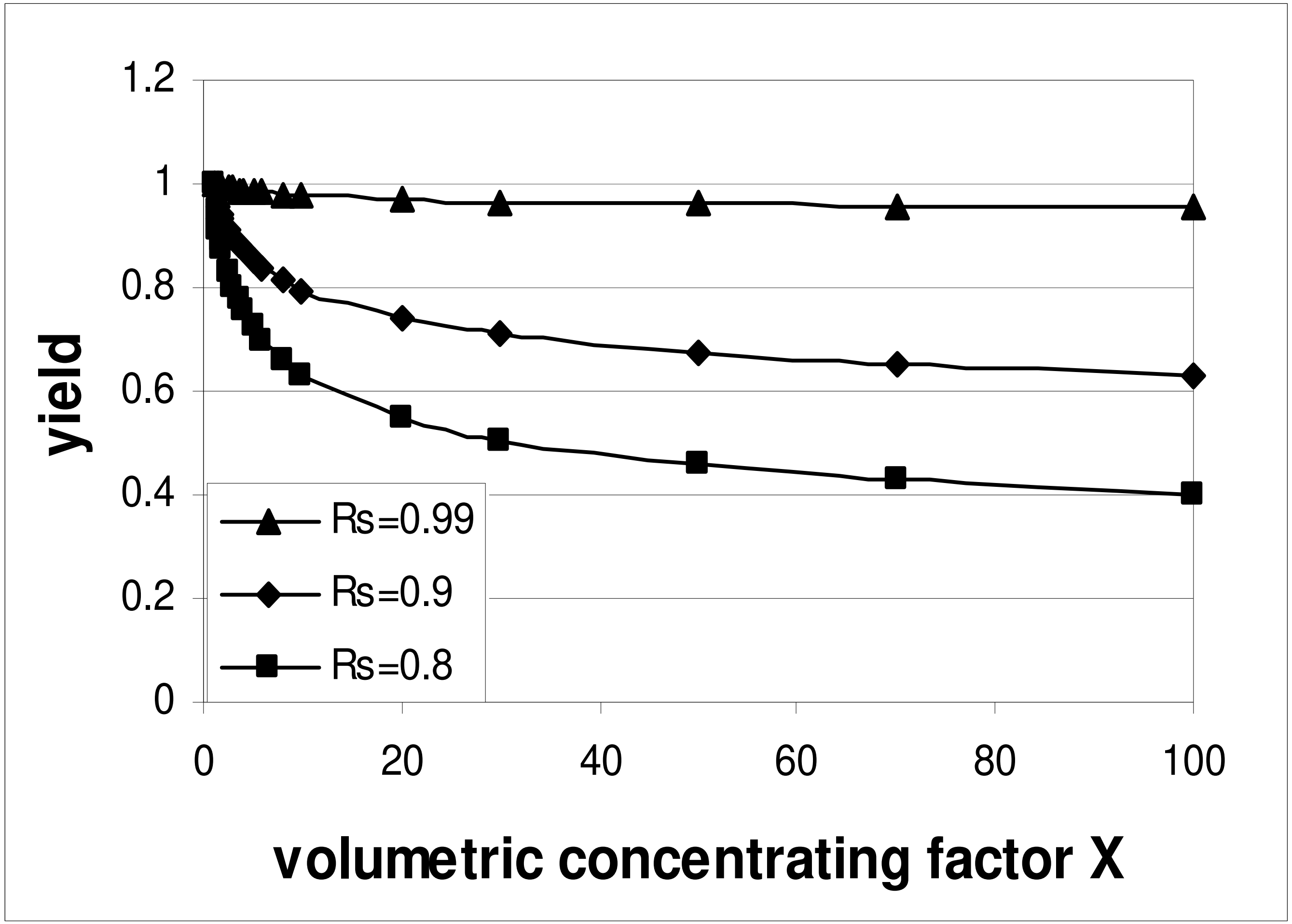
end concentration:

$$\frac{c_K}{c_0} = X^{R_S}$$

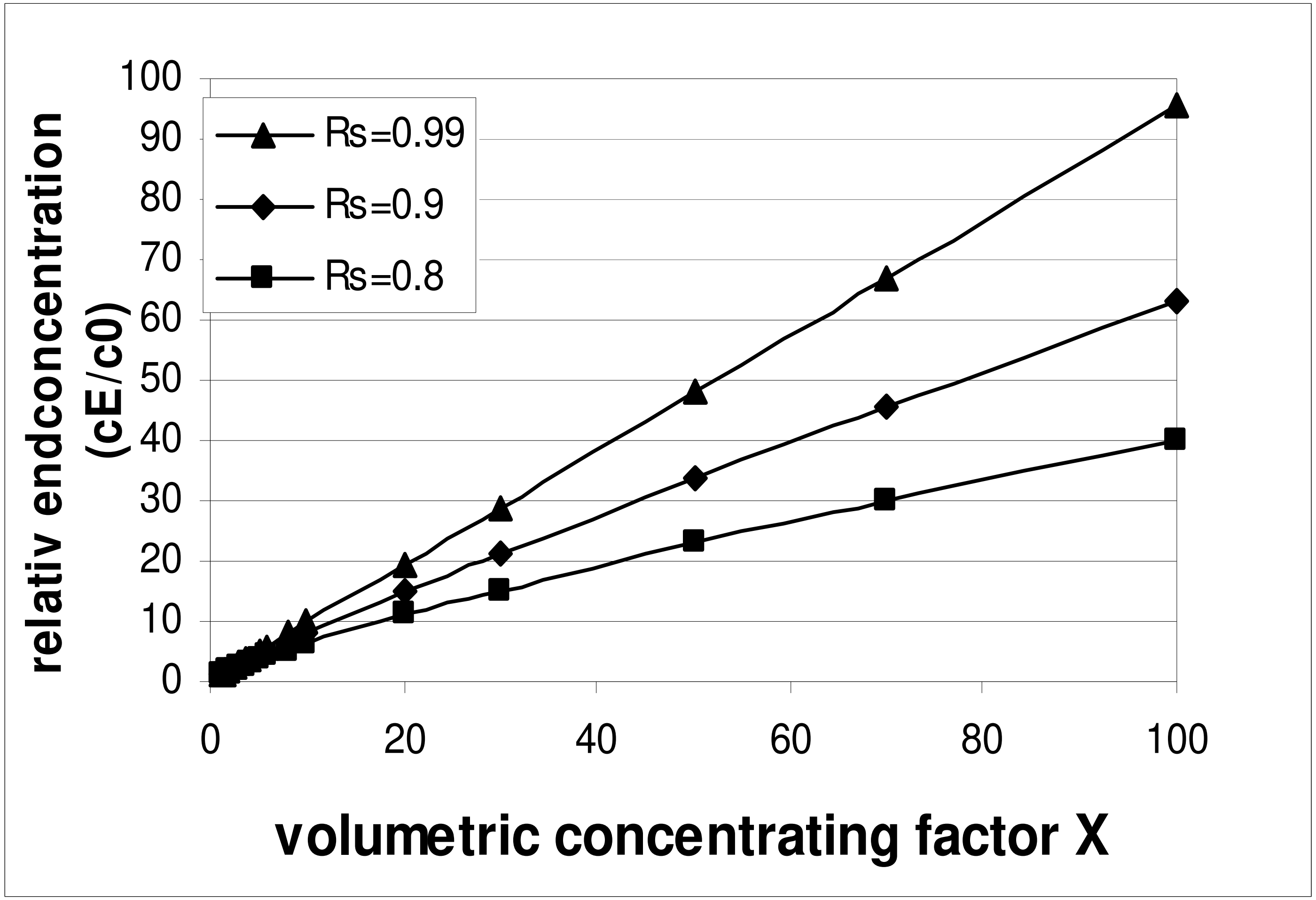
yield:

$$R_{MB} = \frac{V_R c_K}{V_0 c_0} = X^{R_S - 1}$$

Batch process: concentrating



Batch process: concentrating



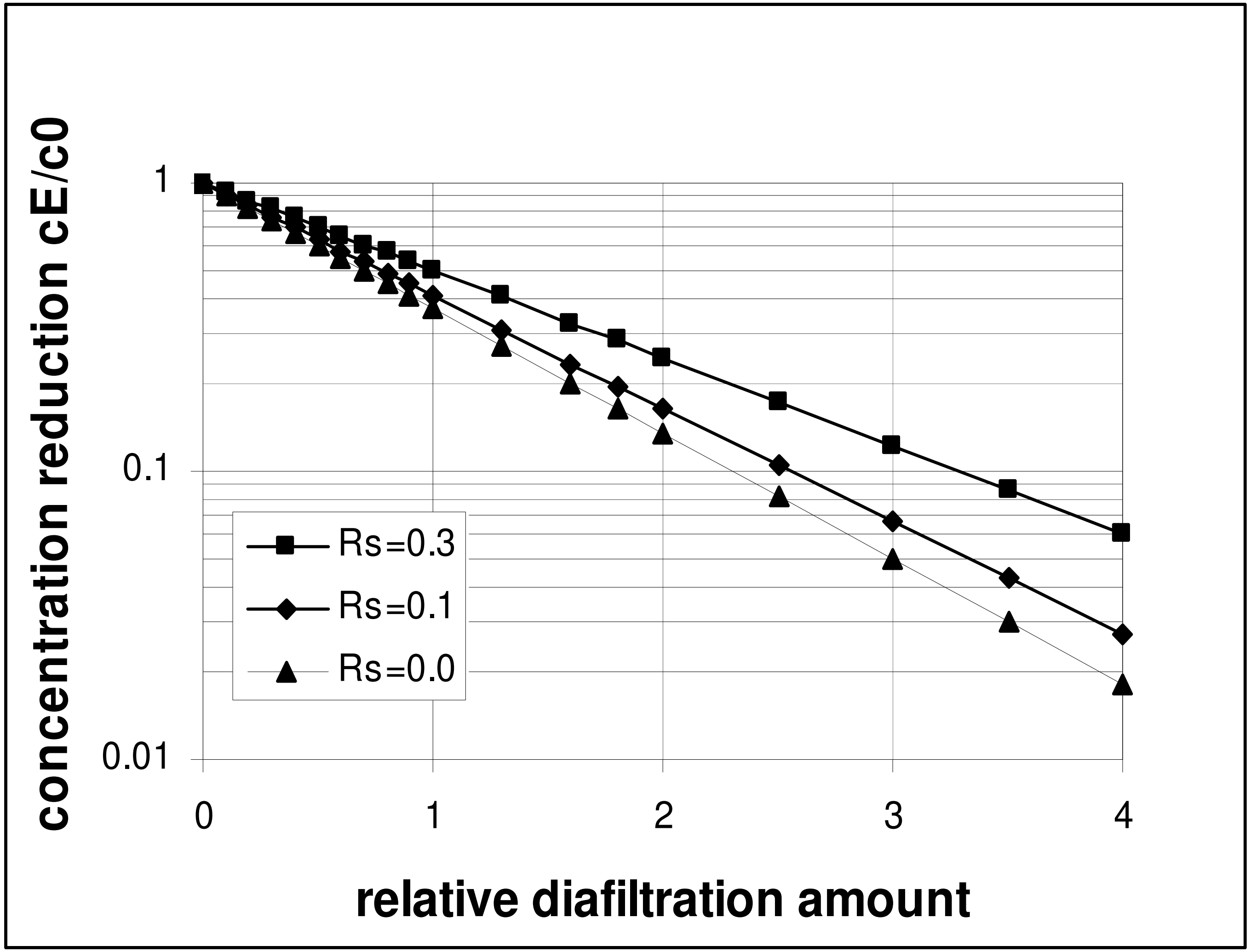
Batch process: diafiltration (at V=c)

