

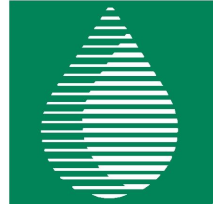
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Membrane Filtration Handbook Practical Tips and Hints

by Jørgen Wagner, B. Sc. Chem. Eng

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This is the second edition of the Membrane Filtration Handbook. In an effort to improve the Handbook, it has been enlarged to include the description of pretreatment, automatic controls and pumps.

This Handbook is the product of many years of experience in the field of membrane filtration, and it is intended to be a mixed bag of information. The Handbook's goal is to provide information about many common problems and help answer questions that newcomers to membrane filtration often face. The book also provides information helpful to the engineer who designs and builds membrane equipment or works with existing plants. Students may also find the Handbook helpful in understanding basic membrane plant design and operation.

The information is based on practical experience rather than theoretical calculations and speculations. Consequently, it is not a traditional textbook commonly found at technical universities. Although there are virtually no mathematical calculations in the Handbook, it will still prove useful to both industry and universities because it contains other pieces of information that are obvious to the "old hand" in membrane filtration but which, to the best of my knowledge, have never been presented in a printed format.

This Handbook is not intended for use by the absolute novice to membrane technology. Although it does describe and explain membranes and membrane technology in quite a bit of detail, some fundamental knowledge of membranes and chemistry is assumed.

Most of the information is based on experience with flat sheet membranes (the DDS plate-and-frame system) and spiral wound elements from Osmonics (DESAL™). Spiral wound elements account for the vast majority of membrane area sold worldwide, while the market share of fiber systems, ceramic systems and tubular systems is relatively small. Although they have their place in the membrane world, the chances of fiber, ceramic and tubular systems becoming major players are relatively small. Therefore, little information regarding these systems has been included in the Handbook.

Membranes are being put to hard work today, but they are relatively unknown to consumers since they are usually hidden within industrial processes. Some industries depend on membranes for the manufacturing of basic products, others need membranes to solve complex separation processes, while others again use membranes to meet environmental standards. Membranes are somewhat like computers: few understand them, only some like them, but we are all dependent upon them. Even if we do not like them, we know that they are necessary to make life easier and more comfortable.

INTRODUCTION

It has taken 35 years to develop sufficiently good and inexpensive membranes to treat a variety of liquids, including waste water. However, there is still a long way to go before it is generally known how to engineer and operate membrane plants. It is my hope that this Handbook will help avoid some mistakes which certainly have been made before.

I want to specially thank Bjarne Nicolaisen for very thorough technical and linguistic advice, and my wife for being an excellent partner discussing technical details. Several other individuals have contributed to the Handbook in various ways, too.

Jørgen Wågner

DEFINITIONS AND BUZZWORDS

Table 1. Definitions and Buzzwords									
ATD	Anti-telescoping device which prevents spiral wound elements from 'telescoping' due to the force of the flow of liquid.								
CA	Cellulose acetate, most often di- or tri-acetate.								
CIP	Cleaning In Place. The ability to clean a system without dismantling.								
Concentrate	The volume of liquid exiting a membrane system after flowing over the membrane, not through it. It is expressed as feed less permeate; it is also called brine, reject and retentate.								
Feed	The volume of liquid entering a membrane system.								
Flow	<table style="border: none; width: 100%;"> <tr> <td style="width: 10%;">lpm</td> <td>Usually means the volume of liquid flowing over the membrane surface.</td> </tr> <tr> <td>lph</td> <td>Liter per hour</td> </tr> <tr> <td>gpm</td> <td>Gallon per minute</td> </tr> <tr> <td>gpd</td> <td>Gallon per day</td> </tr> </table>	lpm	Usually means the volume of liquid flowing over the membrane surface.	lph	Liter per hour	gpm	Gallon per minute	gpd	Gallon per day
lpm	Usually means the volume of liquid flowing over the membrane surface.								
lph	Liter per hour								
gpm	Gallon per minute								
gpd	Gallon per day								
Flux, water	The flux of water under well-defined conditions. Water flux has a definite meaning in reverse osmosis, while in other types of membrane systems it is only used to verify that a membrane is clean and performing well.								
Flux	<table style="border: none; width: 100%;"> <tr> <td style="width: 10%;">lmh</td> <td>Volume of permeate per unit area and time.</td> </tr> <tr> <td>gfd</td> <td>Flux as liter per m² per hour: $lmh = gfd * 1.7$ based on US gallons.</td> </tr> <tr> <td></td> <td>Gallons per ft² per day: $gfd = lmh / 1.7$ based on US gallons.</td> </tr> </table>	lmh	Volume of permeate per unit area and time.	gfd	Flux as liter per m ² per hour: $lmh = gfd * 1.7$ based on US gallons.		Gallons per ft ² per day: $gfd = lmh / 1.7$ based on US gallons.		
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Gallon	1 US gallon = 3.785 liters. 1 Imperial gallon = 4.546 liters								
HF	Hyper filtration; another name for RO.								
HMWC	High Molecular Weight Component, such as a protein molecule.								
Housing	The part of the membrane filtration equipment holding spiral wound elements or other types of membrane elements, also referred to as pressure vessel.								
IC	Inter connector, which is the connector between two spiral wound elements.								
Langelier index	(See SDSI.) If the index is positive, CaCO ₃ scaling is likely. If it is negative, CaCO ₃ scaling is unlikely.								
LMWC	Low Molecular Weight Component, such as NaCl.								
MWCO (cut off value)	Molecular Weight Cut Off is a number expressed in Dalton indicating that 90% of the species with a molecular weight larger than the MWCO will be rejected. MWCO has a clear meaning for RO, but its meaning and value is becoming more and more vague the higher the MWCO is. It depends on the product on which a membrane is tested, and has little meaning for micro filtration.								
PAN	Polyacrylonitrile								
Permeate	The volume of liquid passing through the membranes (also called filtrate).								

DEFINITIONS AND BUZZWORDS

Table 1. Definitions and Buzzwords

ppm	Parts per million. Strictly speaking, mg solute per 1000 gram solution. Used as the equivalent for mg per liter.
Pressure, average	Average pressure, $(P_{\text{feed}} + P_{\text{conc}})/2$.
Pressure, average NDP	The average Net Driving Pressure is the pressure available to drive liquid through a membrane. $(P_{\text{feed}} + P_{\text{conc}})/2 - P_{\text{perm}} - (\pi_{\text{conc}} - \pi_{\text{perm}})$
Pressure, drop	The loss of pressure between inlet and outlet of a membrane system, a housing (pressure vessel) or a membrane element.
Pressure, feed	Either the pressure from the feed pump (standard meaning), or the pressure at the inlet to a membrane stage in a recirculation system.
Pressure, osmotic	A theoretical value which highly impacts reality. The osmotic pressure is a function of the content of salt and other low MW solutes. High MW solutes can theoretically not contribute to osmotic pressure, but in reality a phenomena is experienced which resembles osmotic pressure. The osmotic pressure of electrolytes and low MW solutes can be calculated with some accuracy, but the "osmotic pressure" of high MW solutes can only be determined by experimentation. The osmotic pressure is usually written as π or Π , where $\Pi = i * n * R * T$
Pressure, unit	psi (pounds per square inch): 14.5 psi = 1 bar. Bar: 1 bar = 0.1 mPa = 100 kPa
PS (PSO)	Polysulfone (either polyethersulfone or polyarylethersulfone).
PVDF	Polyvinylidenedifluoride.
Retentate	Another term for concentrate.
SDSI index	Stiff and Davis saturation index. It is similar to the Langelier index, but can be used in high salinity water. See Langelier index.
TFC, TFM	Acronyms for thin film composite membranes.
THM	Trihalogenated Methane precursors. These are chemical compounds of unspecified chemical nature which result from the reaction of halogens like chlorine with organic substances like humic acid. They are considered a carcinogen.
TMP	Trans membrane pressure. See Pressure, average.
TS TDS	Total solids; the total of dissolved and suspended solids. Total dissolved solids. Both values are mostly expressed as mg/l, ppm or %.

THE FOUR MEMBRANE PROCESSES

Reverse Osmosis (RO) is the tightest possible membrane process in liquid/liquid separation. Water is in principle the only material passing through the membrane; essentially all dissolved and suspended material is rejected. The more open types of RO membranes are sometimes confused with nanofiltration (NF).

True NF rejects only ions with more than one negative charge, such as sulfate or phosphate, while passing single charged ions. NF also rejects uncharged, dissolved materials and positively charged ions according to the size and shape of the molecule in question. Finally, the rejection of sodium chloride with NF varies from 0-50 percent depending on the feed concentration. In contrast, “loose RO” is an RO membrane with reduced salt rejection.

Table 2. Comparing Four Membrane Processes

	Reverse Osmosis	Nanofiltration	Ultrafiltration	Micro filtration
Membrane	Asymmetrical	Asymmetrical	Asymmetrical	Symmetrical Asymmetrical
Thickness Thin film	150 μm 1 μm	150 μm 1 μm	150 - 250 μm 1 μm	10-150 μm
Pore size	<0.002 μm	<0.002 μm	0.2 - 0.02 μm	4 - 0.02 μm
Rejection of	HMWC, LMWC sodium chloride glucose amino acids	HMWC mono-, di- and oligosaccharides polyvalent neg. ions,	Macro molecules, proteins, polysaccharides vira	Particles, clay bacteria
Membrane material(s)	CA Thin film	CA Thin film	Ceramic PSO, PVDF, CA Thin film	Ceramic PP, PSO, PVDF
Membrane Module	Tubular, spiral wound, plate-and-frame	Tubular, spiral wound, plate-and-frame	Tubular, hollow fiber, spiral wound, plate-and-frame	Tubular, hollow fiber
Operating pressure	15-150 bar	5-35 bar	1-10 bar	<2 bar

This effect has proven desirable for a number of applications where moderate salt removal is acceptable since operating pressures and power consumption are significantly lowered. So, in exchange for less than complete salt removal, costs are reduced.

THE FOUR MEMBRANE PROCESSES

Ultrafiltration (UF) is a process where the HMWC, such as protein, and suspended solids are rejected, while all LMWC pass through the membrane freely. There is consequently no rejection of mono- and di-saccharides, salts, amino acids, organics, inorganic acids or sodium hydroxide.

Microfiltration (MF) is a process where ideally only suspended solids are rejected, while even proteins pass the membrane freely. There is, however, quite a gap between real life and this ideal situation.

PRODUCTS AND PROCESSES

A vast array of products are being treated using membranes, but water desalination is using over 80% of all membranes having ever been sold. The better portion of the remaining 20% are used for dairy processing, while the remaining are sold for use with many different liquids. Some liquids are waste products, while others are very expensive pharmaceutical products. Table 3 lists some typical applications, the shaded area representing the main product. Note that the permeate as well as the concentrate can be the desired product, and they can be that simultaneously.

Table 3. Type of Membrane Process for Several Products			
		Permeate	Concentrate
RO	dyeing effluent	clean water	BOD, salt, chemicals, waste products
	water	low salinity water	salty water
	whey	low BOD permeate	whey concentrate
NF	antibiotics	salty waste product	desalted, concentrated antibiotics
	dyeing effluent	clean, salty water	BOD/COD, color
	water	softened water	waste product
	whey	salty waste water	desalted whey concentrate
UF	antibiotics	clarified fermentation broth	waste product
	bio-gas waste	clarified liquid for discharge	microbes to be recycled
	carrageenan	waste product	concentrated carrageenan
	enzymes	waste product	high value product
	milk	lactose solution	protein concentrate for cheese production
	oil emulsion	oil free water (<10 ppm)	highly concentrated oil emulsion
	washing effluent	clarified water	dirty water (waste product)
	water	clarified water	waste product
	whey	lactose solution	whey protein concentrate
	xantan	waste product	concentrated xantan

MEMBRANES - MATERIALS, STRUCTURE, LIMITS

MEMBRANE MATERIALS

The selection of membranes offered by the various suppliers in the business may appear to be confusing since many materials may be used to make membranes, and they are provided under an array of trade names. In reality, relatively few materials are actually used in quantity, and only a few basic membrane types form the bulk of the membranes being sold and used.

INTEGRAL MEMBRANES

Cellulose acetate (CA) is the “original” membrane and is used for RO, NF and UF applications. The material has a number of limitations, mostly with respect to pH and temperature. The main advantage of CA is its low price, and the fact that it is hydrophilic, which makes it less prone to fouling. There are many “die hard” membrane users who insist on buying “the same membrane as last time,” and who simply stay with CA because it works for them. An inherent weakness of CA is that it can be eaten by microorganisms.

Polysulfone (PSO) in a number of varieties has been used for UF and MF membrane since 1975. PSO's main advantage is its exceptional temperature and pH resistance. PSO is practically the only membrane material used in high quantity for a number of food and dairy applications. As a rule, PSO membranes do not tolerate oil, grease, fat and polar solvents. However, there is one type of hydrophilic PSO membrane which apparently defies this rule and seems to work well with oil emulsions.

Polyvinylidenedifluoride (PVDF) is a traditional membrane material, but it is not used much because it is difficult to make membranes with good and consistent separation characteristics. Its main advantage is its high resistance to hydrocarbons and oxidizing environments.

COMPOSITE MEMBRANES

Also called thin-film composite membranes, they appear under various acronyms such as TFC and TFM, and were made to replace cellulose acetate RO membranes. The main advantage is the combination of relatively high flux and very high salt rejection, 99.5% NaCl rejection commonly achieved with composite RO membranes. They also have good temperature and pH resistance, but do not tolerate oxidizing environments.

Composite membranes are made in two-layer and three-layer designs, the precise composition of which is proprietary. Generally speaking, a thin-film composite membrane consists of a PSO membrane as support for the very thin skin layer which is polymerized in situ on the PSO UF membrane. The three layer design has two thin film membranes on top of the PSO support membrane.