volumetric diafiltration factor:
$$A = \frac{V_{Wasser}}{V_0}$$

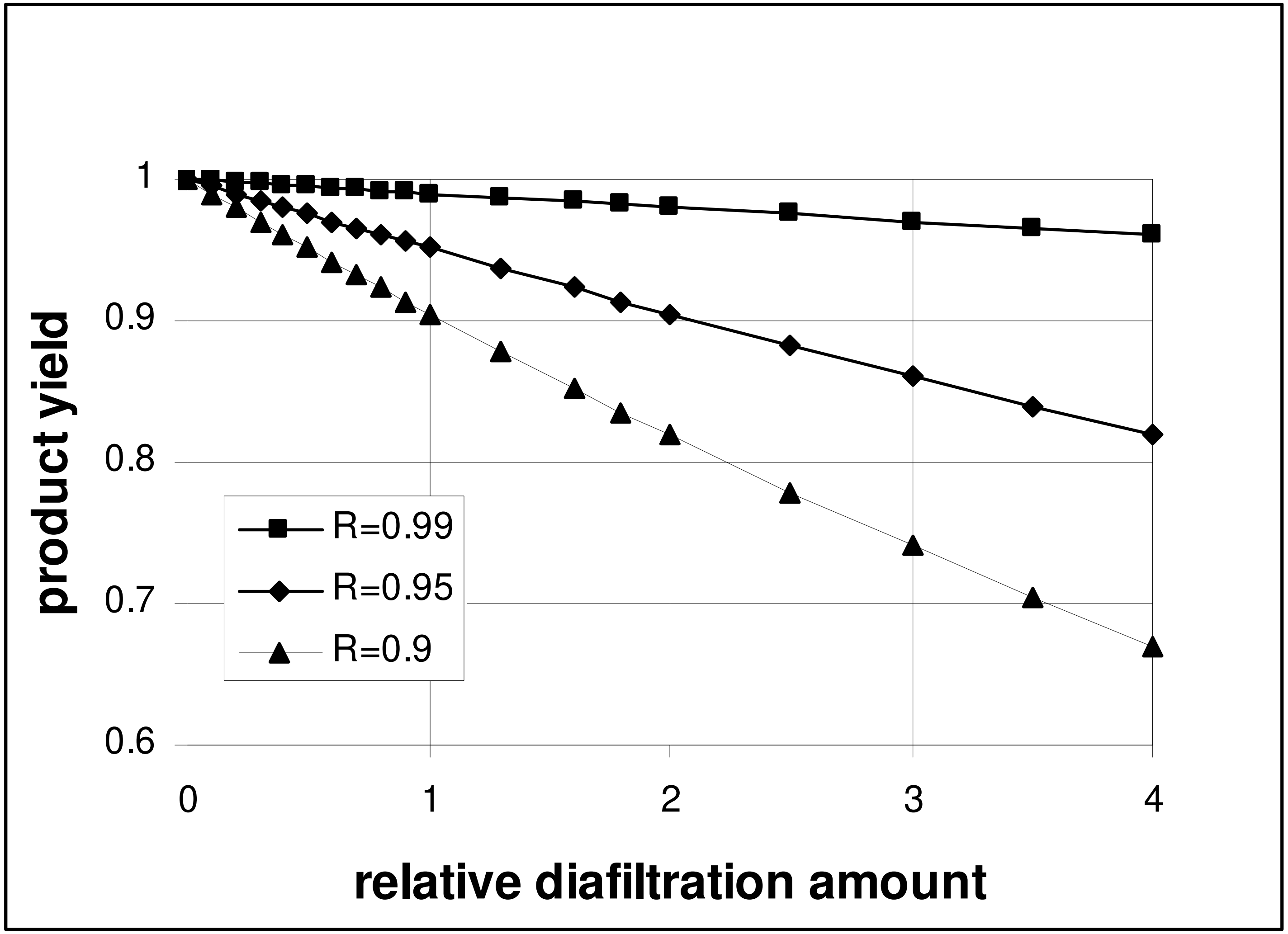
end concentration:
$$\frac{c_E}{c_0} = \exp(A(R_S - 1))$$

yield:
$$R_{MB} = \frac{V_E c_E}{V_0 c_0} = \exp\left(A(R_S - 1)\right)$$

Batch process: diafiltration effect



Batch process: diafiltration yield



Solution-diffusion membrane model

solvent flux:

$$J_{LSM} = A(\Delta p - \Delta \pi)$$

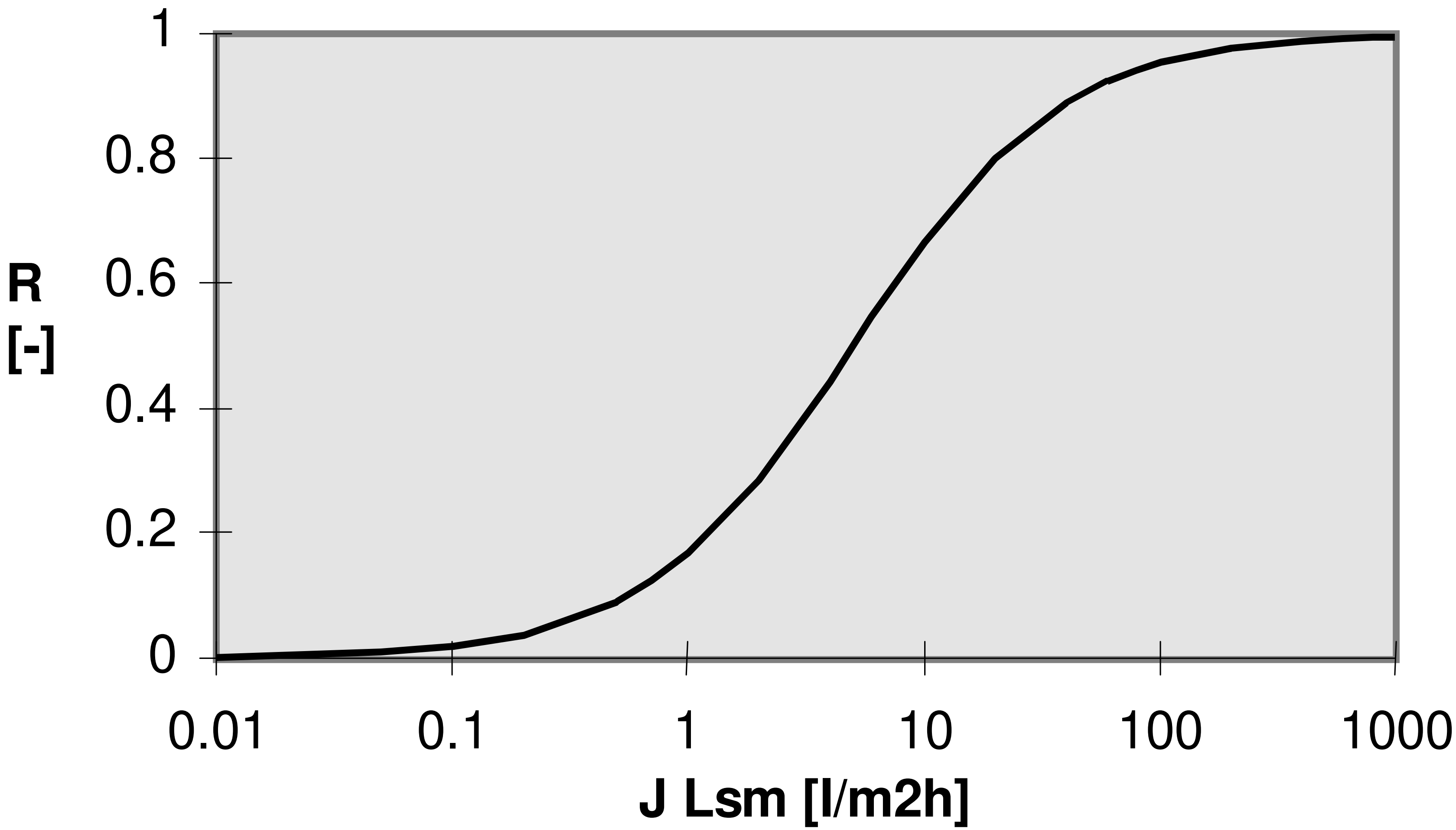
solute transport:

$$J_S = B \Delta c_S$$

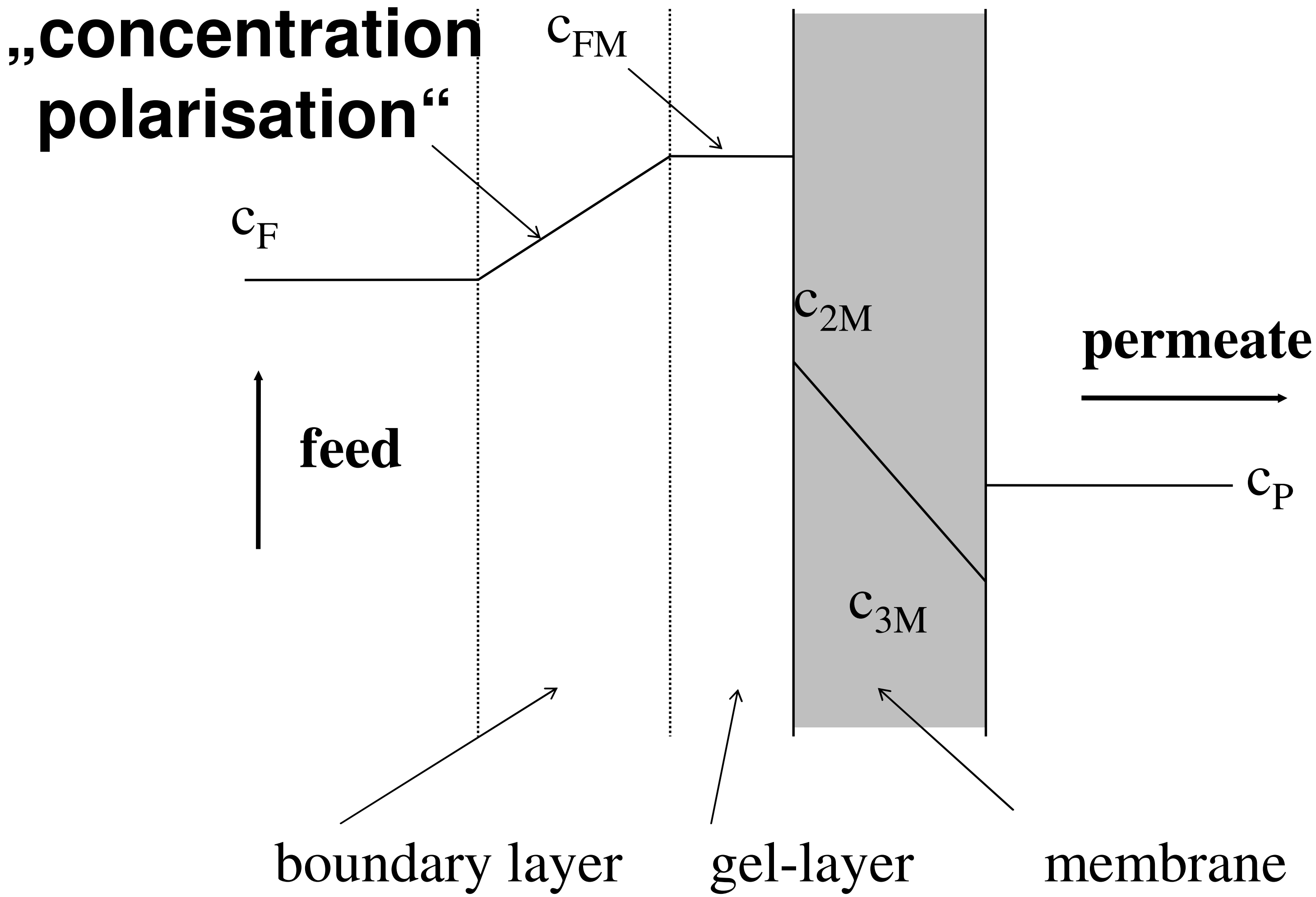
retention:

$$R = \frac{J_{Lsm}}{J_{Lsm} + B}$$

retention curve of a solution-diffusion membrane



Concentration increase at the membrane surface



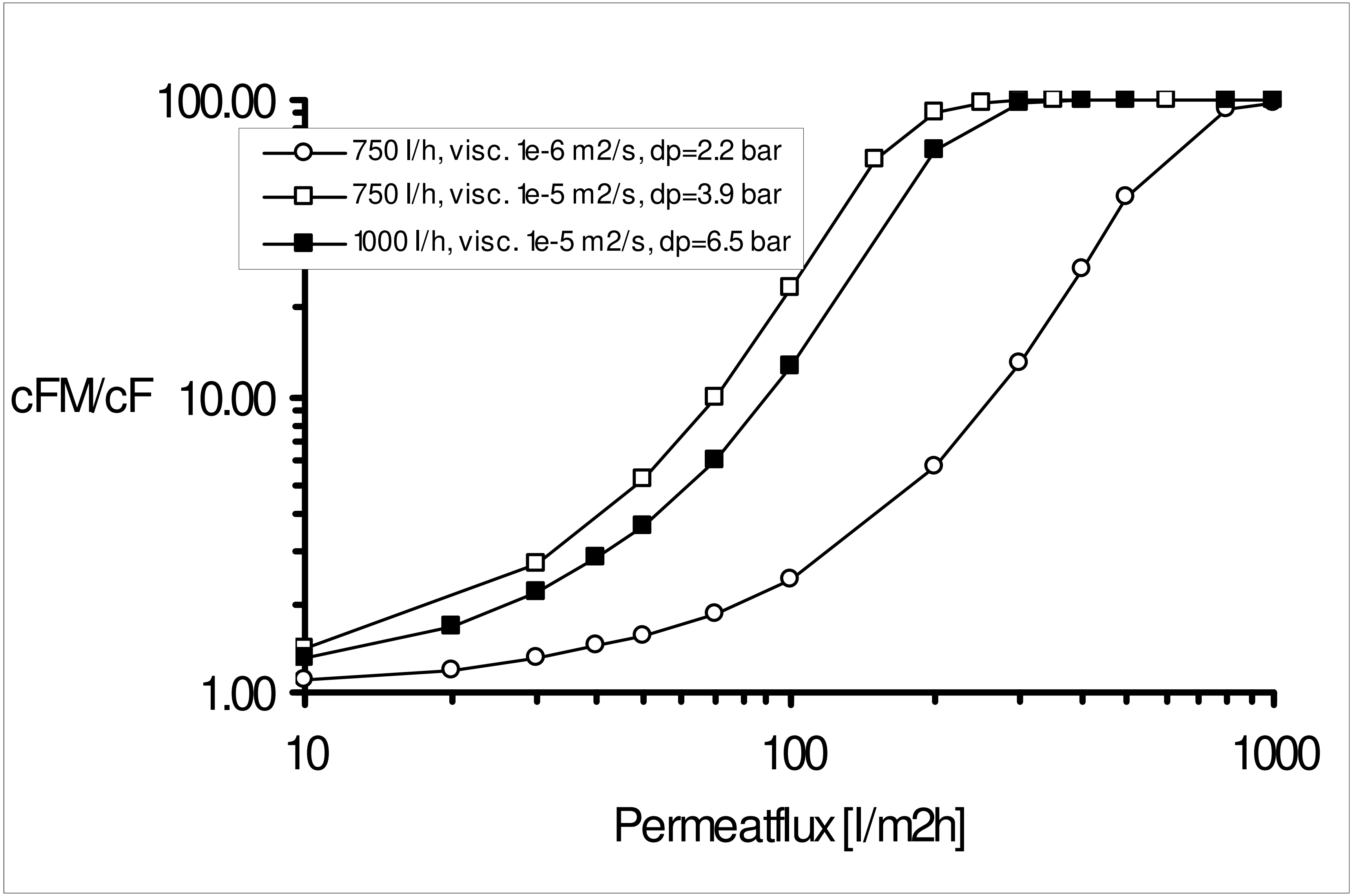
Calculation of concentration polarisation

$$\frac{c_{FM} - c_P}{c_F - c_P} = \exp\left(\frac{J_v}{D}\delta\right)$$

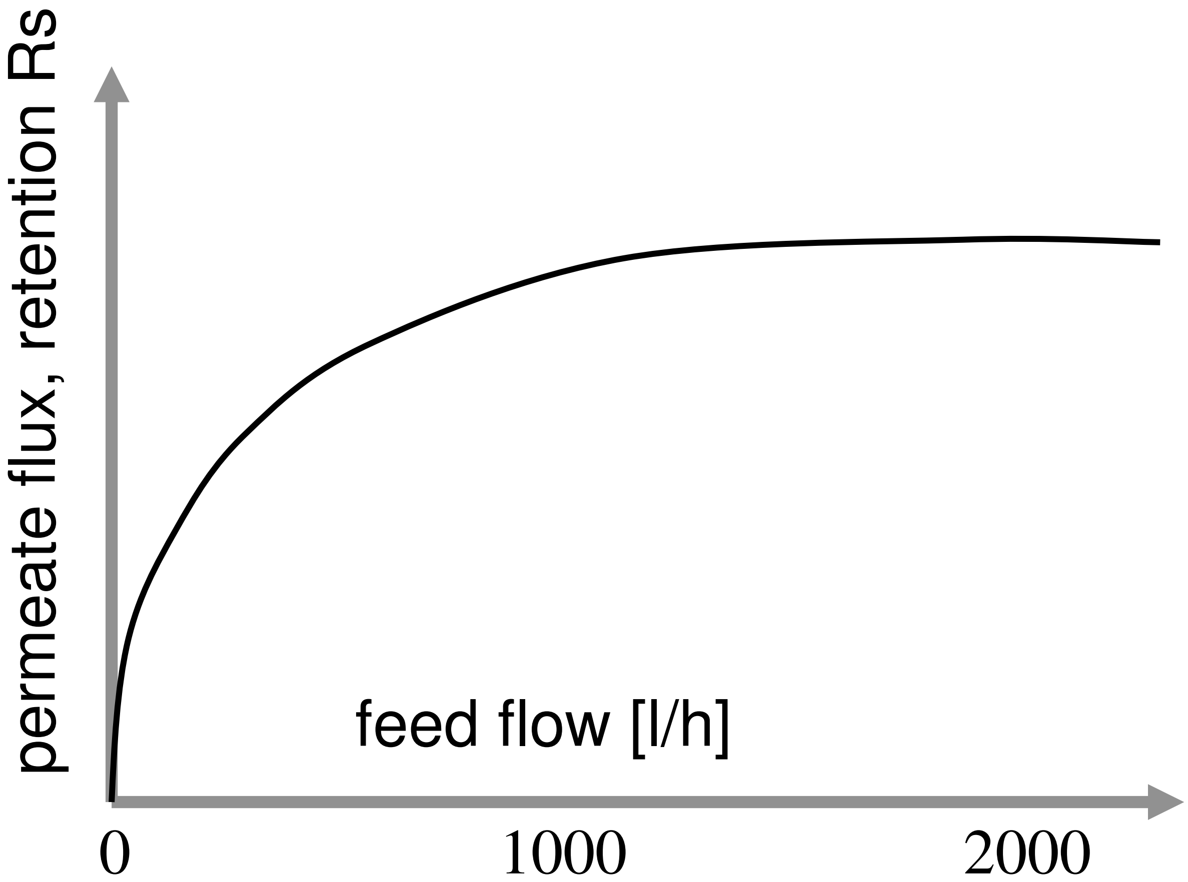
$$\Rightarrow R_w = \left(1 + \frac{(1 - R_s)}{R_s}\exp\left(-\frac{J_v}{D}\delta\right)\right)^{-1}$$

$$\delta = \frac{d_h}{Sh} \qquad Sh = \subset\!\!\!\!/ \cdot \mathrm{Re}^x Sc^y \qquad \mathrm{Re} = \frac{w \cdot d_h}{\upsilon} \qquad Sc = \frac{\upsilon}{D}$$

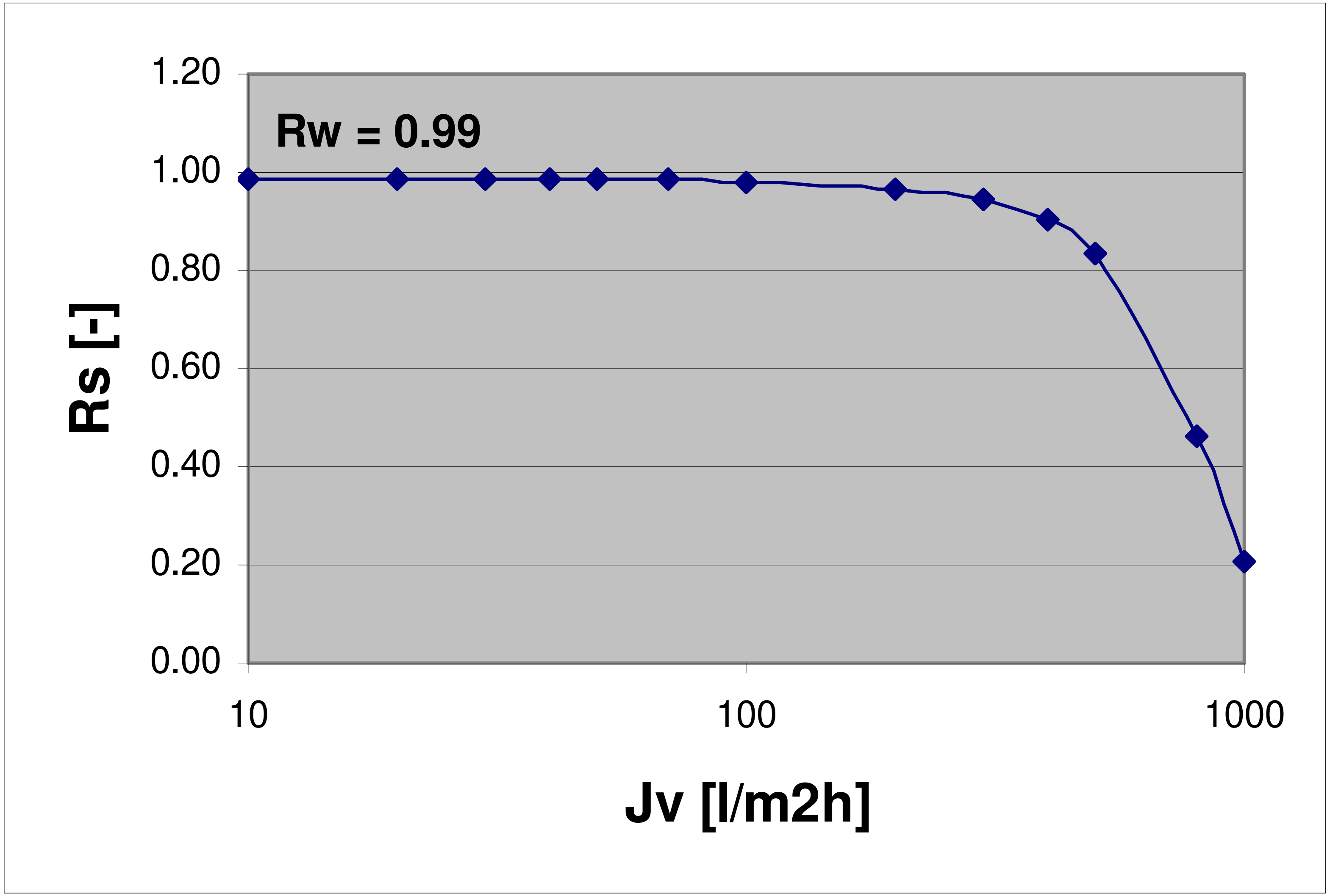
Calculation of concentration polarisation