MEMBRANES - MATERIALS, STRUCTURE, LIMITS

Around 1980, FilmTec marketed the two-layer design which immediately became the industry standard for water desalination, and this type of membrane has dominated the water desalination market ever since. The membrane has been improved over the years but the basic design remains unchanged, and today there are several companies making this type of membrane.

In the mid 1980s Desalination Systems, Inc. (DSI) began making composite membranes with a three-layer design. These membranes had difficulties competing with the two-layer membranes in water desalination, but proved to work better on industrial process streams where it is more stable and less prone to fouling. The three-layer design is available for RO and NF, and it is still the best choice for treating a vast array of difficult process streams. DSI is the only producer of three-layer composite membranes.

Total worldwide consumption of membranes, based on membrane surface area, is approximately as follows.

Composite RO membranes:	85%
Composite NF membranes:	3 - 5%
Polysulfone UF and MF membranes:	5 - 7%
Other membranes:	3 - 5%

Materials like polyacrylonitrile (PAN), ceramic materials (SiO_2) and cellulose (hydrolyzed cellulose acetate) are included in the group of "other membranes."

SELECTION OF MEMBRANE MATERIAL

It can be difficult to select the right membrane and membrane material for a given process, and some general information about the process environment must be available to make a proper selection. The first step is to determine the preferred process (RO, NF, UF or MF) and look at the membrane materials available. Based on the process environment the best suited membrane material can then be selected. Table 2 (Comparing Four Membrane Processes), Table 3 (Products and Processes) and Table 4 (Chemical Resistance of Several Membrane Materials) may be helpful in membrane selection.

Except for established applications, the choice of membrane material may be difficult, and more than one membrane material often comes into question. As a general rule, only well planned and well performed pilot tests will provide good answers to membrane selection questions for given processes.

MEMBRANES - MATERIALS, STRUCTURE, LIMITS

Table 4. Chemical Resistance of Several Membrane Materials

	Composite	CA	PSO	PVDF	PAN	SiO ₂	Cellulose
3 < pH < 8	✓	✓	✓	✓	✓	✓	✓
pH<3 or pH>8	✓	X	✓	✓	✓	✓	✓
Temp >35°C	✓	X	✓	✓	✓	✓	✓
Humic acid	(✓)	✓	X	X	(✓)	X	✓
Proteins	✓	(✓)	✓	(✓)	(✓)	✓	✓
Polysaccharides	(✓)	X	✓	X	(✓)	✓	X
Textile waste	✓	X	✓	(✓)	✓	X	X
Aliphatic hydrocarbon	X	X	X	(✓)	✓	✓	✓
Aromatic hydrocarbon	X	X	X	✓	X	✓	(✓)
Oxidizers	X	(✓)	✓	✓	(✓)	✓	(✓)
Ketones, Esters	X	X	X	✓	X	✓	(✓)
Alcohol	✓	X	✓	✓	✓	✓	✓

✓ means high resistance

(✓) means either that the information is based on theory or that practical results have proved to be dubious

X means high resistance

pH AND TEMPERATURE RESISTANCE

In the section “Membrane Materials”, the pH resistance of the various materials was discussed. When deciding on a membrane process, it is not enough to look at the membrane material. Membranes come in several configuration (plate-and-frame, tubular, spiral wound, etc.) and a membrane system may include a number of other components which have restrictions with respect to pH tolerance. The pH limitations stated by most membrane manufacturers are in reality the limitations presented by the overall membrane configuration or membrane system rather than by the membrane material itself, the weakest material in the whole system determines the limitation.

The predominant membrane configuration is the spiral wound element, and although the following observations are valid for all membrane configurations, the spiral wound element has been chosen as the example.

Membranes are usually cast on a backing material which often is the limiting factor. The most widely used backing material is polyester (PE) which has excellent temperature stability, but limited tolerance to high pH

MEMBRANES - MATERIALS, STRUCTURE, LIMITS

environments. As a result, many membrane specifications state a maximum 11.5 pH limit. However, many membranes can be cast on polypropylene (PP) backings, which have excellent pH stability but limited temperature tolerance, which can make membrane production problematic. The point is that when a suitable membrane material has been identified and a membrane configuration has been chosen, it must be ascertained that this combination is available in a form which will withstand the working environment of the process.

Since spiral wound elements contain many different polymers, there may be other limiting factors than those set by the PE backing material. The central tube and the Anti-Telescoping Device/Interconnector (ATD/IC) are commonly made of PVC or ABS, but neither of these materials have great temperature resistance. PSO is a more expensive material which provides both good pH and temperature resistance, thus it is commonly chosen for central tubes and ATD/ICs in industrial processing.

A specified pH-limitation may be flexible to some degree and can be exceeded for short periods and under the right conditions without detrimental effects. Low pH is usually not as problematic as high pH. Exceeding pH limitations with elevated temperatures is almost guaranteed to cause problems.

COMPOSITE MEMBRANES AND OXIDIZING ENVIRONMENTS

The world is still waiting for a good composite membrane for RO and NF which can tolerate e.g. 20 ppm sodium hypochlorite. Some readily available composite RO membranes have chlorine resistance, but they do not stand up to today's general performance demands and any claim made for chlorine resistant should be taken with a grain of salt. In contrast, most TFM's tolerate hydrogen peroxide reasonably well, at least in limited concentration, at low temperature and for short durations of time.

MEMBRANE STRUCTURE

Literally all RO, NF and UF membranes are asymmetric. This differentiates most membranes from common filters, e.g. coffee filters, which are symmetric or, in other words, are identical on both sides of the filter.

Membranes have a tight top layer facing the product to be treated. This layer is also called the skin layer. It is thin, typically $\ll 0.1$ micron. The membrane itself is 150 - 250 micron, the bulk of the membrane simply providing structural support for the skin layer. The asymmetric structure means that the pores are wider and farther away from the surface, which prevents the pores from being plugged. This provides good fouling resistance, since foulants have a tendency to either be totally rejected or to pass all the way through a membrane.

MEMBRANES - MATERIALS, STRUCTURE, LIMITS

The pore size of membranes can, in broad terms, be stated as follows.

MF	5 to 0.1
UF	0.1 to 0.01
NF, RO	0.001 (theoretical)

So far, pores have not been observed in RO or NF membranes using a microscope, but in spite of this, water passes through the membrane and salt is rejected. The lack of pores in NF and RO membranes means that even membrane scientists do not really know how or why these membranes function 35 years after the production of the first membrane, or at least they do not know in any detail. Let it suffice to say that the first membrane was tested by someone with a practical sense who saw desalinated water come through it. If he had only looked at the membrane through a microscope, he might have rejected it since it did not have any pores and supposedly would not have worked.

In spite of our lack of knowledge, we are able to predict the performance of an RO membrane to some extent. With NF membranes, it is more difficult, and today, if more than three solutes are present in a solution, one can only make an educated guess as to the results of an NF process, even when an accurate and complete feed analysis is available.

MEMBRANES - MATERIALS, STRUCTURE, LIMITS

MEMBRANE MANUFACTURERS Table 6. An Incomplete List of the Major Players as of 2001

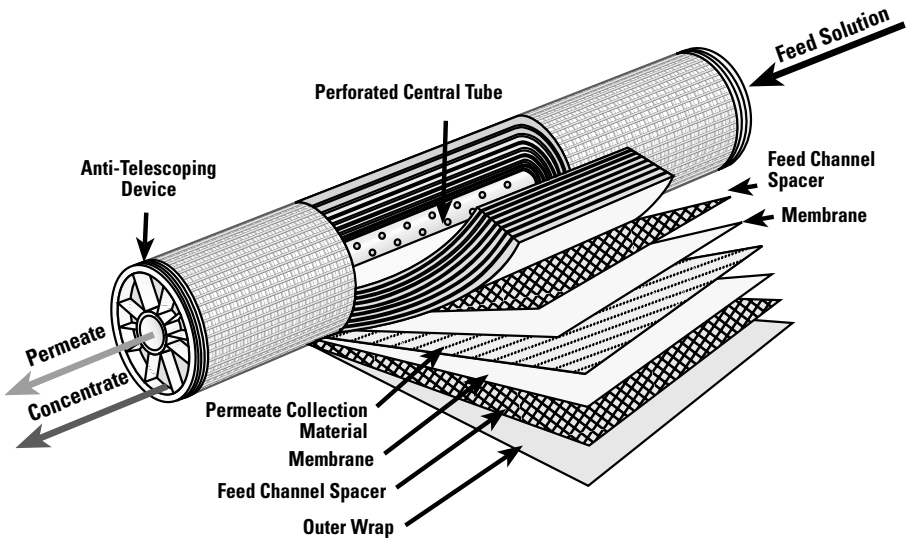
See for example: www.tcn.zaq.ne.jp/membrane/english/MembManufE.htm, (2001)

	Owned By	Company Size	Tubular Membrane	Spiral Wound Element	Fiber System	Ceramic Membrane	RO	NF	UF	MF	Process	Water
PTI		Small		✓			USA		✓		✓	
DSS		Small		✓			DK	✓	✓		✓	✓
FilmTec	Dow Chemicals	Big		✓			USA	✓			(✓)	✓
Fluid Systems	Koch	Medium		✓			USA	✓	✓		(✓)	✓
Hoechst	KC5	Small		✓			Germany	✓	✓		✓	
Hydranautics	Toray	Medium		✓			USA	✓				✓
Kiryat Weizman	Koch	Small	✓	✓			Israel	✓	✓		✓	✓
Koch/Abcor		Medium	✓	✓	✓		USA	✓	✓	✓	✓	
Osmonics		Medium		✓			USA	✓	✓	✓	✓	✓
PCI	Thames Water	Small	✓				England	✓	✓		✓	
Rochem	Pall	Small					Germany	✓			✓	
SCT		Small				✓	France			✓	✓	
Stork Friesland		Small	✓				Holland	✓		✓	✓	
Synder		Small		✓			USA		✓		✓	
Tami		Small				✓	France			✓	✓	
Toray		Medium		✓			Japan	✓				✓
Trisep		Medium		✓			USA	✓	✓		✓	
XFLOW		Small			✓		Holland		✓	✓	✓	✓

MEMBRANE MODULE / ELEMENT DESIGN

As previously mentioned, there are several membrane configurations available on the market.

The spiral wound element type is the workhorse in the membrane world. The spiral wound element design was originally made exclusively for water desalination, but the very compact design and the low price made it attractive to other industries. After a lot of trial and failure, redesigned elements emerged which can be used for a variety of industrial applications in the dairy industry, the pulp and paper industry, for high purity water, and at high temperature and extreme pH, but the number of membrane companies who really can and will develop and supply spiral wound elements for extreme applications is in many cases limited to one.



Tubular membranes have been around for a long time. The design is simple and easy to understand. Universities love tubular membranes because it is so simple to calculate the Reynolds number and to theorize about mass transfer coefficients. Tubular membranes have one big advantage. They can tolerate suspended solids, and most notoriously fibers, to a very high extent.

MEMBRANE MODULE / ELEMENT DESIGN

All tubular membranes suffer from several disadvantages:

- They require a lot of space.
- Change of membranes may be quite difficult and time consuming.
- The tubular systems with large ID (1 inch) use a lot of energy.
- Large internal volume makes flushing and CIP costly in terms of usage of chemicals and water.
- It is costly and difficult for the manufacturer to change the tubular design.

The advantages of the tubular systems sometimes outweigh the disadvantages, and the tubular membrane design has a place in the market, although quite small.

Plate-and-frame (flat sheet) systems were largely pioneered by DDS and actually dominated the dairy market in Europe for 15 years. Lack of development and an inflexible price structure more or less killed the design between 1989 and 1995.

There are several new plate-and-frame systems available in Europe. The best known is the ROCHEM design. Flat sheet systems offer a very robust and compact design, but for a price. Modern flat sheet systems are built to tolerate very high pressure, in excess of 100 bar. There is a small market for this extreme pressure range in treatment of landfill leachate and for desalination of sea water onboard ships.

Fiber systems are (with one exception) similar to tubular systems. Only the ID of the fiber is small, typically <2 mm. The biggest difference from large diameter tubular membranes is that fiber systems are always unsupported. They came early on the market but are quite expensive. The fiber systems are mechanically weak. They have been used to a limited extent for UF of whole milk and are now used also for oil emulsions.

Ceramic systems are very, very expensive. Theoretically, ceramic systems can be very effective for MF. In reality the market is diminutive.

Hollow Fine Fibers was pioneered by DuPont for sea water desalination. They demand extremely good prefiltration. DuPont has ceased production.

TYPES AND VARIABLES OF SPIRAL WOUND ELEMENTS

There is an incredible array of spiral wound elements on the market. In Table 7 some of the variables are listed. See also page 16 for more information.

MEMBRANE MODULE / ELEMENT DESIGN

Table 7. Types and Variables of Spiral Wound Elements

Dimension	Outer diameter of the element Length of the element Internal diameter of the center tube
Outer wrap	Fiber glass Tape Several sanitary designs
End of element	Female connection Male connection
Center tube	Several types of polymers used, PSO becoming the standard for industrial applications
Feed spacer	30 mil nominal 0.75 mm 47 mil nominal 1.20 mm 90 mil nominal 2.30 mm Even higher spacers are available. (1 mil = 1/1000 inch)
Spacer type	Diamond type (standard) Several free channel designs are on the market
Membrane support	Polyester (standard) Polypropylene
Brine seal	U-cup seal Lip seal No seal
ATD	Star-type Hole-plate type
Glue	Several types of glue used

TYPES AND VARIABLES OF TUBULAR MEMBRANES

Table 8. Types and Variables of Tubular Membranes

Dimension	Internal diameter of the tube, typically 1 or 0.5 inch Length of the tube, typically 3.3 meter and 5 meter Number of tubes per module.
Membrane housing material	Stainless steel PVC No support
End cap	Connects the tubes in a bundle in parallel. Connects the tubes in a bundle in series.

MEMBRANE MODULE / ELEMENT DESIGN

TYPES AND VARIABLES OF PLATE-AND-FRAME SYSTEMS

The name “plate-and-frame” covers membrane modules of very different constructions, all using flat sheet membranes. The other systems mentioned will usually be easily recognizable as a spiral wound element, tubular membrane or fiber systems. Not so for the plate and frame modules. What they have in common is a flat sheet membrane, but the arrangement of plates and membranes in a module differs widely. The major plate and frame producers is shown in Table 9.

DDS M30	Vertical module with a circular membrane used for RO and NF. The construction is obsolete.
DDS M35-M39	A family of horizontal modules with oval membranes numbered 35 through 39. Used for UF and MF, mostly in the dairy industry. Good for highly viscous product. The membranes are mounted on PSO support plates.
Millipore	Square cassette systems, mostly for laboratory use or for small scale pharmaceutical production.
Rochem	DISK-TUBE, 8-inch diameter circular membrane for RO, NF and UF using a housing like a spiral wound element. This type of module can work at pressures up to 200 bar.
Rhone Poulenc	Pleiade. Square module looking like a plate heat exchanger used only for UF. The system uses numerous big gaskets. Almost obsolete.
Valmet Flootek	The CR-filter is an ingenious system, which can operate on very dirty water and still give high flux. Unfortunately the investment is very high.

TYPES AND VARIABLES OF FIBER SYSTEMS

Dimension	Internal diameter of the fiber Length of the fiber Number of fibers per module.
Housing material	Stainless steel PVC PSO

See Table 11 for a comparison between the various membrane modules.

MEMBRANE MODULE / ELEMENT DESIGN

COMPARING MEMBRANE MODULES AND ELEMENTS

The following table is a qualitative comparison of the capabilities of various membrane module and element types.

Table 11. Comparison Between Several Membrane Modules

	Spiral wound element	Tubular high price	low price	Plate and frame system	Hollow wide fiber system	Hollow fine fiber	Ceramic
Membrane density [m ² /m ³]	high	low		average	average	very high	low
Plant investment	low	high	low	high	very high	medium	very high
Tendency to fouling	average	low		average	low	very high	medium
Cleanability	good	good		good	low	none	good
Variable costs	low	high	low	average	average	low	high
Change of membrane only, see note 1	no	yes	no	yes	no	no	yes
Flow demand	medium	high	medium	medium	high	low	very high
Prefilter other demands (see also table 26)	≤ 50 μm. no fibers	sieve		≤ 100 μm. few fibers	≤ 100 μm. few fibers	≤ 5 μm extreme pretreatment	sieve

Note 1) Membrane systems can be designed in such a way that a change of membrane means a complete change of a major part of the hardware. Most tubular and flat sheet designs are made in such a way that only the membrane is changed, leaving the bulk of the system unchanged.

MORE ABOUT SPIRAL WOUND ELEMENTS

HOUSING DESIGN

There are several different designs of housings on the market. The housings can be segmented by material (stainless steel and polymer), or by function (housings with a side port entry and exit, or with entry and exit through the end caps).

Polymer housings are almost exclusively made from glass Fiber Reinforced Polyester (FRP). The design is over 30 years old and works well, but is certainly not without problems. It functions well in systems for desalination of ground water and sea water. For all other products its use is problematic. Most polymer housings use a tension ring to secure the end cap.

Stainless steel housings were originally made for dairy use exclusively. Today they are used much more widely, and are constructed with side ports as standard. Some stainless steel housings are constructed in the same way as glass fiber reinforced housings, which makes it exceedingly difficult to remove the caps. Stainless steel housings should be electro-polished on the inside. Otherwise it is next to impossible to push elements in and out of them.

There are only three standard diameters for glass fiber reinforced housings: 2.5-inch, 4-inch and 8-inch. Stainless steel housings are available in a wider variety of standard and non-standard diameters.

Table 12. Glass Fiber and Stainless Steel Pressure Vessels. Comparison		
	(FRP)	Stainless Steel
Pressure	200 bar	rarely above 80 bar
Temperature	<70°C	<100°C
Side port entry	difficult / rare	easy / standard
End cap entry	standard	non-standard
Sanitary	no	yes (possible)
Price	100%	150 - 200%
2.5", 4.0", 8.0"	water standard	difficult
3.8", 5.8", 6.3"	not available	dairy standard
6.0"	military standard	not used
4.3", 8.3"	not available	Koch dairy standard

MORE ABOUT SPIRAL WOUND ELEMENTS

Unfortunately for Europeans, stainless steel housings based upon American inch measurements are most commonly used. The standard dairy sizes are not too difficult to obtain, but the 2.5-inch, 4-inch and 8-inch diameters are rare in Europe and quite difficult to find.

See Table 12 for a summary of the discussion above.

Stainless steel housings with side port entry and exit are available in two varieties: the 4-port style, which uses the housing as a building block with no external product manifold, and another type which uses an arrangement with external manifolds. (See Figure 1). One can argue which type is better, but it is a fact that most systems are built with external manifolds.

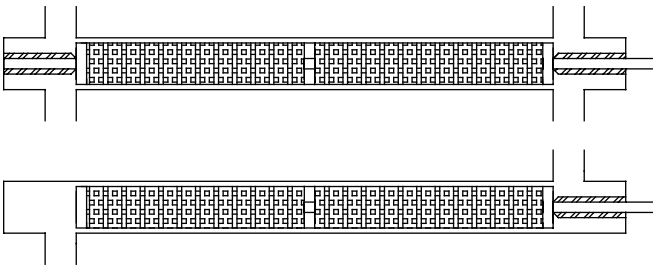


Figure 1. Steel Pressure Vessels

Upper Vessel: 4 port style. No external manifolds.
Lower Vessel: 2 port style. With external manifolds.

The main advantage of side entry is that it allows the high flow needed in sanitary systems. In water desalination this design is rarely used.

The world of spiral wound element dimensions is a jungle. Outer diameter, element length and internal diameter of the center tube is not standardized. This makes it quite difficult to change from one element manufacturer to another, and it creates a lot of problems for the housing manufacturers.

NUMBER OF ELEMENTS PER HOUSING - PRESSURE DROP

In order to determine the maximum number of elements per housing, several parameters must be considered:

- First make a distinction between RO/NF and UF/MF
- Then review the process
- Third, take into consideration that an element can tolerate only a limited pressure drop

MORE ABOUT SPIRAL WOUND ELEMENTS

Two main points shall be discussed in more detail.

- Trans-membrane pressure (TMP)
- Pressure drop per housing

Trans-membrane pressure represents the change in pressure between the inlet of a housing and the outlet of a housing. The pressure decrease is a result of feed passing through the elements. See Table 13 for an example.

Table 13. Pressure Drop in Spiral Elements. Example.		
Example: Housing with 4 elements. Pressure drop 0.7 bar per element. This corresponds to 2.8 bar pressure drop per housing.		
Inlet pressure, bar	Outlet pressure, bar	avg. TMP, bar
4.0	1.2	2.6
16.0	13.2	14.6

Table 14. Pressure Drop in bar per 40" Element					
Element type	Mil	Size	Max. allowed	Typical	Seen at end user
Standard water	30	2.5" 4.0" 8.0"	0.7 bar	0.3 bar	0.1 - 0.7 bar
Dairy	30	3.8" 4.2" 5.8" 6.3"	1.0 bar 1.0 bar 1.0 bar 1.0 bar	1.0 bar 1.0 bar 0.7 bar 0.7 bar	0.7 - 1.2 bar 0.7 - 1.2 bar 0.5 - 1.2 bar 0.5 - 1.2 bar
Specialty applications	47 90 90	4" 4" 6"	1.2 bar 1.2 bar 1.0 bar	1.0 bar 1.2 bar 1.0 bar	0.5 - 1.0 bar 0.5 - 2.0 bar 0.5 - 1.2 bar

Table 15. Number of Elements per Pressure Vessel					
		RO	NF	UF	MF
Water:	Typical Range	6 1-8	6 1-6	3 1-4	2 1-2
Process liquids:	Typical Range	4 1-4	4 1-4	3 1-3	2 1-2

MORE ABOUT SPIRAL WOUND ELEMENTS

It is easy to see that when the feed pressure is, for instance, 10 bar the difference between trans-membrane pressure at the inlet and the outlet is small enough to be considered unimportant. But when the feed pressure is in the range of 1 to 5 bar, there is a huge difference in trans-membrane pressure. Since it is best to have the same trans-membrane pressure for all elements in a housing, the maximum number of elements is smaller for low pressure operation.

LIMITATIONS OF MEMBRANES AND SYSTEMS

TEMPERATURE

MEMBRANES IN GENERAL

CA as a material has an inherent temperature limitation, and CA membranes are limited to an upper operating temperature of approximately 35°C.

PSO, PVDF and PAN can tolerate higher temperatures. PSO and PVDF membranes are known to operate at 95°C without problems. PSO membranes will operate at temperatures up to 120°C.

Composite membranes can, as a general rule, operate at least up to 80°C, and they will withstand higher temperatures at low pressure during, for instance, thermal disinfection.

The temperature capability of a membrane system is, in most cases, not dictated by the temperature limitation of the membrane, but primarily by the membrane configurations and other components in the membrane system.

SPIRAL WOUND ELEMENTS

Spiral wound elements traditionally have had an upper temperature limit of 45°C. This is still valid for standard elements used for water desalination, but there are now spiral wound elements available on the market capable of higher temperature limits. Although a maximum temperature of 45°C is not a limitation in water desalination, it is a problematic limitation for food and process industry applications. After much trial and error, a few companies have succeeded in producing temperature stable elements.

The elements used in the dairy industry have been operating at higher temperature (and pressure drop) than originally specified by the element producers for years. Today, the 55°C limit printed for a dairy standard element reflects the real limit; this temperature is rarely exceeded in normal dairy operations.

Osmonics has developed elements which have proven to tolerate temperatures well over 55°C. The elements are produced with a variety of spacers. They are sold under the trade name DURATHERM® membrane elements. The following elements are available mid 2001. (see Table 15a)

The product flux should be watched and kept below 35 l/mh, thus ensuring that the operating pressure is kept low. It is also recommended to calculate the Wagner units.

LIMITATIONS OF MEMBRANES AND SYSTEMS

	Operation	Sanitizing
DURATHERM HWS	50°C	90°C
DURATHERM STD	70°C	90°C
DURATHERM PRO	80°C	90°C
DURATHERM Excel	80°C	90°C
DURATHERM Elite	90°C	90°C

Elements with wider feed spacers can operate on feed containing high dissolved solids. It is standard to use a 50 mil spacer, but wider spacers are available, e.g. 90 mil spacers, which allow treatment of even more difficult liquids. Depending on the type of membrane these elements can operate up to 90°C continuously. One example is elements from DESAL™ membrane products under the trade name DURATHERM® Excel. The good temperature stability ensures that these elements can be thoroughly pasteurized, or that they can operate continuously at a temperature which is sufficient to make any discussion about microbial growth very academic.

UF of carrageenan is one of the processes where membranes have been operated at 80 - 90°C for years. A more recent application is RO of evaporator condensate for silica removal, operating at close to 90°C.

Just for the record: DESAL™ membrane elements have been pioneered for industrial sizes operating on non-water liquids at 140°C. This is probably very close to the limit for polymeric membranes.

		Continuous max. °C	Short time max. °C
Standard water elements	max. °C (Max bar)	45 (42)	50 (42)
4", 6" dairy elements	max. °C (Max bar)	50 (42)	55 (42)
DESAL™ Elements with special spacer	max. °C (Max bar)	45 (42)	80 (5)
Duratherm® elements	max. °C	70	90
Duratherm® Excel elements	max. °C	80	90

LIMITATIONS OF MEMBRANES AND SYSTEMS

Please see element specifications from the supplier for limitations which must be taken into consideration such as pH, flux and pressure.

A positive aspect of high temperature operation is the increase in flux that results from high temperature (See Optimizing Pressure and Temperature). Operation at 90°C will increase flux from 100% to 300% at the same pressure. But it is often better to reduce pressure (actually NDP) to one third and save substantial amounts of electricity.

High temperature can be viewed as problematic, but the author most often finds high temperature membrane operation to be advantageous even though the system must be engineered with more care and more emphasis on a number of details than normal. The main rule to remember is this: the higher the temperature, the more one needs to be aware of the physical stress on the elements and the membrane.

- Excessive trans-membrane pressure can flatten the membrane excessively (“compaction”), resulting in an irreversible drop of flux.
- Excessive pressure drop can cause membrane and/or polymer materials of construction to move and sometimes break, eventually resulting in a complete failure of the membrane.

SYSTEMS OTHER THAN SPIRAL WOUND ELEMENTS

- Fiber systems can usually tolerate temperatures up to 80°C.
- Low priced tubular systems with an unsupported membrane tube will normally be specified with a maximum operating temperature of 35°C.
- Higher priced tubular systems with a supported membrane, for instance a stainless steel support arrangement, can tolerate >80°C.
- Hollow fine fiber systems are limited to <50°C.
- Plate-and-frame systems will, depending on the actual design, be able to operate at temperatures of >80°C. Older systems may have problems with pressure stability during high temperature operation.

PRESSURE

All membranes are sensitive to pressure. The word compaction is often used to describe the irreversible ‘flattening’ of a membrane due to pressure. Besides the membranes’ own ruggedness, it is vital to properly support the membrane to prevent pressure squeezing the membrane into the support material.

It is important to read the manufacturer’s specifications and follow them carefully. This type of specification is usually based on experience rather than theoretical calculations, so why repeat somebody else’s bad experience?