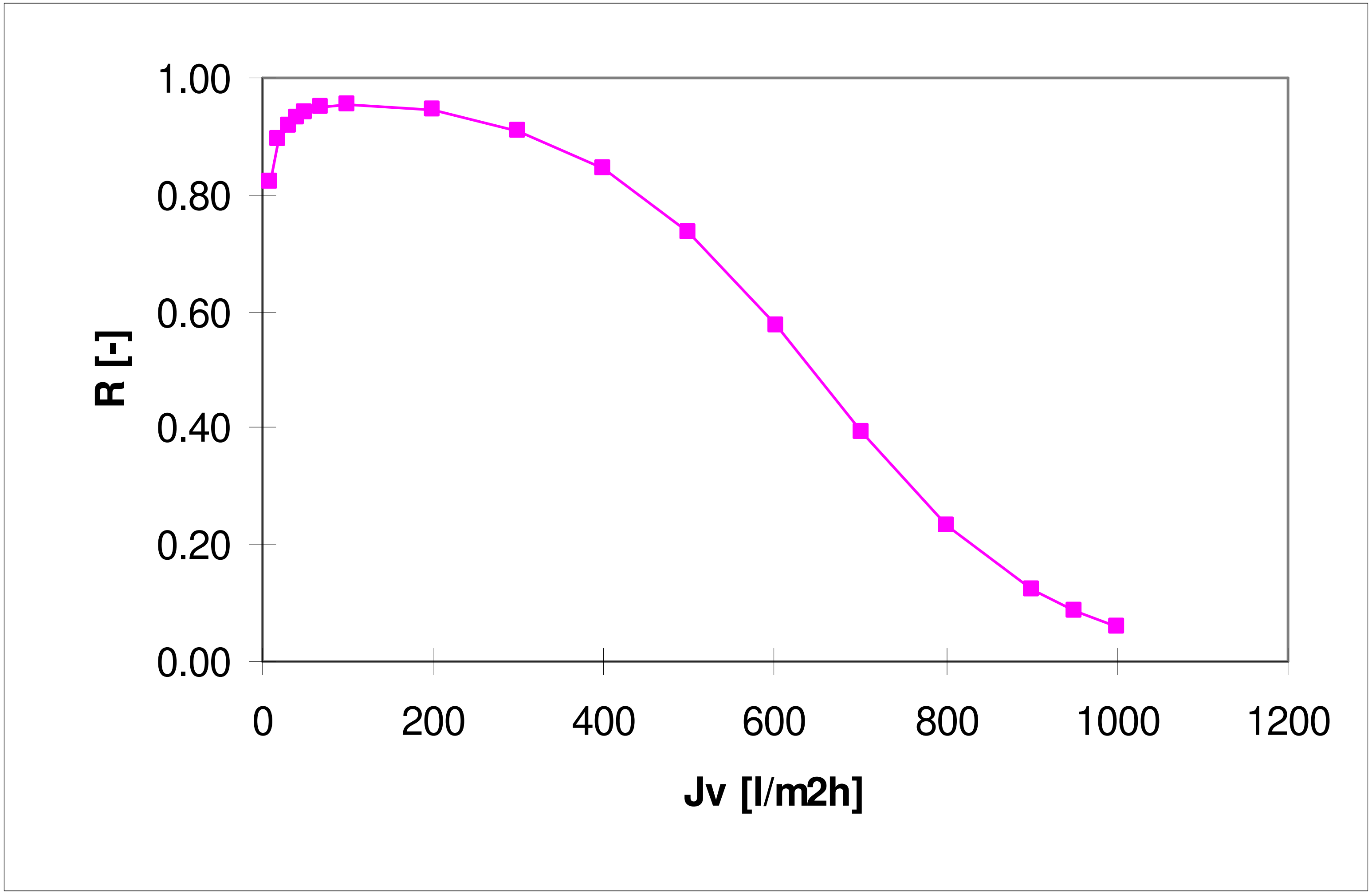
Influence of feed flow



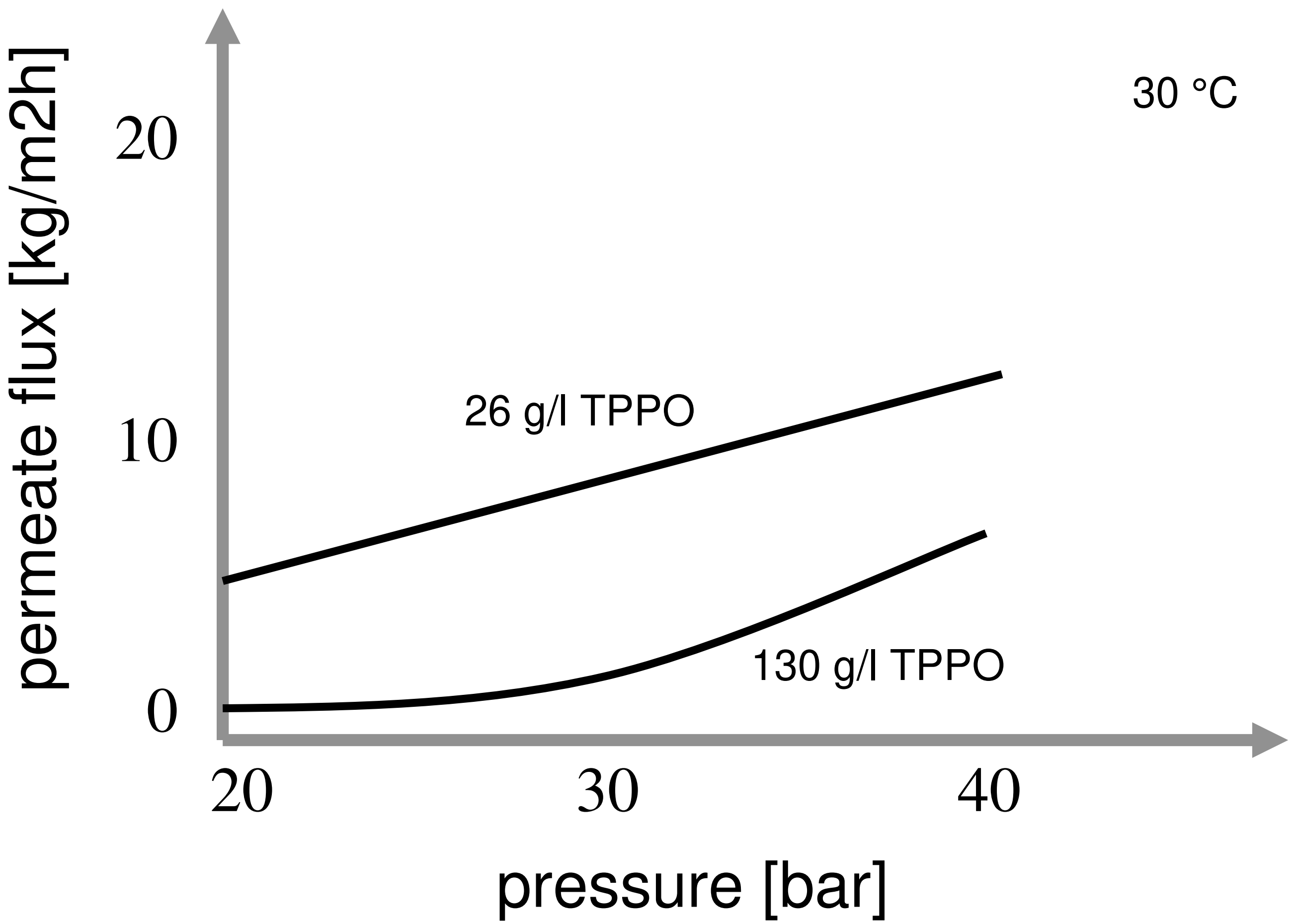
Retention curve due to conc.-polarisation



Retention curve: SDM + conc.-polarisation



Influence of pressure



Questionnaire I

Question	Example	Background
what are the main components of the feed ? molecular weight, particel size and shape	solution of 20 g/l reactive dye, Mw 800 g/mol, 10 g/l NaCl	membrane choice, cut-off
solids present ?	100 µm prefiltered	module choice, channel blocking
what should be retained, what should permeate ?	retention of dye, permeation of NaCl and water	process and membrane choice
requested concentration in concentrate and permeate	100 g/l dye, 2 g/l NaCl in concentrate, dye yield > 99%	osmotic pressure, membrane choice
requested capacity, batch / continuous	2 batches/day, 16m3 each	plant size, membrane area
use of concentrate and permeate	concentrate = product permeate = waste water treatment plant	membrane process separated into 2 streams. One is product, second sometimes waste

Questionnaire II

Question	Example	Background
temperature and allowed temperature range of feed	enters at 80°C, may be cooled, solubility curve known	membrane/module choice, temperature stability
pH, allowed change	pH neutrale	membrane stability
by-components, organic solvents	various bye products from synthesis, no org. solvents	membrane stability
viscosity	feed 2 cP at 80°C, 5 cP at 40°C	pressure drop, module choice
solubilitys	dye 300 g/l at 40°C, influenced by salt concentration	max. concentrating factor optimisation of diafiltration
experience with similar products on a membrane plant	yes, known application, personal experience	
alternative processes	salting-out and filter press	advantages/disadvantages, costs
analytics for measurement of membrane retention	NaCl = titration with AgNO3, dye = UV/VIS	
GMP, sterile, biological growth	no	requirements membrane modules and plant
exclusion of air, inertisation	not required	oxidation

Development of a membrane process

step 1: feasibility: project evaluation, questionnaire, order of magnitude for size and cost

step 2: lab test, membrane screening, cost and size estimate

step 3: process optimization in bench or pilot, plant design (modules, loops, stages, flows, pressures)

step 4: long term pilot: stability, changing feed, adaption of prior design. Decision for production plant.

step 5: detailed plant design, building and start-up

step 1: project evaluation

- feasibility
- orders of magnitude
- experiences (own or literature)
- may be a one day lab experiment