LIMITATIONS OF MEMBRANES AND SYSTEMS

Table 17. Typical Pressure Limits, bar		
	Standard	Special
Tubular membrane, supported	42	70
Tubular membrane, unsupported	7	–
Spiral wound element systems	42	70, 120
Plate and frame systems	40	200
Wide fiber systems	25	–
Fine fiber systems	70	200

Compaction is a function of pressure and temperature. (See Table 18)

Table 18. Guidelines to Avoid Compaction (not valid for CA membranes)		
Pressure	<20 bar	Minimal compaction
Temperature	<15°C	Compaction will be minimal
	15 to 50°C	Restrict pressure to 30 bar max.
	>50°C	Severe compaction is possible
	>80°C	Keep pressure below 5 bar Some compaction is inevitable

There are no firm rules available regarding maximum allowable temperature and pressure. The guidelines in Table 18 are valid for all membranes, except CA membranes. Table 18A provides some general rules concerning the temperature/pressure relationship expressed in what has been dubbed as Wagner units. Please note that temperature is more dangerous than pressure.

Table 18a. Guidelines to Avoid or Minimize Compaction	
Pressure [BAR] x Temperature [°C] = Wagner units	
< 1200	Safe operation. Standard elements
1200 - 2000	Difficult. Special element design
> 2000	Very difficult. Rarely possible. Very special element design

LIMITATIONS OF MEMBRANES AND SYSTEMS

Consequently, when operating close to the upper temperature limit it is advisable to restrict pressure as much as possible.

	Lower pH limit	Upper pH limit
PSO	1 *)	14 *)
PVDF	0	12
CA	4	7
TFM	1 **)	12 ***)
Ceramic	0	12 to 14

*) Low pH and high temperature at the same time may reduce water flux, sometimes irreversibly to zero.

**) The trend is to increase high pH stability of TFM.

***) Valid at room temperature. At elevated temperature membrane deterioration can be rapid. Various types of polyamide TFM exhibits significant differences in stability at low pH.

pH

Most membranes, with CA membranes being the notable exception, are very resistant to extreme pH values. The major limitation is the use of polyester backing for many membranes, which limits the upper practical limit effectively to pH 11.5. The functionality of many membranes changes at very high pH values, but they may still be useful and functional. Most membranes are stable at low pH values.

FEED FLOW

There is no such thing as an absolute upper feed flow limit. The mechanical strength of the membrane module or element sets the limit.

VISCOSITY

Viscosity of the feed is not in itself a problem, but high viscosity leads to higher pressure drop for a given flow. As long as the pressure drop is acceptable and the flux is satisfactory and stable, viscosity does not pose an operational problem. Handling high viscosity feeds in a membrane system is more of an engineering problem than a membrane problem.

SYSTEM COMPONENTS

A membrane system consists of more than just membranes. Key components for design of membrane systems are discussed in this section.

HEATING/COOLING AND HEAT EXCHANGERS

The use of multi-tube (tube and shell) heat exchangers is very common for heating and cooling in membrane systems. The heating or cooling medium is on the outside of the tubes, and the products are on the inside. This construction allows for high pressure, and it is easy to find equipment which will withstand pressure as high as 70 bar.

The multi-tube heat exchanger works differently than a conventional plate heat exchanger. The main differences are:

- The product temperature change in one pass is small, typically 0.5°C or less
- The product flow is very high, compared to the flow of heat exchange medium

Multi-tube heat exchangers are normally chosen because the required cooling of the product is normally limited to the removal of pump energy rather than actually heating or cooling the product. The temperature is typically kept constant for long periods of time. The pressure drop over a multi-tube heat exchanger is deliberately very low.

Multi-tube heat exchangers can be purchased from, for instance, APV Nordic and Uniq Filtration.

VALVES

Various industries have different requirements to the type of valves used in a membrane system. The following is a list of examples.

- The dairy industry: Sanitary butterfly valves and needle valves
- Water purification: Ball valves and needle valves
- The pulp and paper industry: Any type, mostly ball valves
- Waste water applications: Any type, mostly ball valves

Some mechanical engineers claim that ball valves and butterfly valves cannot be used for flow or pressure control. In theory this may be right, but in the membrane world practice contradicts this standpoint. These types of valves are difficult to use for control purposes, but not impossible. A very positive aspect of ball valves and butterfly valves is the capability of allowing a huge difference in flow and pressure drop, which is often needed to achieve the correct conditions for both production and cleaning.

SYSTEM COMPONENTS

A major headache in membrane system design is a recirculation plant with a high volumetric concentration ratio, which means that the system must be controlled based on a very small flow of concentrate. The type of valve needed here is a needle valve. If the concentrate does not contain suspended solids this type of valve will probably perform just fine, but even small amounts of suspended solids can effectively block the concentrate outlet through a needle valve and cause major control problems.

When operating with a liquid which is heavily loaded with suspended solids, the control problem can be solved by the 'always-plugged-concentrate-valve' concept in the following way. Two timers and an automatic valve are installed with the valve normally fully closed. Timer one determines the length of the period between valve openings. Timer two determines how long the valve is open. When timer one is activated, the concentrate valve opens fully and a fast flow of concentrate occurs. When timer two is activated the concentrate valve closes fully. In this way an astonishingly accurate control of the concentrate discharge can be achieved.

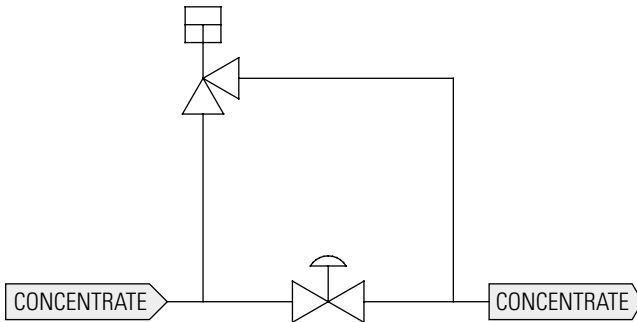


Figure 2. Concentrate Valves

The control valve for the concentrate is often too small for the very large flow of water during CIP. Therefore, it may be necessary to install a CIP valve in parallel to the concentrate valve (See Figure 2). The CIP valve is often a 3" or 4" butterfly valve. If the length of pipe from the tee to the valve is shorter than or equal to three times the inner diameter of the pipe, the design is considered to be sanitary. In RO systems, it is possible to use a large dairy low pressure piston valve, although that is against all rules. The trick is to route the high pressure to the side of the piston pressing against the seal at the outlet; in other words direct flow opposite to the standard direction of flow. During production, pressure keeps the valve closed; the valve cannot be opened. During CIP and flush, the line pressure is so low that the valve can be opened (Inventor: Tom Sirnes).

SYSTEM COMPONENTS

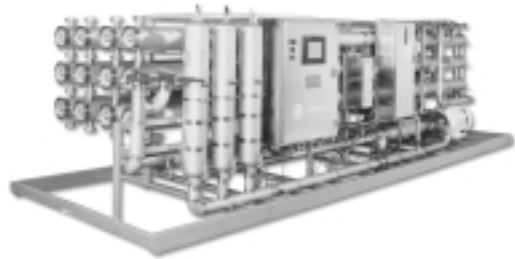
Ball valves and butterfly valves are, according to the textbooks, not suited for regulation due to their characteristics. However, experience shows that these valves are quite acceptable for regulation of membrane filtration plants.

A pump can act as an unusual valve. A positive displacement pump controlled by a frequency converter can be used as a back pressure valve in systems treating highly viscous products and liquids with high suspended solids. This setup can also be used on shear sensitive products like egg white.

PRESSURE GAUGES

Pressure is the driving force in membrane filtration systems, and it must be monitored. Only pressure gauges containing a diaphragm should be used. The gauges must be heavily dampened. One of the major headaches using Bourdon type gauges is that they lose adjustment and make accurate pressure reading impossible.

The author favors pressure transmitters, because they provide more accurate readings and are easier to calibrate. They work with signals which can be used in data logging, and for electronic control of membrane systems. The



accuracy of pressure transmitters is typically ten fold better than that of a Bourdon type gauge, which is important when determining the pressure drop in a membrane system, an important parameter to monitor. If there is an increase in pressure drop over the normal value, and if the flow condition is correct, then it is an indication that physical scaling or plugging of the membrane is taking place.

Pressure drop is almost impossible to measure with ordinary gauges. This is because pressure gauges intended for 40 bar operating pressure may have a maximum pressure indication of 60 or 100 bar, and even a good pressure gauge has an error in the order of 1%, which translates into one bar. In order to calculate the pressure drop, the outlet pressure reading is subtracted from the inlet pressure reading. If one gauge shows 40 bar and the other gauge 38 bar, the difference can, in reality, be anything between zero and four bar due to the inherent inaccuracy of the pressure gauges. In other words, pressure gauges can lead to highly erroneous results, whereas a pressure transmitter will provide more reliable data.

FLOWMETERS

Flow measurements and flow control are strict requirements in a membrane system. Rotary flowmeters are commonly used, and they are adequate for routine readings taken by operators, but they have some shortcomings. Usually they only provide a visual reading and do not provide signals which can be used by data logging. Also, they are mostly useless if the product is turbid or colored, and they will give false readings if the density or viscosity of the product is different from water. All in all, they are only acceptable for daily monitoring.

The only type of flowmeter which always seems to work is the magnetic flowmeter. This type may seem expensive, but it is very accurate and leaves no doubt about the actual flow in a system. ProceData in Silkeborg, Denmark supplies fairly inexpensive and quite good magnetic flowmeters, which can be delivered in a sanitary version meeting dairy standards. There are several much larger suppliers of magnetic flow meters too, e.g. Krohne (D), Siemens (D), Fischer and Porter (UK) and Danfoss (DK).

Most flowmeters on the market can be used for general purposes, and there are many other types available, like the Bürchert flowmeter which uses a small paddle device to indicate flow. This type of flowmeter is worth testing for many applications since it can be delivered in a version tolerating up to 90°C and high pressure. Very high flows, abrasive particles and fibers in the product may present problems for this type of flowmeter.

The permeate flowmeter deserves special attention. The problem here is that the permeate flow during production and during the CIP cycle can be very different. In a UF system it is not uncommon that the CIP flow is higher by factors of 10 to 30. In this situation, the flowmeter can act as a throttle which, in general, is neither desirable nor acceptable. One solution is to build in bypass valves for CIP, and another is to use a magnetic flowmeter which can be chosen with a diameter suitable to measure both the production and CIP flow.

Very few flowmeters can tolerate the pressure, pH and temperature prevalent in RO and NF systems. This must be taken into careful consideration when selecting flowmeters for these types of membrane processing.

TANK DESIGN

The tanks used in membrane systems should be made with either a conical or slanted bottom to allow total drainage. Otherwise it is inevitable that particles, crystals or other settlements collect in the bottom of the tanks, and this will sooner or later lead to chemical, mechanical or bacteriological

SYSTEM COMPONENTS

problems, or a combination of the three. The tanks should have loose covers allowing access for flushing and manual cleaning.

It is also important that the tanks, whenever possible, are kept free from built-in devices such as a heating coil or a level switch. All measuring devices should be placed outside the tanks. Level control is best done with a pressure transmitter, and temperature measuring devices should be placed in the pipes leading to the plant rather than in the feed tank.

The best suited material for the tanks is stainless steel. Most other materials have inherent temperature limitations.

100 to 300 liter tanks are adequate for industrial membrane systems. For pilot plants, 50 liters is a fair size.

It is common to have a permeate tank placed next to the feed balance tank in larger UF systems, and it is customary to build the two tanks as a unit with an overflow. This allows permeate and concentrate to be separated during production, but still allows permeate to flow freely to the feed balance tank during flushing procedure and CIP when an unusually large volume of water flows as permeate. APV-Pasilac pioneered this design, which has proven to be the most practical in many membrane systems.

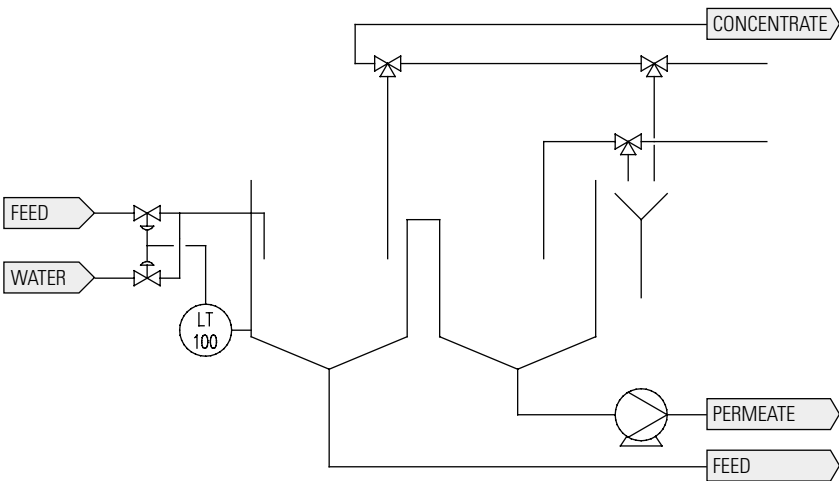


Figure 3. Double Feed Tank

Level control of the liquid in the tanks can be done inexpensively using a pressure transmitter and two pneumatic valves. The level transmitter

transforms the level in the tank into a signal of 3 to 15 psi. The two pneumatic valves controlling feed and water level should be split range, meaning that one operates in the range of 3 to 9 psi (water valve) and the other in the range of 9 to 15 psi (product valve). Please see Figure 3, Double Feed Tank. Sanitary level transmitters designed for the food industry are produced by Uniq Filtration.

When the tank is empty, both valves are fully open. When the level rises, the water valve will close fully. At a higher level the product valve starts to close, and is now ready to regulate the amount of product flowing into the tank. This is an elegant solution, since the water supply acts as a security should the feed flow stop, and it also allows easy rinsing and cleaning. To start rinsing, the flow of product is simply stopped.

It is recommended that a manually adjustable pressure transmitter be used for regulation of the inlet valves; it is a simple solution, that works just fine in real life.

CLAMPS, FLANGES AND THREADS

The only connector systems which have proven to be consistently good and reliable in all applications is the TriClover type clamp. It is somewhat expensive, but it offers many advantages for clamps up to 6 inches in diameter. For clamps larger than 6-inch diameter, other brands of high quality flanges are usually used because the allowable pressure is limited by the TriClover (Tri-Clamp® type). TriClamps are not universally accepted, but they are widely used. The name Tri-Clamp has become so commonly used that it often designates this type of clamp in general rather than the original product from TriClover.

If financially feasible, thread connectors should not be used. They are non-sanitary and difficult to dismantle and assemble correctly.

Flanges come in many different types, and a type of sanitary flange actually exists. They are bulky and heavy, and may be demanded in the chemical industry.

MATERIALS OF CONSTRUCTION

In the author's opinion, there is a simple rule which helps prevent many kinds of mechanical problems in membrane systems: Use good quality stainless steel for all parts and devices that come into contact with liquids in a membrane system. This may sound like a piece of expensive advice, but it is quite surprising how often polymers fail, and how often the limitations of non-stainless steel components show up after a few years of operation, with

SYSTEM COMPONENTS

costly retrofitting as a result. Ordinary steel should never be used for any components coming into contact with the process liquid. Rust will form, and rust flakes entering the membrane system will lead to endless problems.

Using stainless steel as the construction material is not only natural but mandatory in a number of industries, like dairy, pharmaceutical and petrochemical. In water desalination it is still common to use PVC, brass and very low quality stainless steel. But this practice introduces restrictions that are hard to accept in the long run.

Reasonably priced stainless steel fittings up to 3-inch diameter are readily available, and even 4-inch diameter fittings are not too expensive. But prices for fittings above 4-inch diameter tend to soar because there is very little demand for larger diameter stainless steel fittings.

Note that the designation “stainless steel” is not very good because the non-corrosive nature of the material is only true under certain conditions. For instance, seawater from the North Sea is problematic but can be handled with ordinary stainless steel types, probably because the water is cold. Water from the Red Sea, which is lukewarm, is very highly corrosive, calling for the use of stainless steel which is considerably better and much more expensive.

An effective cleaning regimen can help to actively prevent corrosion of stainless steel parts in a membrane system. This is achieved by cleaning all surfaces thoroughly once a day. Even better is a wash with nitric acid to passivate the stainless steel surfaces. These practices have kept systems in operation for many years, which otherwise should have corroded quickly.

Only polymer materials of the best quality available should be used in membrane systems. This group includes materials like PSO, PVDF, C-PVC, Delrin and several other mechanically strong materials with good chemical and thermal resistance. However, PE and PP is used extensively in the low price water market since they are sufficient for this application.

The following products are all homogenous materials:

- ABS** Useful material in water desalination systems.
- Delrin** Also called POM; it is an excellent material. Its biggest weakness is limited resistance in low pH environments.
- PE** Polyethylene has good chemical stability but very limited temperature stability.
- PP** Polypropylene is chemically a very resistant polymer. The temperature stability is limited, and it has a tendency to creep.

- PSO** In its many varieties PSO is probably the best material to use in membrane applications. It is totally resistant to temperature and the pH values found in membrane systems. Its main weaknesses are a tendency to become brittle, and a high sensitivity to ketones and aromatic compounds.
- PVC** PVC is mostly used for low pressure piping. It is inexpensive, but has severe temperature limitations. It can only be used for un-demanding applications, such as the desalination of ground water.
- C-PVC** Chlorinated PVC has significantly better temperature stability than ordinary PVC. The present political lobbying against the PVC industry may preclude it from being an acceptable construction material in the future.
- PVDF** An excellent but rather expensive material. It has good heat stability and is chemically almost as resistant as Teflon.

The following products are composite materials:

- FRP** Glass fiber reinforced polyester is widely used for housings. It has become the standard in water desalination in spite of its obvious shortcomings. Corrosion resistance is its prime advantage, closely followed by low price.
- Epoxy** A very special type made only in Germany by Membratec. The housings are thin walled, but can nevertheless tolerate very high pressure.

Gaskets are often a forgotten item when reviewing materials. It seems that EPDM is a material which is very useful in almost all cases. It does not make sense to try to save money here. In the author's opinion, a cheap material like nitril rubber does not last, and it is costly and troublesome to replace gaskets in a membrane system.

PIPES

There is a lot of piping in membrane systems. Usually it is easy to get the type of pipe needed. Quite often dairy type pipe turns out to be the best and the least expensive, simply because large quantities are produced. The quality and the nature of the interior surface of dairy piping is excellent.

As much as possible, avoid welding since welds are potential corrosion hazards. Use pull-outs to make T's and branches in the tube system. Pull-outs are used extensively in the dairy industry. They are easiest made with thin walled tubes.

PUMP TYPES AND PUMP SELECTION

No pump - no membrane filtration - its as simple as that. Fortunately, there are many pumps available. Unfortunately, only a few designs are suitable in membrane filtration.

Pumps are the weak point in a membrane system, and pumps simply cannot be too good. The following types are used in membrane filtration systems:

- Single-stage centrifugal pump
- Multi-stage centrifugal pump
- Piston pump
- Diaphragm pump
- Mohno-type pump (rarely used)

Membrane systems are intended to operate continuously 24 hours per day, 365 days per year, and the pump quality must match this requirement. The operating conditions of a membrane system are often considered unusual from a pump manufacturer's point-of-view since flow and pressure can vary considerably and they are rarely at the design point.

Ordinary centrifugal pumps (3,000/3,600 rpm) with closed impellers are used almost exclusively. Centrifugal pumps designed for the dairy industry are particularly useful because they have very "flat" characteristics, which is an advantage when they are used as recirculation pumps.

Positive displacement pumps should be avoided if not strictly necessary. They are expensive and heavy, but most of all they vibrate and cause pulsation in the pipe system. A safety valve is needed to prevent damage to the pipe system and the membranes. The alternative is to use centrifugal pumps, which is easily done in larger systems. Centrifugal pumps for low flow and high pressure are hard to come by, so positive displacement pumps are needed for small RO systems. The author is aware that there are a number of plants driven by positive displacement pumps, however, this does not change the general suggestion to avoid these pumps.

The pumps used for recirculation deserve special attention. The main problem is that although the pressure increase generated by the pumps is small, e.g. 2 bar, the pressure in the feed line may be as high as 40 bar, so the recirculation pump casing must be very sturdy and the mechanical seal must be of special design. The pump bearings which take the axial load must also be very strong. Such pumps are not easy to find and they are expensive. There are five companies in Europe dominating this market. They are APV-Pasilac, Stamp, Grundfos, Alfa Laval LKM and KSB.

PUMP TYPES AND PUMP SELECTION

PUMP TYPES

Definitions	
Low Speed	anything below 3600 rpm
High Speed	anything above 3600 rpm

CENTRIFUGAL, SINGLE-STAGE

LOW SPEED

Low speed pumps are very widely used, meaning 3000 rpm by 50 Hz and 3600 rpm by 60 Hz. Lower RPM is also used, but the investment tends to increase. Low speed pumps are mainly used for large volumes.

In the case of a volumetric flow well over 100 m³/h, it may be worth while to consider 1500 rpm/1800 rpm pumps. A few pumps operate at 1000 rpm (in Europe), and their main advantage is very high energy efficiency. These large pumps are used in the sugar industry, pumping 6000 m³/h, and the capital needed is paid back in low energy consumption.

It is most common to use closed impellers which provide the most gentle treatment of the product and increase efficiency. Open impellers are rarely used in pumps for a membrane filtration plant.

HIGH SPEED

High speed pumps are mainly used in sea water desalination. Several different types of pumps are on the market.

Sunstrand (USA) has sold single-stage centrifugal pumps operating at up to 30,000 rpm for years. That means that in one stage they can deliver 70 bar or more. The energy efficiency of the smaller pumps tends to be poor, although better than one may expect. The larger pumps operate at a reasonable efficiency. The real advantage is a very small pump housing. One problem is the complicated gear box needed and the high noise level. These days they have severe competition from more efficient multi-stage pumps.

EnviroTech (USA) sells a peculiar pump, Roto Jet, where the whole high pressure side is static. A drum with water is rotating fast and the velocity energy of the liquid is transformed into pressure energy in a Pitot tube sticking into the liquid at the periphery of the drum where the speed is highest. The pump design makes it possible to see the Pitot tube where the pressure is generated. It is a very unusual design.

PUMP TYPES AND PUMP SELECTION

CENTRIFUGAL, MULTI-STAGE

LOW SPEED

Multi-stage centrifugal pumps are used in quantity. There seems to be an industry standard dictating a maximum of 26 bar discharge pressure. It is easy to obtain pumps below 26 bar, but troublesome to get pumps rated at over 26 bar.

Grundfos (Denmark) is a market leader in Europe for flows of up to 50m³ and pressures below 26 bar. They are under severe competition from several other pump producers who want a share of the market. These pumps usually operate year after year without maintenance. Standing still is just about the worst condition for them; for one thing, they can freeze, and that is destructive.

Tonkaflo (USA) produces pumps designed for RO. Tonkaflo is not well known in Europe; they compete head-on with Grundfos. Tonkaflo pumps can deliver up to 40 bar, but they sell best for high pressures over 26 bar.

KSB (Germany) produces a vast array of pumps, almost all industrial. They produce very interesting large, industrial multi-stage centrifugal pumps which are capable of delivering several hundred cubic meters per hour of water at very high pressure.

Sulzer (Switzerland) makes similar pumps as KSB, but they are not so well known.

HIGH SPEED

Grundfos (Denmark) has produced multi-stage centrifugal pumps operating at 5000 - 6000 rpm. These pumps can produce 70 bar with a few stages. The speed is achieved by a flat belt drive. These pumps are often driven by a Pelton turbine, which again is driven by RO concentrate (energy recovery).

POSITIVE DISPLACEMENT PUMPS

These pumps deliver an almost constant flow, regardless of the pressure. There are of course practical limits. There are several type of pumps, and some are - so to speak - more positive than others.

Piston pumps. A pump with one or more pistons is the original type of piston pump. There are numerous pump suppliers in the market making small, three piston pumps, but only few of them produce pumps suitably designed for membrane systems.

PUMP TYPES AND PUMP SELECTION

The homogenizer pump is a very expensive and also a very robust pump. The main application is milk homogenizing and treatment of other products containing fat.

Diaphragm pumps are almost as good as the homogenizer pumps. However, they tend to be even more expensive, with one exception. Diaphragm pumps are mostly used for quite low flows and high pressures.

All positive pumps cause pulsation in the pipe system. Pulsation dampeners are commonly installed and they help, at least as long as they function well. No matter what is done there will always be some pulsation, and that tends to cause tubes to break and causes minor problems with loose nuts and bolts in the long run. For laboratory test work, positive displacement pumps are difficult to avoid. In most industrial systems, they can be avoided.

RECIRCULATION PUMPS FOR RO SYSTEMS

Multi-stage RO and NF systems with recirculation in each loop need specially designed pumps. The challenge is that the feed pressure to the pump can easily be 40 bar, and in rare cases up to 64 bar. Two types of pumps are used:

1. One stage centrifugal pumps
2. Bore hole pumps (multi-stage centrifugal pumps with submerged motors.)

ONE STAGE CENTRIFUGAL PUMPS

Ordinary single stage pumps have been used to recirculate water in high pressure boiler systems for years. The pumps differ from ordinary pumps in three construction details:

- a. The pump casing is thick and designed for high pressure.
- b. The bearings taking the axial load are stronger than normal.
- c. The mechanical seal must be of special construction.

All these details are well known and can be handled; this type of pump is still preferred over the bore hole pump. The only known draw back is the price for the pump and the price for a replacement mechanical seal.

A big advantage is that many pumps available in this niche market are sanitary.

PUMP TYPES AND PUMP SELECTION

BORE HOLE PUMPS

The main advantages to bore hole pumps are:

- a. They can operate at very high in-line pressure.
- b. They are very quiet.
- c. The price tends to be relatively low.
- d. They are standard pumps.

The main disadvantages to bore hole pumps are:

- a. Limited operating temperature; typically a maximum of 50°C.
- b. Little tolerance to viscosity.
- c. The large number of gaskets between stages are vulnerable to burning out when operating on solutions containing sugar or any sticky substance.
- d. It is quite difficult to determine if it rotates the correct way.
- e. Special surveillance of motor temperature and ampere consumption is needed.
- f. The electric cables are a concern and they may cause a pump failure.

The bore hole pumps are designed to work on cold drinking water in a bore hole deep under the ground, and they are very well suited for that. They can be placed about 200 meters below the surface and will pump water year after year. The pressure on the pump discharge port is more than 20 bar.

However, it is an illusion to think that the pressure on the suction side of the pump is high; it is rarely more than a few psi. This fact explains the numerous problems experienced in the early days using bore hole pumps as recirculation pumps.

PUMP FLOW AND PUMP PRESSURE

Many people have problems understanding the relationship between the pressure and the flow coming from a pump. The following will address some aspects of this issue.

The primary objective of a pump is to move liquid, and it does not as such generate pressure. Pressure is created when a restriction in the discharge line is introduced, such as a valve. The various types of pumps have different abilities in overcoming such restrictions, and they react differently to the introduction of a restriction.

In Figure 4 the so-called pump characteristics of three pumps are shown: a single-stage centrifugal pump, a multi-stage centrifugal pump and a piston pump. The following can be discerned from the curves:

PUMP TYPES AND PUMP SELECTION

Table 20. Pump Characteristics. Overview

Pump type	Pressure	Flow
Centrifugal single-stage	There is a maximum pressure, where flow is zero. Pressure can vary from P_{max} to almost zero. P_{max} is typically <10 bar.	The flow can vary from nil to a large figure. The limit is set by the maximum motor power, the inlet port and the outlet port.
Centrifugal multi-stage	There is a maximum pressure, where flow is zero. Pressure can vary from P_{max} to zero. P_{max} is typically <26 bar, but it can be 70 bar.	The flow can vary from nil to the max design flow. A typical flow range is from $FLOW_{max}$ to one third that value. $FLOW_{max}$ is set by the maximum motor power and internal restrictions in the pump.
Piston	Pressure is in principle unlimited. The limit is set by the motor and the physical strength of the pump housing and the piping.	Flow is almost constant.