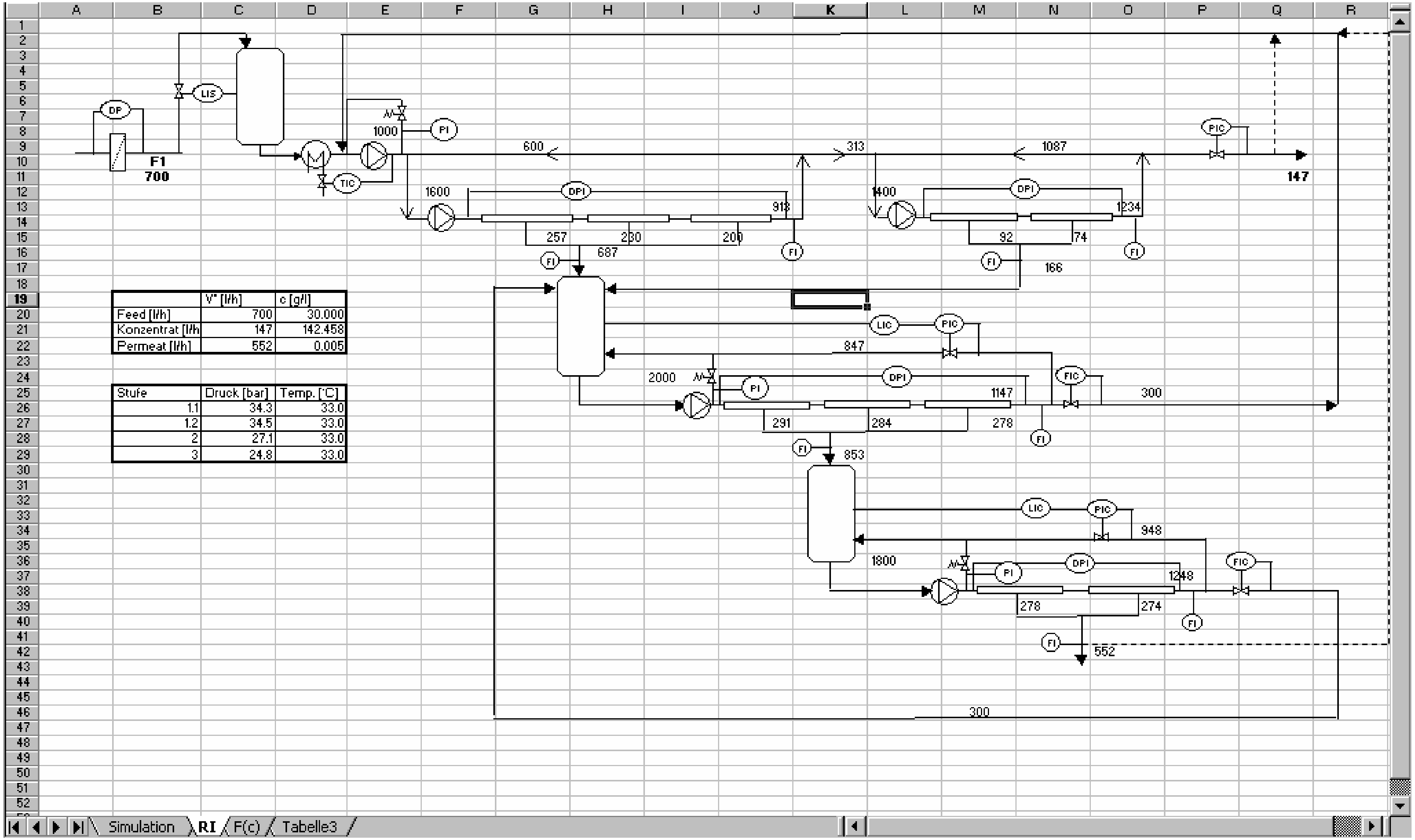
step 2: membrane screening

- choice of membrane (later scale-up!)
- measurement of performance (R, Jv)
- 2 pressures, 2 temperatures
- possible concentration factors
- indications of fouling

step 3: process optimization bench/pilot

- influence of parameters (p, T, velocity, pH, Concentration/Diafiltration)
- measurement of performance (R, Jv, Δp)
- circulation run (fouling, backflush, cleaning)
- plant design (modules, loops, stages, flows, pressures, process integration)

step 3/4: process simulation



	V' [l/h]	c [g/l]
Feed [l/h]	700	30.000
Konzentrat [l/h	147	142.458
Permeat [l/h]	552	0.005

Stufe	Druck [bar]	Temp. [°C]
1.1	34.3	33.0
1.2	34.5	33.0
2	27.1	33.0
3	24.8	33.0

step 3/4: process simulation

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	**Feeddruck [bar]**		34.3					27.1			24.8		
3	**Retentatdruck [bar]**		33.0					25.5			23.8		
4	**RetDruck Param. [bar]**		**33.0**					**21.5**			**16.1**		
5													
6	**m Feed Roh [l/h]**		700			**AK**	4.75						
7	**cF TPPO Roh [kg/l]**		**0.030**										
8	**Rs**		**0.97**	**0.97**	**0.97**	**0.95**	**0.95**	**0.98**	**0.98**	**0.98**	**0.98**	**0.98**	
9	**Pumpendurchsatz [l/h]**	**1000**	1600			1400		2000			1800		
10	**Konzentrate [l/h]**									**300**		**300**	
11	**Rezirkulation [l/h]**		-	-	600	-	1087	-	-	847	-	948	
12	**p [bar]**		34.0	33.5	33.2	34.1	33.4	26.8	26.4	26.2	24.5	24.2	
13	**T [°C]**		**33.0**	33.0	33.0	33.0	33.0	**33.0**	33.0	33.0	**33.0**	33.0	
14	**Module**				**12**		**8**			**12**		**8**	
15	Fläche [m2]				96		64			96		64	
16	AK				1.75		1.13			3.84		2.84	
17	Regeldifferenz							0.10			0.52		
18	Δp [bar]		0.59	0.43	0.31	0.82	0.73	0.71	0.53	0.37	0.58	0.42	
19					1.33		1.55			1.61		1.01	
20	Hydr. Widerstand Wickelement		0.075			0.12		0.06			0.06		
21			1.1.I	1.1.II	1.1.III	1.2.I	1.2.II	2.I	2.II	2.III	3.I	3.II	
22	Feed (Stufe) [l/h]		1000	1343	1114	313	1308	1153	1709	1425	852	1522	
23	Feed (Modul) [l/h]		1600	1343	1114	1400	1308	2000	1709	1425	1800	1522	
24	Permeat [l/h]		257	230	200	92	74	291	284	278	278	274	
25	Konzentrat (vor Rezirk) [l/h]		1343	1114	**913**	1308	**1234**	1709	1425	**1147**	1522	**1248**	
26	Konzentrat (nach Rezirk) [l/h]		1343	1114	313	1308	147	1709	1425	300	1522	300	
27	m TPPO F (Modul) [kg/h]		65.54	65.20	64.83	176.91	176.30	8.55	8.52	8.49	0.39	0.38	
28	m TPPO P [kg/h]		0.34	0.37	0.39	0.60	0.51	0.03	0.03	0.04	0.00	0.00	
29	m TPPO K (vor Rezirk) [kg/h]		65.20	64.83	64.44	176.30	175.79	8.52	8.49	8.45	0.38	0.38	
30	m TPPO K (nach Rezirk) [kg/h]		65.20	64.83	39.60	176.30	21.00	8.52	8.49	2.21	0.38	0.09	
31	cF (Modul) [kg/l]		0.040963	0.048530	0.058213	0.126361	0.134826	0.004274	0.004984	0.005956	0.000215	0.000253	
32	cP [kg/l]		0.001342	0.001601	0.001931	0.006530	0.006932	0.000093	0.000109	0.000133	0.000005	0.000006	
33	cK [kg/l]		0.048530	0.058213	0.070551	0.134826	0.142458	0.004984	0.005956	0.007366	0.000253	0.000307	
34													
35	Arrheniusfaktor		3777	3753	3700	2113	1658	3800	3800	3800	3800	3800	
36													
37	Jv (c) [l/m2h]		10.84	9.88	8.73	3.33	2.86	15.86	15.74	15.58	16.47	16.46	
38	Jv (c, p) [l/m2h]		11.30	10.11	8.80	3.86	3.03	12.80	12.52	12.24	12.24	12.09	
39	Jv(c, p,T) [l/m2h]		8.02	7.18	6.26	2.89	2.30	9.08	8.88	8.68	8.68	8.57	
40			**0.80**					**0.80**			**0.80**		
41													

step 4: long term pilot on site

- process stability
- changing feed
- staff hands-on training
- different operation modes
- adaption of prior design
- decision for production plant

step 5a: plant design

- limits to other processes
- energies
- in-house / external
- detail design
- components choice
- controll system
- operation modes

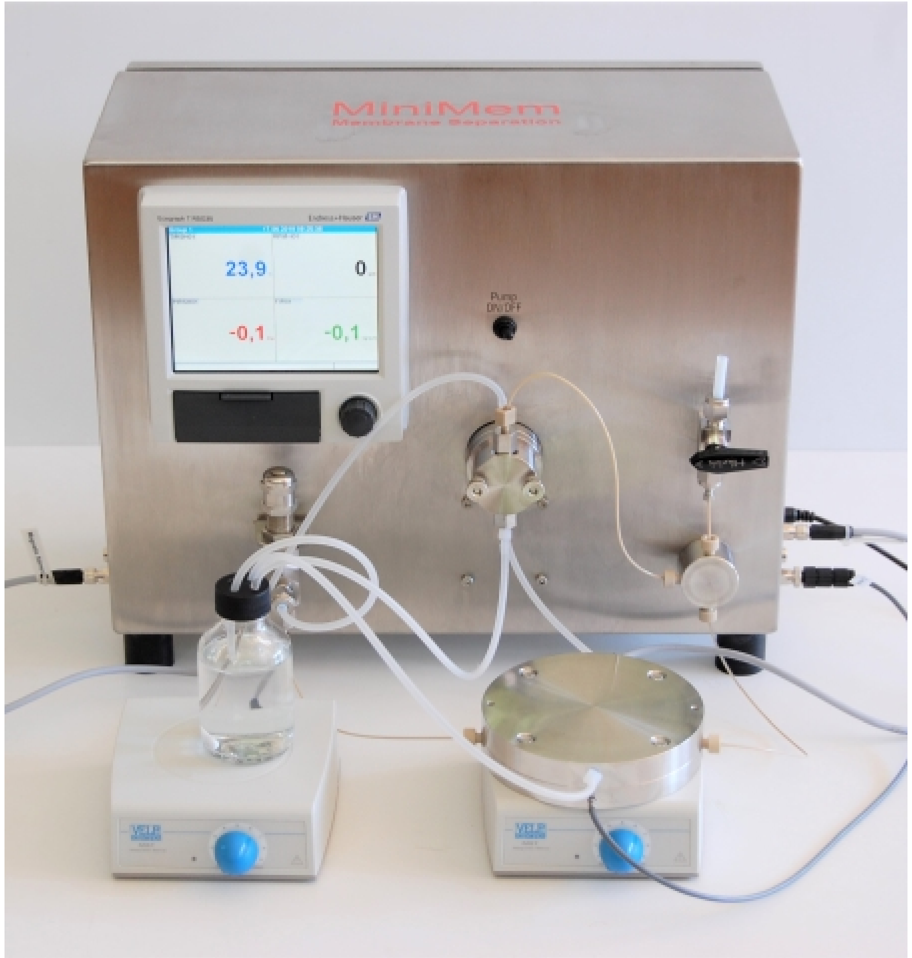
step 5b: construction and start-up

- construction supervision
- functional tests
- water tests
- product run

Membrane unit types

- lab
- bench top
- pilot
- industrial
- municipal

Lab unit MiniMem



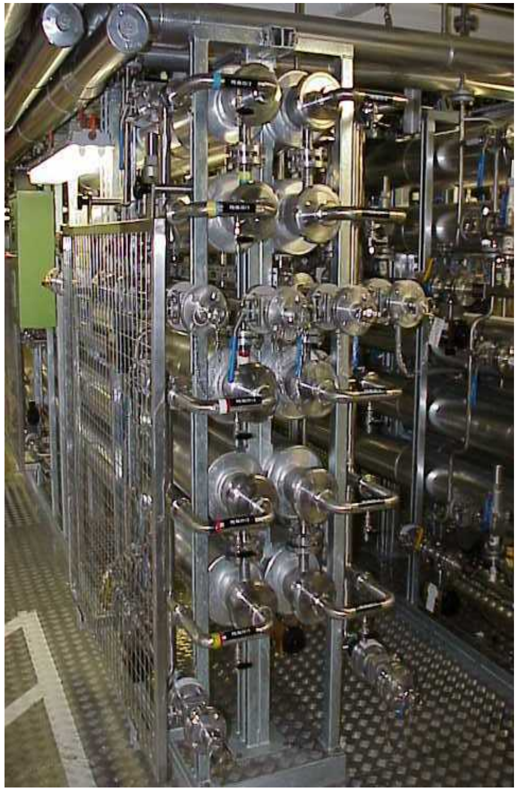
- aqueous and all organic solvents
- minimum operating volume 10ml
- up to 50 (100) bar
- operation possibilities: concentration, circulation, diafiltration, batch / conti
- different modules 30-120cm2 membrane area