REGULATION OF PUMPS IN MEMBRANE SYSTEMS

THROTTLING VALVE

The simple way to restrict flow and/or pressure is to use a throttling valve. This method can be used on centrifugal pumps, but not on positive displacement pumps. Simplicity is the only advantage. However, there are several disadvantages:

- a. Noise. Dissipating energy usually creates a lot of noise which can be so severe that an operator can not work in the same room as the plant.
- b. Shear force and cavitation. The shear force can damage sensitive products like proteins. Cavitation can eat away a valve surprisingly quickly.

Sometimes it is suggested to bypass liquid from the discharge side to the suction side of a pump to regulate pressure and/or flow. The author DOES NOT suggest this practice; it is an inherently unstable way to regulate pressure and/or flow.

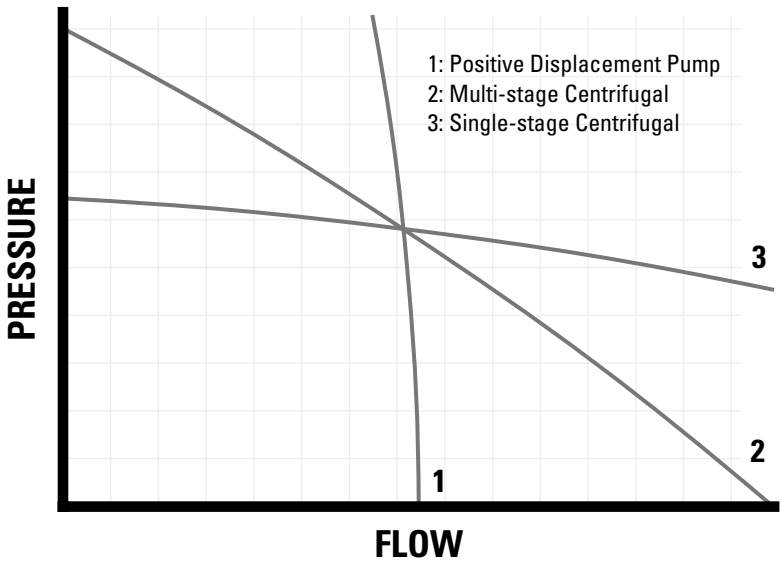
FREQUENCY CONVERTER

A frequency converter is the modern and very effective way to regulate a pump. There is no waste of energy, no noise and no shear forces - only the capital expense to buy the converter. A frequency converter can be used on all types of pumps.

PUMP TYPES AND PUMP SELECTION

The price of frequency converters is dropping fast, partly because the number of users has reached “critical mass”, and partly due to the advance of electronics. The electronic components have become so small and inexpensive that frequency converters are being factory installed in smaller pump motors as standard, which means that they will become standard for bigger motors, too.

Figure 4. Typical Pump Curves



The energy savings from using a frequency converter can be substantial. If 2 kWh are saved, that corresponds to >16000 kWh in one year, which again corresponds to US\$ 1000 (price valid in Northern Europe).

MATERIAL OF CONSTRUCTION FOR PUMPS

There is a very simple rule to follow: Only use pumps whose liquid contact parts are made of stainless steel (or better), or a robust polymer.

Do not ever use a pump constructed from cast iron or bronze. These materials do not last, and they create endless problems from corrosion, which cause membrane problems long before there are problems with the pump.

SELECTED PUMP MANUFACTURERS

Table 21 (page 46) is a very incomplete list in the sense that it only represents pumps known to the author. It also represents the major pumps

PUMP TYPES AND PUMP SELECTION

sold in Northern Europe. All pumps listed are used in membrane filtration systems. Two are listed because they use highly unconventional technology. The author is very much aware that there are many good pumps not mentioned.

PUMP MANUFACTURERS WITH MEMBRANE EXPERIENCE

APV Fluid Handling, Denmark, and **Alfa Laval LKM**, Denmark, have supplied stainless steel, sanitary pumps to the dairy industry and to membrane filtration systems for years. They manufacture and sell several types of well suited pumps:

Low pressure pumps

Single-stage centrifugal. Pressure increase #5 bar. The W-pump series is very robust and durable. In the standard version they tolerate up to 15 bar feed pressure, and they are available in a special version tolerating up to 40 bar feed pressure.

High pressure pumps

Multi-stage centrifugal. Special pumps for RO have been developed providing approximately 15 bar pressure per pump. Two or three pumps in series are required to provide sufficient pressure for RO operation.

Homogenizer type piston pumps (Rannie). A very good, very expensive sanitary pump. It is prone to vibrations and cannot be recommended if a centrifugal type pump can be used.

Stamp is a German pump manufacturer. Stamp can supply sanitary pumps for high pressure systems, and in the author's opinion, Stamp is considered a company making reasonably priced high quality pumps.

Alfa Laval LKM has the same range of pumps as APV.

Hilge is a German pump manufacturer, supplying sanitary pumps. Hilge pumps are especially suited for very high volumes as well as for low volumes.

Tonkaflo is an American company making multi-stage pumps for high pressure and relatively low flow. Although the pumps from Tonkaflo are not well known in Europe, they are widely used in the USA for RO systems. Tonkaflo pumps and Grundfos pumps can often do the same job. An advantage of Tonkaflo pumps is that they can deliver pressures well above that of the Grundfos' CRN series.

Grundfos is a Danish manufacturer of high quality pumps designed for water. In reality, Grundfos pumps are used for a multitude of different types of waste water, too. All parts that come into contact with the liquid are stainless steel in a Grundfos CRN type multi-stage centrifugal pumps. The

PUMP TYPES AND PUMP SELECTION

CRN type covers the range of up to 60,000 lph from 2 to 26 bar, and under certain conditions up to 70 bar. Grundfos pumps are generally not well suited for low pressure and high volume. The BM-type pumps tolerate high feed pressure, their main disadvantage is limited temperature tolerance. Grundfos pumps are considered to be of high quality and relatively inexpensive.

Table 21. Selected Pump Manufacturers

	Single-stage centrifugal pump, max 3600 rpm, max 16 bar feed pressure							Other type of pump
	↓	↓	↓	↓	↓	↓	↓	
	Single-stage centrifugal pump, max 3600 rpm, max 40 bar feed pressure							
	Single-stage centrifugal pump, more than 3600 rpm							
	Multi-stage centrifugal pump, max 3600 rpm							
	Multi-stage centrifugal pump, more than 3600 rpm							
	Piston pump							
	Diaphragm pump							
	Other type of pump							
Alfa Laval LKM	✓	✓		✓				Dairy pump
APV Horsens	✓	✓		✓				Dairy pump
Grundfos				✓	✓			Industrial and water
Hilge	✓							Dairy pump
RotoJet			✓					Industrial, up to 160 bar
KSB	✓	✓		✓				Industrial, also large flow
Lewa						✓		Industrial, very high pressure
Mohno							✓	Tolerates suspended solids
Tonkaflo				✓				Water
Rannie Gaulin						✓		Homogenizer pump (dairy pump)
Stamp	✓	✓		✓				Dairy pump
Sunstrand			✓					High flow and pressure; water
Wanner							✓	Industrial, small flow
Speck						✓		Low flow, industrial, water

PUMP TYPES AND PUMP SELECTION

KSB is a German manufacturer of robust, norm pumps for industrial purposes.

Single-stage centrifugal pumps are used world wide for pressures up to 15 bar. They are very good, and expensive. This type of pump is mostly used when demanded by the end user.

Multi-stage, high pressure centrifugal pumps are mostly used for boiler feed water. They are extremely durable, and quite expensive.

They are rarely chosen based on price, but they are extraordinarily durable.

Wanner is an American manufacturer of small, reliable membrane pumps which cover the range of up to 4,000 lph and up to 60 bar. The Wanner pump is non-sanitary, but is considered to be one of the best, non-dairy, high pressure pumps.

There are numerous other pump suppliers in the market, but only a few of them produce pumps of suitable design for membrane systems. Particular care should be taken in the case of small, three piston pumps. It is tempting to choose an inexpensive pump of this type, but only a few are designed for continuous operation, and most of them are very noisy. Most types also have an inherent problem regarding the lack of a secure barrier between oil and product.

SELECTING THE RIGHT PUMP

Selecting the right type of pump is not always easy. The following should be considered a very crude guideline valid for membrane filtration systems only. The pressure mentioned is the pressure difference between inlet and outlet, unless otherwise described.

WHERE NOT TO USE CENTRIFUGAL PUMPS.

Shear sensitive products. The best example is egg white for which a slow moving piston pump is used.

Highly viscous products. It is traditional to use the Mohno type of pump, but that may not be the best since very special centrifugal pumps are available. Only when special control loops are built will the Mohno type possibly be necessary.

Table 22. Simple Pump Selection Guide

Up to 10 bar pressure increase	Single-stage centrifugal pump
Up to 26 bar pressure increase	Multi-stage centrifugal pump
Above 26 bar pressure increase	Multi-stage centrifugal pump or positive displacement pump

PUMP TYPES AND PUMP SELECTION

Table 23. Pump Selection as Function of Flow and Pressure

bar	Piston pump															
	Diaphragm pump												Single-stage centrifugal			
	Multi-stage centrifugal															
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
	70	✓	✓			✓	✓			✓			✓			
40	✓	✓			✓	✓		✓	✓			✓				✓
25	✓	✓		✓	✓	✓		✓	✓			✓				✓
15	✓	✓		✓	✓	✓		✓	✓			✓				✓
5	✓	✓	✓		✓	✓	✓		✓		✓				✓	
	0.5 m ³ /h			2 m ³ /h				10 m ³ /h				>50 m ³ /h				

There is a trend that centrifugal pumps become ever more popular.

Table 24 reflects what is chosen, rather than the capabilities of the pumps as specified by the pump producer. The pressure increase is typically <5 bar.

Table 24. Selection of Recirculation Pump

	Single-stage		Multi-stage	
	Sanitary	Industrial	Industrial	Industrial
Feed pressure	External motor	External motor	External motor	Submerged motor
max. 5 bar	✓	✓	✓	✓
max. 10 bar	✓	✓	✓	✓
max. 16 bar	✓	✗	✓	✓
max. 40 bar	✓	✗	✗	✓

PUMP SELECTION PROGRAMS

Pump manufacturers have begun to provide programs rather than big binders. That does not make the pumps better, but it seems to ensure that it is easier to update the information. It also tends to be easier for the lay user to find a suitable pump.

PUMP TYPES AND PUMP SELECTION

APV Horsens has for several years had a pump program available. The newest version runs under Windows.

KSB has a program available. The small version is quite comprehensive, but it is not so easy to use. The big version is really big and may not be of much use for the end user.

Tonkaflo® also has a program called PumpTools which graphically presents the flow and boost information of each pump family.

There are most certainly more programs available on the market.

THE SEAL BETWEEN THE PRODUCT AND THE WORLD

The homogenizer type pump has water cooled lip seals which is considered sanitary. Their one weakness is that the water supply must never fail. Should that happen, the seal may wear out very fast. The homogenizer type pump has excellent separation between the oil of the crank shaft sump and the product. There are oil lip seals to remove the oil, followed by a water flush of the piston, followed by the lip seal for the product. The construction is not totally safe, but close.

The traditional low-cost tri-piston pump for water has only one set of gaskets between the product and the oil. It works fine as long as the gaskets are perfect. It is claimed that it also works in reality, but the author has a deep mistrust in this design based upon experience. A tiny leak will allow water to get into the oil and vice versa. This experience may be outdated, but the design is inherently dangerous.

A diaphragm pump is unusual in the sense that it has no traditional seal. The seal is the diaphragm, which is also doing the pumping. It is fine as long as the diaphragm does not break. This type of pump is only used for small volumes and for high pressures. The pumps are, all-in-all, working quite well.

Centrifugal pumps can have many different types of seals installed. From experience, it is known that mechanical seals are necessary because stuffed seals simply do not work. Experience also tells us that carbon-steel or carbon-ceramic in most cases works quite well. It is highly recommended to have water flushed (water cooled) seals. It removes what may leak out and it cools the seal. The water flushing is deemed unnecessary by some pump manufacturers, and it must be admitted that the water flushing consumes a lot of water. Still, the author continues to recommend it.

PUMP TYPES AND PUMP SELECTION

FINAL REMARKS ABOUT PUMPS

It is the author's experience that pump selection approaches religion in the sense that there are very strong opinions and strong traditions which are not always backed by technical reasons. The important thing is that the pumps chosen do the job they are supposed to do, and there can be quite a few types and brands of pumps capable of performing a given task.

CHRISTMAS TREE OR MULTI-STAGE PLANT DESIGN

The so-called Christmas tree design is traditionally used in water desalination systems, and just as traditionally, the multi-stage design is used for membrane systems in the food, chemical and pharmaceutical industries.

The multi-stage plant design will always work, while the Christmas tree design only functions well in applications where the flux is constant over long periods of time. The principle of the Christmas tree design is shown in Figure 5 and the principle of the multi-stage system design is shown in Figure 6.

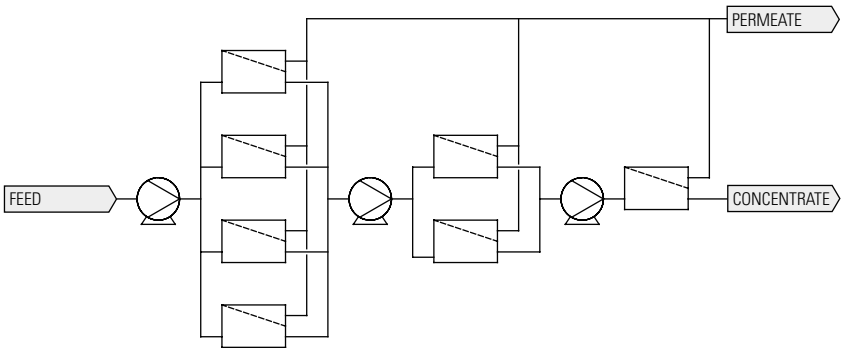


Figure 5. Christmas Tree (single pass) Design

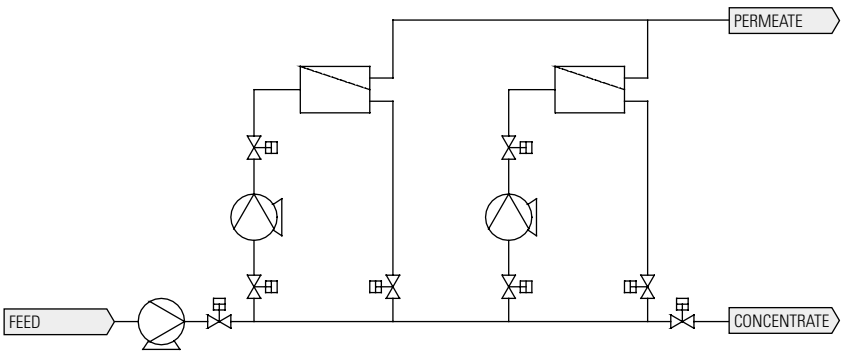


Figure 6. Multi-stage Recirculation Design

CHRISTMAS TREE OR MULTI-STAGE PLANT DESIGN

It will be useful to establish a few simple rules for choosing a system design for a given application:

1. Only use the Christmas tree design for RO and NF. It very rarely works well for UF and MF because (1) flux and pressure are not proportional, and (2) feed pressure, NDP and pressure drop are all of the same order of magnitude.
2. It has been proven that dairy applications only work well when using the multi-stage system design.
3. Pharmaceutical applications tend to work better using the multi-stage system design.
4. Operating in a batch mode, which has not been described here, should not be used for industrial applications, except for very small volumes or when specifically demanded by the end user.

The major advantage of the Christmas tree design is its simplicity. There is only one pump and a minimum of piping. The main problem is that the feed flow chosen often borders on being too low or too high, and any disturbance of the flux will tend to de-stabilize the system.

The Christmas design works best when the membrane area in each loop does not differ widely. In reality, the membrane area in the individual loops may differ by a factor of two or three. If it differs more it is either a very special application, or a design which can be improved.

Enlarging or changing a multi-stage system is relatively un-complicated. It is in most cases possible to add or remove one or more housings in each loop. Further, it is most often possible to add or remove one or more recirculation loops. In other words, a major plant enlargement or change of operating conditions is possible without a major rebuilding of the plant. In contrast, a Christmas tree design is difficult or impossible to modify without a major redesign of the whole system.

The multi-stage design offers several advantages and it is being used more and more, even in water desalination applications. The standard arguments against multi-stage systems are that they are more complicated and more expensive. It is correct that they are more complex, but the price difference is not large.

CHRISTMAS TREE OR MULTI-STAGE PLANT DESIGN

The foregoing can be viewed as the ideal way to build systems. In case of price competition, it may be decided to offer an industrial system which is not technically the best such as the more simple Christmas tree design rather than multi-stage design. The end user may pay penalty for not choosing the best system though, primarily due to lower process reliability and flexibility.

PLANT FUNCTIONS (START, STOP, FLUSH)

A membrane filtration system must be easy to operate during startup, production, shutdown, flushing and cleaning. It is all too easy for an operator to make costly mistakes if a membrane system is not designed, built and equipped to meet the various demands during the different phases of operation. The following pages provide a description of the operational phases in which a membrane system must be able to perform.

STARTUP

The startup phase is the period during which the operational condition of a membrane system changes from idle to production. The startup is difficult to describe in terms that cover all cases. During startup the whole system is pressurized, water is purged from the system, and product replaces water. Startup also includes reaching the correct flow and pressure conditions for the production phase. The rule of thumb “Pressure before Flow” is valid for all systems. It means that the systems shall be properly pressurized before the flow of product is started.

Pressurization is a critical period for most membrane systems. The membrane must be pushed gently but firmly against its support. At the same time, the liquid flow will push a spiral wound element against the end cap of the housing from which it may have strayed during a plant shutdown. Pressurization of a membrane system should always be performed slowly and gently!

The immediate effect of the pressure is that the permeate flux is very high for a short period of time, which can be seen very clearly if flowmeters are installed. After a few seconds, the permeate flux slows down, which is the clear sign that the membrane is firmly pushed against its support. In RO systems it may look different since the permeate side may be filled with air.

Pushing spiral wound elements correctly against the end cap of the housing can be a bit tricky, and the correct use of valves in the system is essential. The movement of the elements cannot be directly observed. An incorrect procedure may damage the elements and the result will clearly be observed when product is introduced into the system.

A surprising error can occur in plants using spiral wound elements. The first rapid permeate flux that occurs upon pressurizing the system can cause a water jet effect so violent that it pushes the elements away from the end cap such that they become disconnected. When the permeate flux stabilizes and the feed flow hits the elements, they are slammed back against the end cap. If lucky, they will seat themselves correctly on the product end adaptor. If not, either inter-connectors or the product end adaptor breaks, or the element does not connect. The result is that product can flow directly into

PLANT FUNCTIONS (START, STOP, FLUSH)

the center tube of the element, which is where the permeate is supposed to collect. The corrective action is to re-install the elements or change them totally.

A correct and gentle startup requires either a well programmed frequency converter or several carefully positioned valves. Frequency converters are relatively new. They are the best but also the most expensive way to avoid problems with pressure or flow shocks. Operating a plant without a frequency converter requires a valve arrangement shown on Figure 7, with one regulation valve after the feed pump and one regulation valve after each booster pump.

Systems with ceramic and fiber membrane configurations can tolerate pressure on the permeate side. All other systems can only under very special conditions tolerate pressure on the permeate side. For fiber systems it is even mandatory to valve off the permeate during startup. For most systems, never exceed 0.5 bar permeate back pressure. The permeate back pressure is usually negligible, but in the case of a tubular system mounted vertically, for instance, a sizeable back pressure from the sheer height of the element (which typically is 3 meters long) can be experienced. This situation produces an average feed pressure of 1.5 bar and an average permeate back pressure of 0.15 bar as described, with 10% of the pressure not available as NDP. There are good reasons to mount long housings horizontally, although it is not absolutely mandatory.

It can be discussed whether to start a system on water or directly with product. Both options are possible. The author favors the start on product, but one must consider what is best from plant to plant and from product to product.

SWITCHING FROM STARTUP TO PRODUCTION

After the system has been started on water, the common procedure is to displace water with product in the feed tank. In this way water is replaced in the system and a gradual buildup of solids takes place.

In RO and NF systems, it is common to bleed a small volume of concentrate off to drain. In UF and MF systems it is more common to close the concentrate valve completely and let the solids build up faster. When it is determined by flux, TS or conductivity readings that the concentrate composition is close to the correct value, it is time to adjust the flow of concentrate by choosing the correct valve setting for the production mode.

Starting a multi-stage membrane system with recirculation loops can be very tricky. The least troublesome procedure is as follows. The last recirculation

PLANT FUNCTIONS (START, STOP, FLUSH)

loop is started first and product is fed into the system. When the flux is approximately correct in the last loop, the second last loop is started. Additional loops are started until the plant is operating at the correct capacity. The stages which were idle at the time of startup may not be necessary until many hours later. In UF systems this actually helps to prevent excessively fast fouling and overloading of the pretreatment system. It also protects the membranes in the system by preventing a surge of HMWC which occurs if the startup of the system is performed by first starting stage 1, then starting stage 2, etc.

PRODUCTION

Production is a steady state condition which is reached after startup. It will not be commented on here.

PRODUCT DISPLACEMENT AFTER PRODUCTION

At the end of the production cycle a surprisingly big part of the concentrated product may still be in the system, especially when the concentration ratio is high. It is essential to recover this, since it represents value and production time, and if discharged it may cause a high BOD load. In systems with refractometer control, recovery of this product is easy. Simply continue feeding water to the system until the solids in the concentrate line drops to a predetermined value, and then either lead the stream to drain or recover the remaining solids.

In systems with ratio control, the ratio setting is maintained when displacement of the product starts. Product displacement continues until the concentrate is too diluted for recovery, for instance after a predetermined time of adding water to the system.

It is often advantageous to use permeate to displace the product in the shutdown phase, because it has the correct temperature and a composition which does not disturb the fresh product. If permeate is not used, temperature controlled, softened water is a good choice.

FLUSHING

After a production cycle, a membrane filtration plant should be flushed with a volume of water about three times larger than the internal volume of the system or, as a rule of thumb, 5 liters of water per m² membrane area. During flushing, the concentrate is led to drain. Usually permeate is also led to drain, but in RO and NF systems the permeate can go back to the feed tank, which is also commonly used for cleaning. A large volume of water is required in a very short time during the flushing cycle. A good size water line is recommended because the water consumption may be as high as

PLANT FUNCTIONS (START, STOP, FLUSH)

1,000 lpm for a few minutes. The sewer line must also be sized to take this flow. See more in section “Water Supply and Drain.”

CLEANING

The cleaning cycle is sometimes referred to as Cleaning In Place (CIP). This is a way of saying that the system does not have to be disassembled in order to perform a thorough chemical cleaning. It is advantageous to have a 100 - 300 liter CIP tank, which can most often also be the product balance tank used during production. This size tank is adequate even when the CIP flow is in the order of 100 m³/h.

Cleaning may be performed sequentially, meaning that a smaller part is cleaned while the rest is still in production. Or, the complete plant can be cleaned at once.

It is most common to clean a complete system. However, sequential cleaning, where only part of the system is cleaned, is used more and more. It is primarily done in larger UF systems. There are several advantages:

- The main advantage is that the system is producing 24 hours per day.
- It offers reduced cleaning costs simply because cleaning a small unit can be done more efficiently than a large system.
- The demand to water supply and drain capacity is reduced.
- The membranes will last longer because they are cleaned only when needed.

The main disadvantage is that it is a capital intensive option. Sequential cleaning is mainly practiced in the pharmaceutical and the pulp and paper industry.

Cleaning of the complete system is the more common design. Both permeate and concentrate is recycled through the CIP tank during cleaning. It is essential that all pipes are designed for the volume of water flow during CIP, which can be up to 10 times higher than during production. In UF systems, and even more pronounced in MF systems, the permeate flow during CIP can be extremely high. Using a design flux of 200 to 300 l/mh is recommended.

It is also highly recommended to use low pressure during CIP. A feed pump pressure of a few bar will almost always be adequate. If a separate CIP-pump is needed, an ordinary, inexpensive single-stage centrifugal pump can be used.

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The cleaning time and chemicals required will be discussed later.

DISINFECTION

Most of the comments provided in the “Cleaning” section are also valid here. A membrane system can be disinfected chemically, which is the traditional way, or it can be disinfected with heat, which for membrane systems is the new approach.

It is important during chemical disinfection that the pressure is high enough to force some disinfecting liquid through the membrane to the permeate side.

Heating and cooling should be ramped during thermal disinfection and the temperature change should not exceed 3°C per minute. Otherwise, membranes and membrane elements may suffer from thermal shock. Great care should be taken when operating at elevated temperature since most polymer materials become soft and can only tolerate limited stress. It is therefore essential to limit NDP, flow and pressure drop at temperatures above 50°C. Observe the maximum temperature specified by the membrane manufacturer. A temperature of 80°C should preferably be reached. Higher temperature is more effective for disinfection but is not really required.

Also see the sections on Pasteurization, Disinfection, and Sterilization.

A simplified flow sheet of systems may appear as shown in Figure 7.

The figures on the next pages show flow conditions during the cycles mentioned above. Note the valves needed to change from one cycle to another.