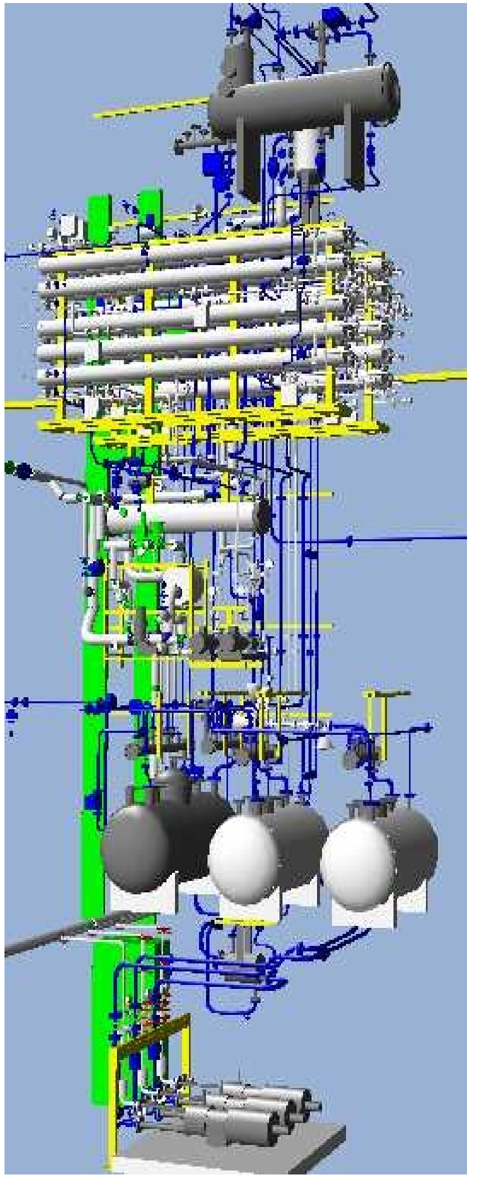
Bench scale unit MaxiMem

- aqueous and all organic solvents
- Flat, spiral, tubular membranes
- up to 40 (80) bar
- operation possibilities: concentration, circulation, diafiltration, batch / conti
- Batch size 1-100 l

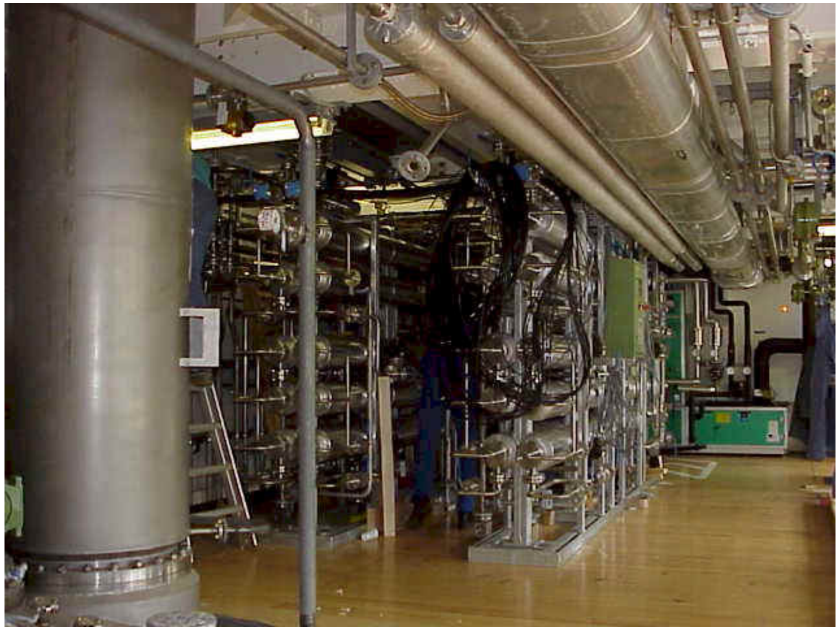
Versions of PiloMem pilot units

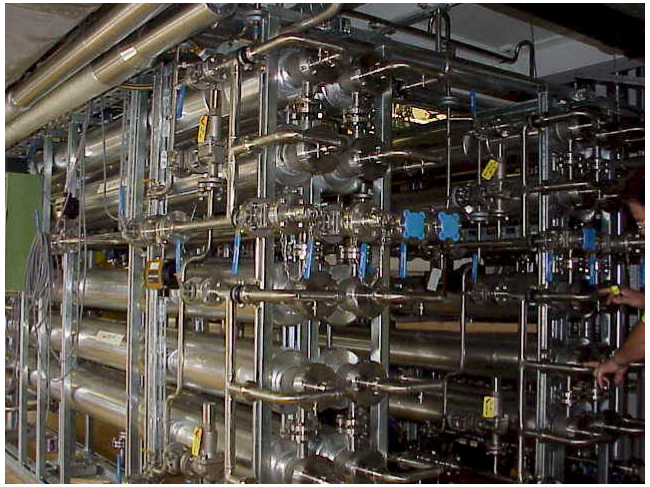
Industrial





Industrial





Membrane plant components

- membrane module
- piping (material, pressure, connections)
- pumps (centrifugal, side channel, piston/membrane)
- measurement and controll (p, Δp, T, Flow, frequency converter, pressure controll valve)
- vessels

Application of membrane processes

- biotechnology
- food
- chemical industry production and waste
- water treatment

Biotechnology

Product	Process
	Mikrofiltration
cell suspension, lysate bakteria, fungi, yeats, mamallian cells, colloids	concentrating, clarification, washing, desalting, buffer exchange
	Ultrafiltration
Peptide, Proteine, Enzyme, Polysaccharide, Lipide	concentrating, clarification, washing, desalting, buffer exchange, decolorization
proteins of diifferent Mw	pre-fractionation
solutions upstream of chromotografie	clarification, solvent exchange
	Nanofiltration
solutions of low molecular weight substances (Mw 300-1500): antibiotics, peptides, vitamins, sugar	concentrating and desalting, solvent exhange
	Umkehrosmose
all dissolved substances	concentrating

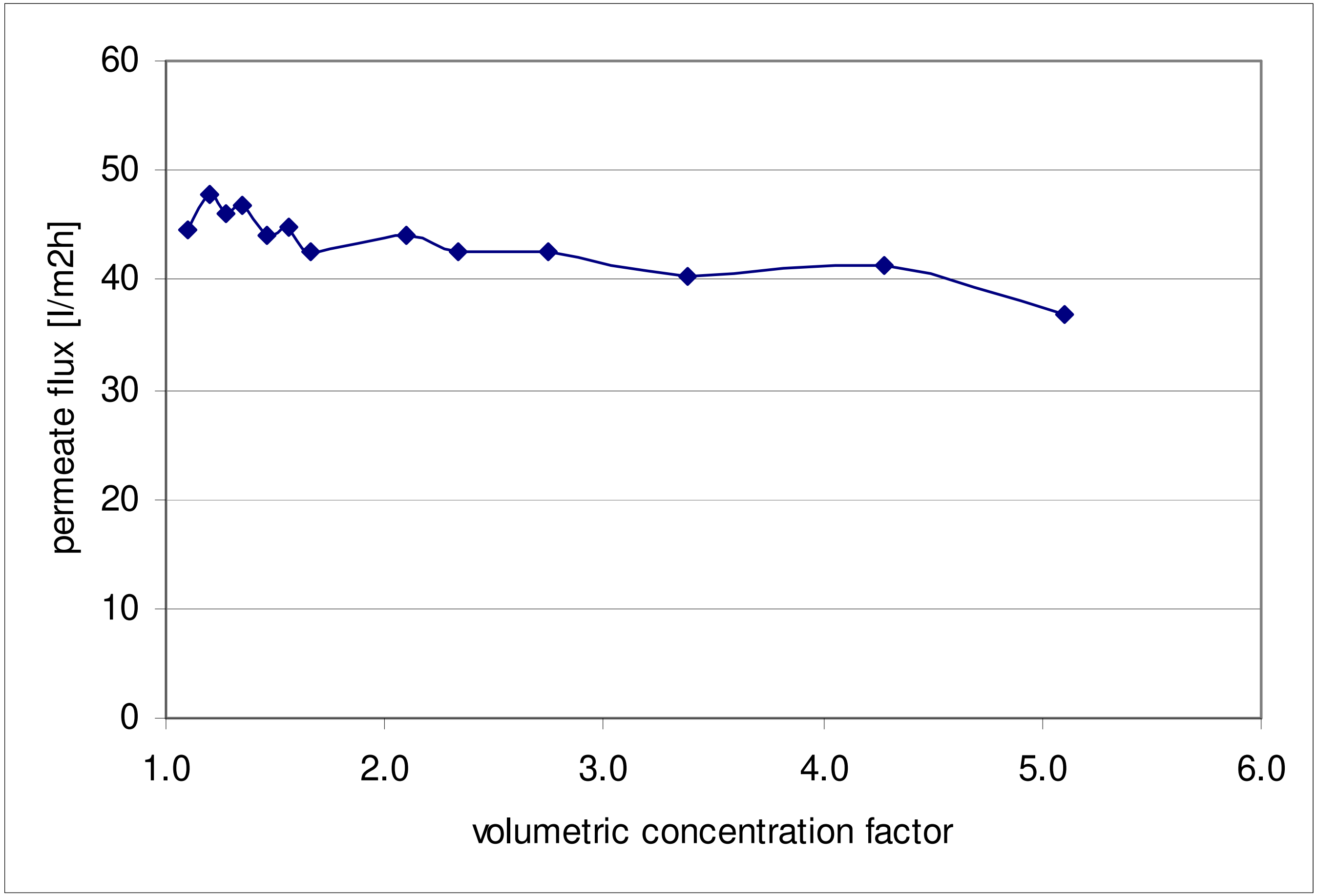
Biotechnology, a tyical downstream process

- Microfiltration for product recovery from fermentation broth or lysate
- Ultratfiltration for retention of higher-Mw proteins,
  (diafiltration of lower-Mw product)
- Nanofiltration for buffer-exchange upstream of a chromatografie
- Chromatografie for specific product cleaning
- Nanofiltration for product washing
  (removal of eluent, buffer, NaCl)
  and concentrating of product

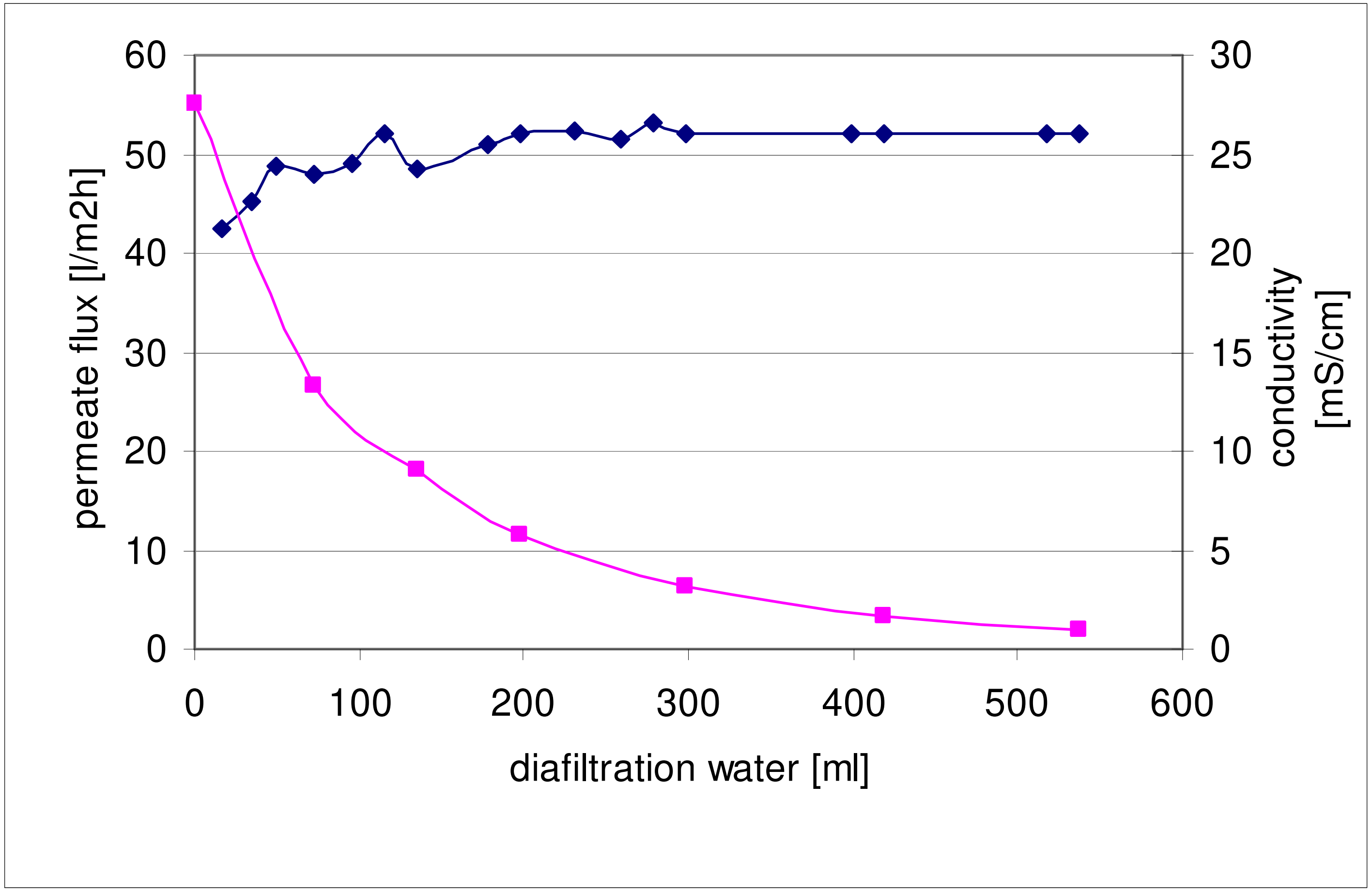
Biotechnology, application example N

- specialty chemical manufacturer for biotech
- production scale 5-10l/Batch
- fermentation and MF for cell retention
- product N, Mw 900 g/mol must be purified
- Tris-buffer or NaCl must be removed
- Nanofiltration tested in Lab
  (250 ml, AK=5, DF=10)
- product / salt ratio shifted by factor 34
- further optimization possible
- „production plant“ built

Biotechnology, application example N



Biotechnology, application example N



Food

Main reasons for use of membrane processes in the food industry:

- moderate operating conditions
- no additional chemicals

Food

Clarification:	**fruit juice** **sugar sirup** **wine** **acetic acid** **gelatine** **bacterial count reduction in milk**
Concentration:	**fruit juice** **cheese whey (sugar)** **olive oil waste water** **plant extracts**
Desalting:	**cheese whey**
Water recovery:	**water recovery bottle wash**

Chemical Industry

Water treatment: demineralized water

(from boiler feed water to chip industry)

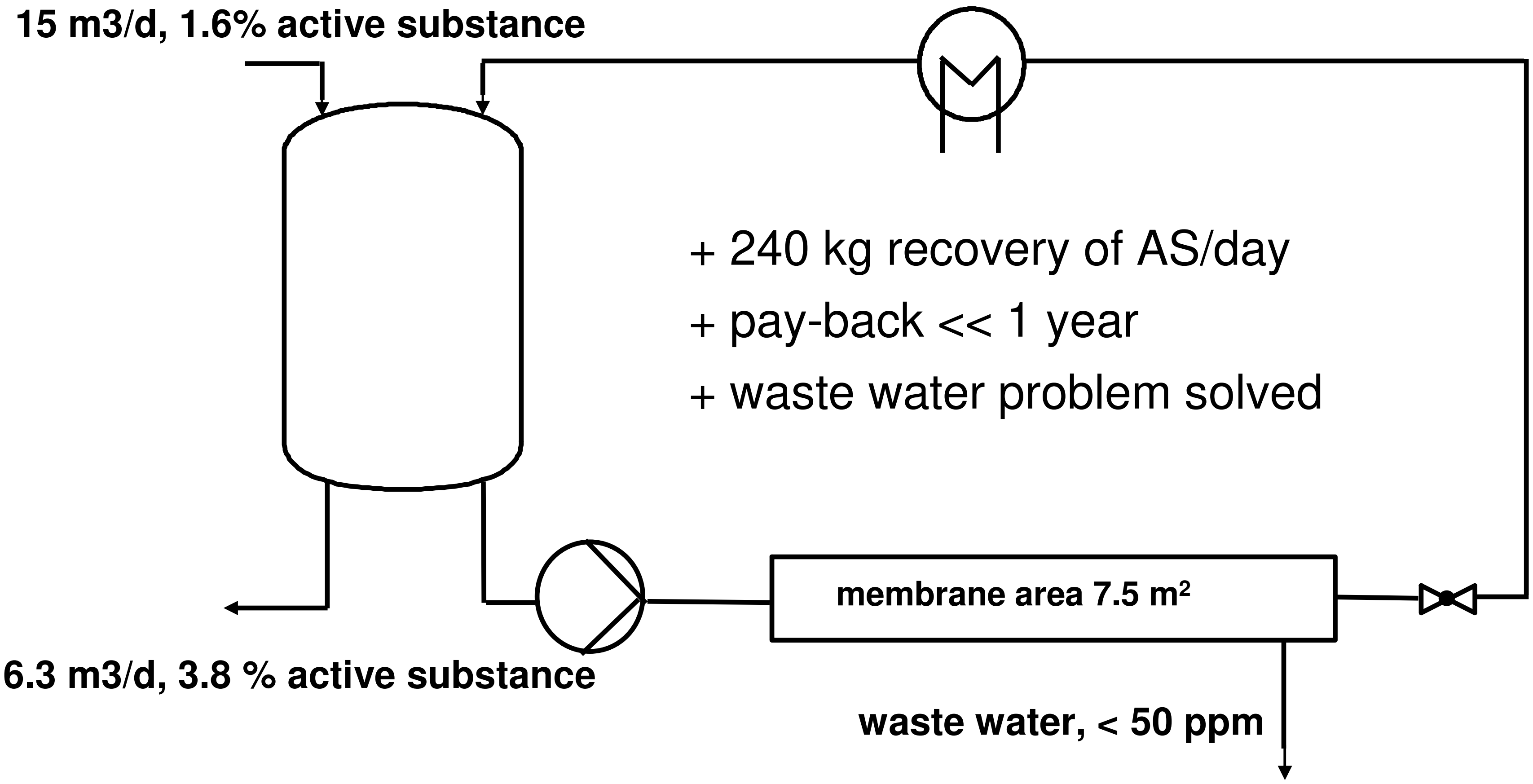
Waster water treatment / water recovery:

dye and chemicals production
oil/water separation
textile and paper industry
metal etching bath
chemicals recovery

Desalting: liquid dye
optical brightener

Extraction solution recycling

Reverse osmosis for product recovery

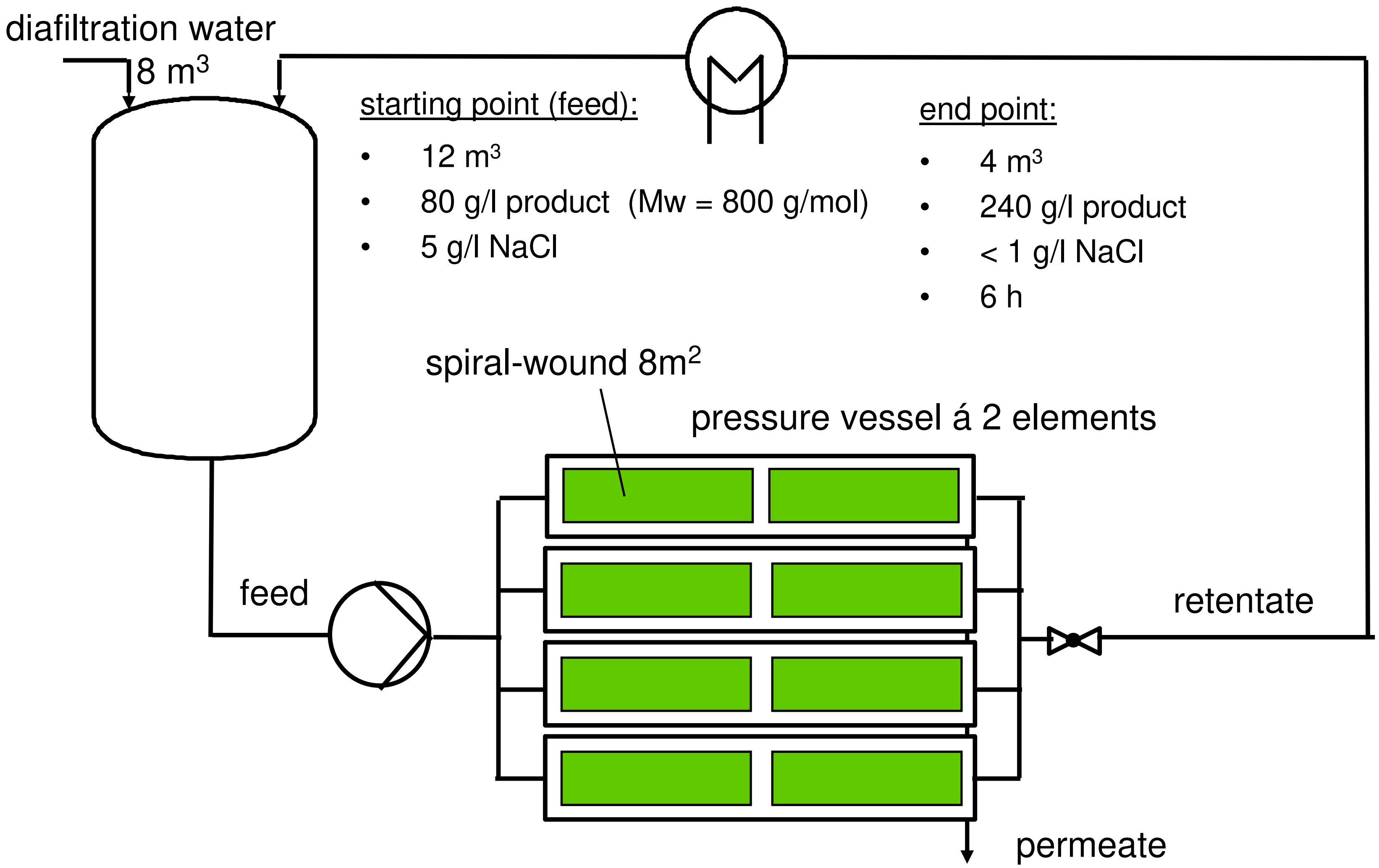


+ 240 kg recovery of AS/day
+ pay-back << 1 year
+ waste water problem solved

Nanofiltration: concentration and desalting of a liquid dye

	Starting point (feed)	End point
Batch size	12 m^3	4m^3
Dye concentration	80 g/l	240 g/l
NaCl	5 g/l	1 g/l
Batch time		6h
Membrane area		60 m^2

Dye concentration and desalting: NF



NF-plant (tubular modules)

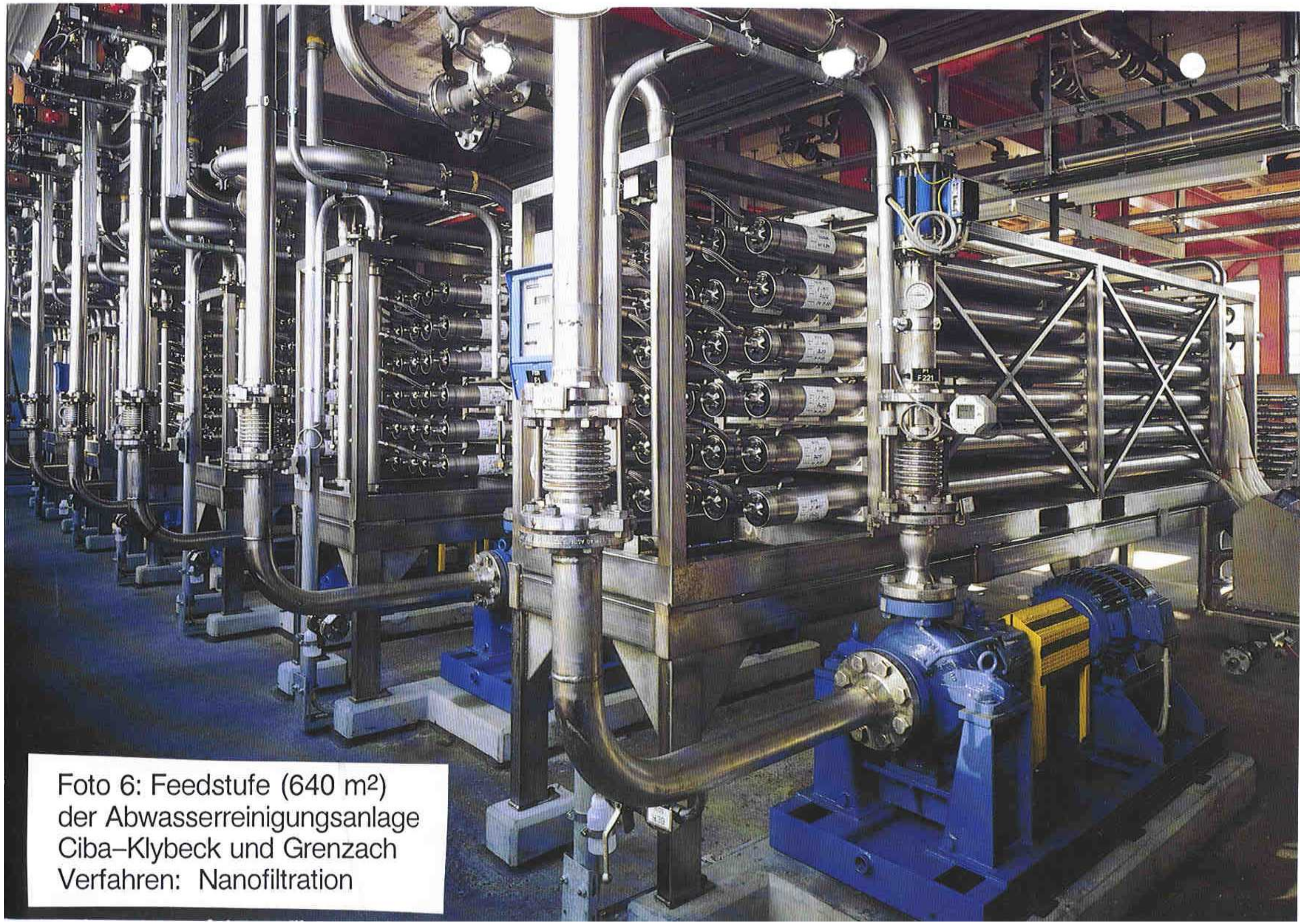


Foto 6: Feedstufe (640 m²)
der Abwasserreinigungsanlage
Ciba–Klybeck und Grenzach
Verfahren: Nanofiltration

Energy cost example NF

pump 16m3/h, 25bar = 11kw / 0.7 = 16kW: 16 kWh für 2600 kg/h permeate = 1.3 EUR

evaporation: 2.6 to vapor for 2.6 to water = 85 EUR

➡ energy costs nanofiltration = 1.5 % of evaporation

5000 h / year

➡ energy savings = 418'000 EUR / year

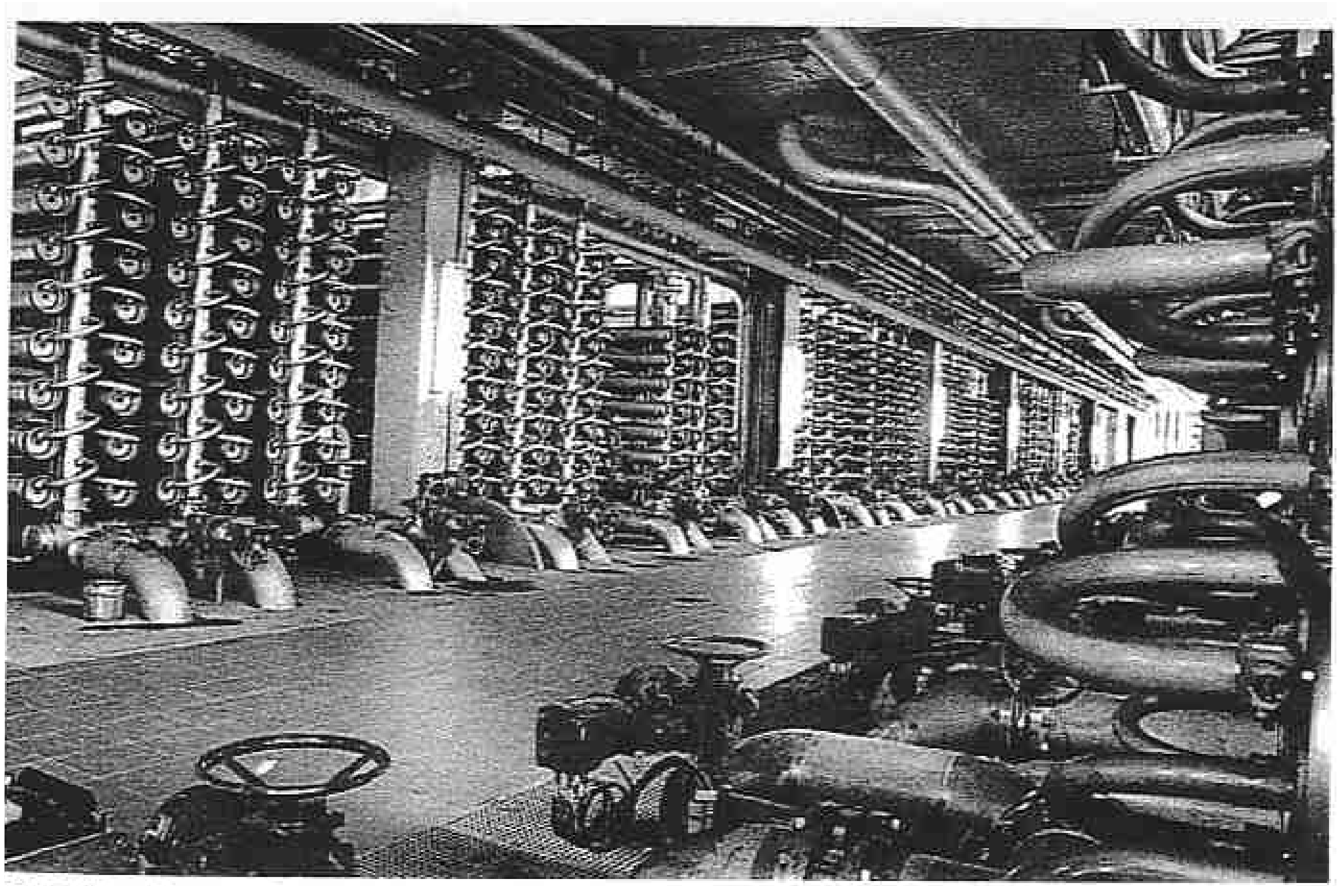
unit cost 300'000 EUR

Drinking water supply

- sanitation
- desalting
- color removal
- THM, heavy metal removal

NF plant Méry-sur-Oise

150 Mio EUR, 340´000m2, 140´000m3/day



Typical observations MF-RO

„permeate flux to low“

<u>pressure ⇑</u>

permeate flux ⇑

osmotic pressure controlled

<u>pressure ⇑</u>

permeate flux =

gel-layer controlled

try to increase cross-flow

(but this increases pressure drop)

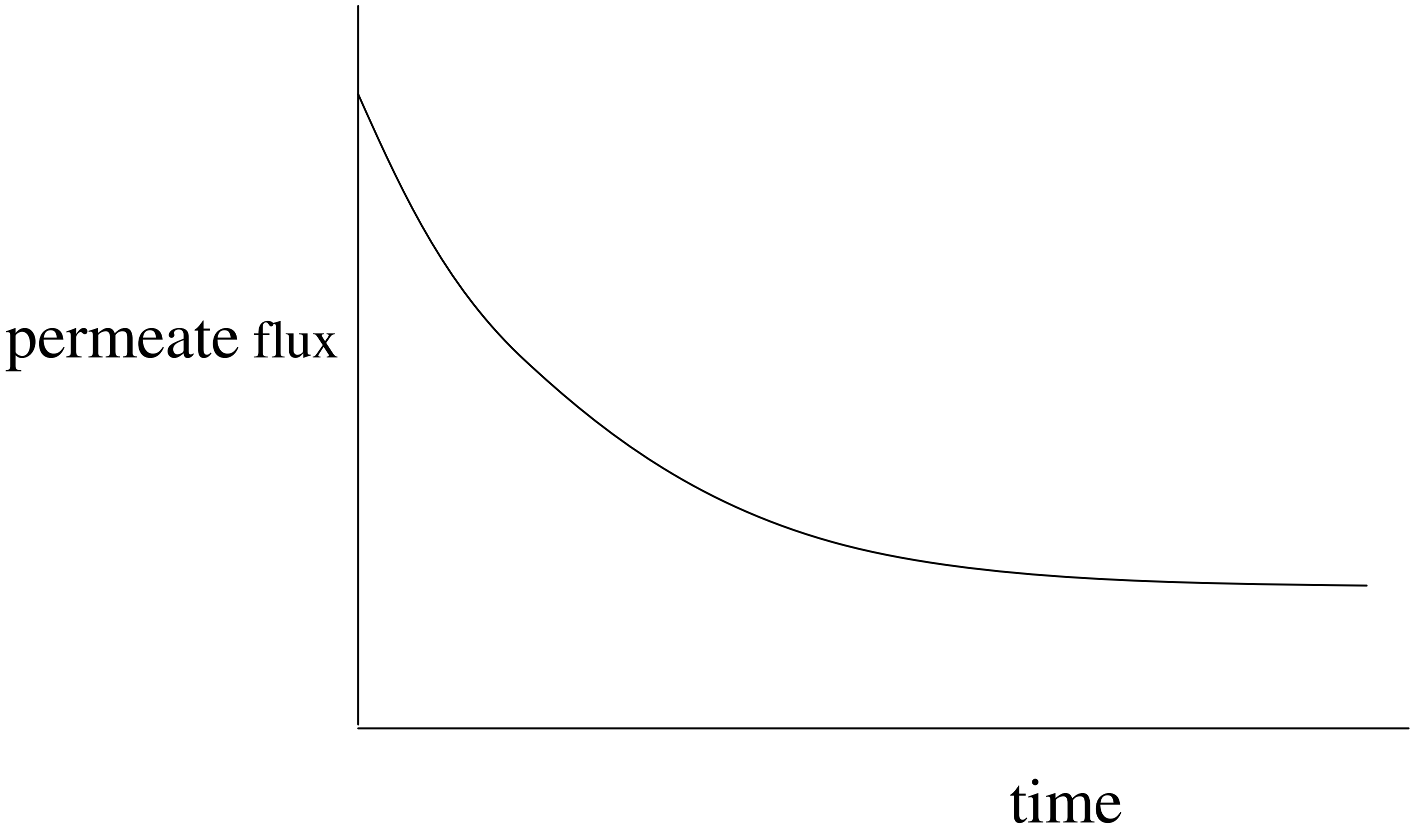
decrease viscosity

increase temperature

increase solubility

UF, NF, RO : 10 - 50 l/m2
MF : 50 - 200 l/m2h

Membrane cleaning



Reasons of flux decline

- fouling (biofouling)
- scaling (precipitations of product or by-product)

Membrane cleaning

- product layer (supersaturation due to concentrating).

  Flush with solvent. Sometimes enzymatic

  or other membrane cleaner neaded

- anorganic precipitation

  (typical scaling by $CaCO_3$). Acid clean

- biofouling: membrane cleaner often caustic

Membrane cleaning principle

- flush product with water
- high feed flow, low pressure partly permeate clossed
- high temperature
- often caustic/acid/caustic clean with water flush
- support by supplier of membrane cleaning substances
- check cleaning success with water test