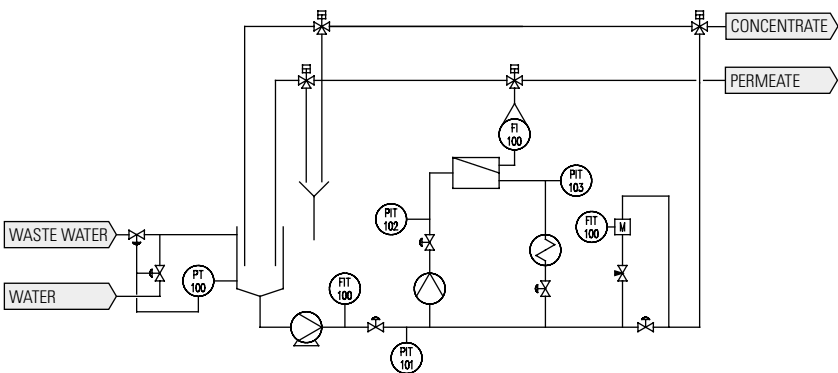


Figure 7. Generalized Multi-stage Design

PLANT FUNCTIONS (START, STOP, FLUSH)

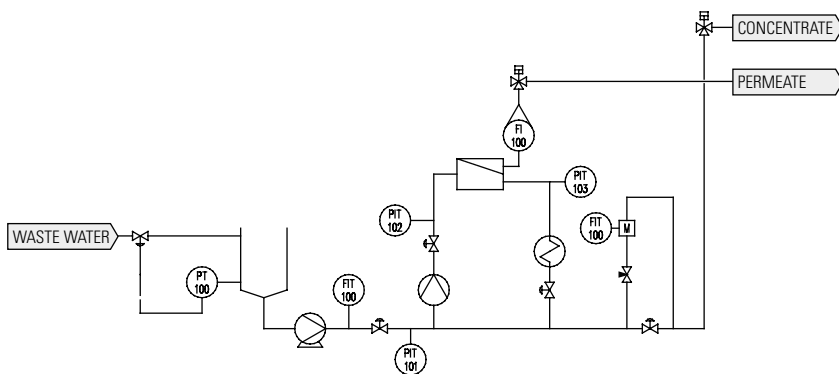


Figure 8. Start RO

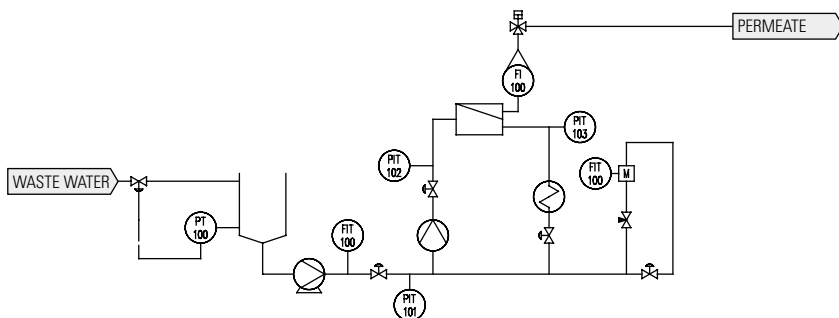


Figure 9. Start UF

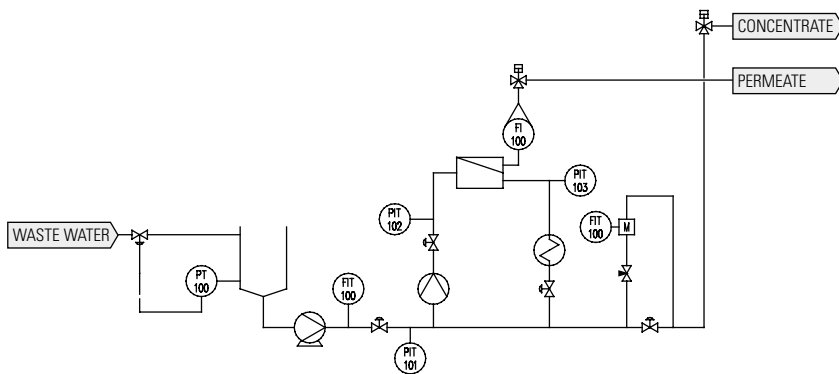


Figure 10. Production

PLANT FUNCTIONS (START, STOP, FLUSH)

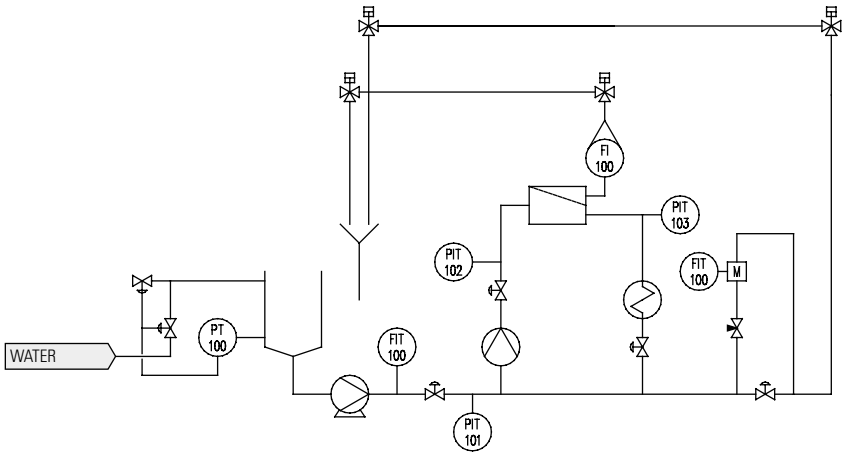


Figure 11. Flush

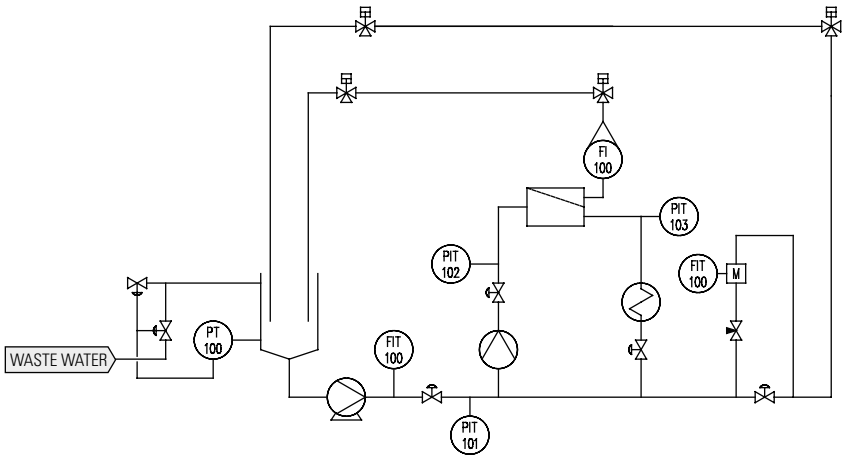


Figure 12. CIP

Pretreatment prior to membrane filtration is extremely important and the nature and thoroughness of the pretreatment is, in many cases, determining the overall plant performance.

Two facts should be kept firmly in mind when deciding pretreatment strategies:

- a. **“Membranes do not lie.”** This means that membranes do exactly what they are able to do under the given circumstances. If the membrane and the raw feed stream are not compatible and the membrane does not perform to expectations, then it is not a fault or deficiency of the membrane.
- b. **“Membranes are designed to reject dissolved solids.”** Most membrane systems work very poorly if the feed contains a substantial amount of suspended solids, or if solids precipitate during the process of membrane filtration. A main objective of the pretreatment is therefore to ensure that the feed does not contain disturbing amounts of suspended solids or species which may precipitate, for instance due to an increase in concentration during the process.

The author does by no means claim to give more than an introduction to pretreatment. One will not find engineering details; the objective is to simply point out a number of things which may be troublesome rather than be intended as a “cookbook” for pretreatment. It is the plant producer or plant operator who must ensure that pretreatment is performed thoroughly, correctly and according to the guidelines of this book.

The following four pages provide an overview of various pretreatment methods, and they are followed by ten pages where several specific products and their problems are described.

All good principles for pretreatment of the feed to membrane filtration equipment can be condensed into three rules of which rule number 3 applies to pretreatment as well as operation of the plant. If these rules are followed, the chances for good plant performance improve dramatically.

- Remove harmful suspended solids
- Remove oxidizers
- Prevent precipitation in the plant

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Pretreatment strategies may have widely varying purposes, and sometimes they are aimed toward completely opposing goals. See Table 25.

Increasing solubility	pH, temperature, complexing
Decreasing solubility (causes crystallization)	Controlled crystallization to produce micro crystals, e.g. by heat-and-hold
Retard crystallization	Using an anti-scaling agent
Removing solutes with low solubility	Using ion exchange media, e.g. Ca - Na exchange
Removing suspended solids	Applying filters, centrifuges/decanter, precipitation, sedimentation, flotation
Removing organic solvents	Distillation
Reduction of heavy metals Oxidizing of heavy metals	$\text{Cr}^{+6} \rightarrow \text{Cr}^{+3}$ $\text{Fe}^{+2} \rightarrow \text{Fe}^{+3}$ followed by precipitation as hydroxide
Killing microorganisms	Pasteurization, sterilization and chemical treatment. Whenever possible remove the dead microorganisms
Secure high concentration of one strain of microorganism	Fermentation of egg white
Removing dissolved organic solids prior to reverse osmosis	Use nanofiltration or ultrafiltration, e.g. to remove humic acid or dissolved mineral oil

Suspended solids in the feed is a very difficult problem to handle, and conventional filtration is by far the most common pretreatment method. Centrifugation is used to some extent, foremost in the dairy industry.

Microorganisms present a special problem. Regardless of whether they are dead or alive, they can foul membranes. Alive, the fouling can be caused by the microorganism itself, by its metabolic products or by its interaction with material in the feed solution. Dead, the cell debris, mainly the cellular membrane, can cause fouling. Removing cell debris and metabolites from a feed stream can be surprisingly difficult, and the various materials from the cell are often very resistant to oxidizing and high-pH environments.

Tables 28 and 29 present an overview of the most common methods used in pretreatment. Although the array of pretreatment methods is quite impressive, the number of methods commonly used is small. Therefore, if

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one needs to pretreat a product not mentioned here, there is a good chance that one can use the same pretreatment for similar products listed in the table. Although the information in this section is organized by industry, it could have just as well been listed according to product type.

Examples

Protein: Cheese whey, milk (cow, goat, horse, buffalo), soy protein, pea protein, enzymes, egg white, blood plasma, fish stick water and gelatin

Polysaccharide: Carrageenan, pectin, agar, guar gum, xantan

Fruit juice: Apple juice, pear juice, pineapple juice

The demand to prefiltration varies a lot. Tubular membranes are tolerant of particles in feed, but all other systems need filtration of the feed. Table 26 provides some guidelines:

Table 26. Prefiltration Demands		
	Flow channel	(See also Table 11)
Tubular systems	1 inch	Filtering in mm-size
Tubular systems	0.5 inch	Around 0.5 mm will be adequate
Fiber systems	<2 mm	100 micron or better is necessary
Plate systems	<1 mm	50 micron or better is necessary
Spiral wound element	90 mil	100 micron or better is necessary
Spiral wound element	47 mil	50 micron or better is necessary
Spiral wound element	30 mil	10 micron or better is necessary
Hollow fine fiber systems	undefined	Extremely sensitive UF or NF of the feed is recommended

Table 27 presents an overview of the most common materials found on the surface of membranes.

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Table 27. Materials Interfering with Membranes

Interfering Materials	In-organic	Organic	Biomass	Fibers
Acid	X			
Algae			X	
Aluminum hydroxide (Al(OH) ₃)	X			
Aluminum oxide (Al ₂ O ₃)	X			
Bacteria			X	
Barium sulphate (BaSO ₄)	X			
Calcium carbonate (CaCO ₃)	X			
Calcium phosphate (CaHPO ₄)	X			
Cations		X		
Chalaza		X		
Chromium+3 (Cr(OH) ₃)	X			
Dyeing, polyamide, polyester, cotton		X		X
Fat		X		
Fibers (textile)		X		X
Filter aid	X			
Fines (fruit, cheese, casein, etc)		X		X
Flocculating agents		X		
Grass			X	X
Grease		X		
Hair			X	X
Humic acid		X		
Iron hydroxide (Fe(OH) ₃)	X			
Latex		X		
Magnesium carbonate (MgCO ₃)	X			
Manganese (Mn(OH) ₂)	X			
Medium density fiberboard effluent		X		X
Metal filings	X			

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Table 27. Materials Interfering with Membranes (continued)

Interfering Materials	In-organic	Organic	Biomass	Fibers
Oil		X		
Paint		X		
Paper machine effluent	X	X		X
Protein		X		
Pulping effluents	X	X		X
Sand, Silica (SiO ₂)	X			
Silicon oil	X			
Silt	X			
Solvents		X		
Strontium sulphate (SrSO ₄)	X			
Yeast			X	

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Table 28. Pretreatment Methods – 1

	Physical	Chemical	Thermal	Electrochemical
Centrifuge/decanter	X			
Complexing		X		
Dissolved air flotation	X			
Electro flocculation		X		X
Filter	X			
Flocculation		X		
Heat-and-Hold	X		X	
Membranes (UF, NF, MF)	X			
Ozone, Cl ₂		X		
Pasteurization			X	
pH		X		
Sedimentation	X			
Distillation	X			
Temperature change			X	
UV				X

The term FILTER means several different types of filters. Traditionally, they are dead end filters, but cross flow filters exist too. The most common types of filters used in connection with membrane filtration systems are cartridge filters, bag filters, sand filters, moving band filters and precoat filters.

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Table 29. Pretreatment Methods – 2

	Dairy	Food	Waste Water	Drinking Water	Process Water
Centrifuge/decanter	X	X			X
Complexing				X	
Dissolved air flotation			X		X
Electro flocculation			X		
Filter	X	X	X	X	X
Flocculation			X		
Heat-and-Hold	X				
Membranes (UF, NF, MF)				X	X
Ozone, Cl ₂				X	
Pasteurization	X	X			
pH	X	X			
Sedimentation			X		
Distillation		X			X
Temperature change	X	X	X		X
UV				X	
UV + H ₂ O ₂			X		

ALGAE, BACTERIA, YEAST, VIRA

As a general rule, the count should be less than 100 per ml. However, sometimes as little as 10 per ml can be problematic while at the same time sometimes 108 per ml does not represent a problem. An experienced application engineer should be consulted because experience and experiments are the only reliable means to select adequate pretreatment.

Heat treatment or chlorination followed by conventional filtration are methods that are used with some success.

BIOFOULING

Biofouling is a term used to describe deposits of microbes, bacteria, yeast, cell debris or metabolic products. Biofouling is far from well defined, but however it is defined, general experience bears out that it is usually difficult to remove. The success of pretreatment is limited to ensuring that the feed

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product has a very low cell count, and that the membrane filtration equipment is operated at a bacteriologically safe temperature.

There are several pretreatment strategies which will achieve the goal of inhibiting or arresting microbial growth for as long as the treatment is ongoing, but they leave the liquid open to continued bacterial growth once the treatment stops. However, there are two exceptions to this occurrence:

1. Addition of harsh chemicals such as hypochlorite in concentrations which leave an excess of the chemical in the feed to ensure continued growth prevention.
2. Heating and operating at 75°C or higher. This strategy is generally not used at this time except for a few systems producing high purity water, treating pulp and paper effluent and treating evaporator condensate.

BLOOD PLASMA

Blood is a by-product from every slaughterhouse. In some cases it is simply discharged to the sewage system. In other cases it is collected, mixed with other waste and dried at very high temperature. There is a small market for good quality blood products.

Blood does not coagulate if there is little or no calcium available, and coagulation of blood can be prevented by addition of a complexing agent for calcium. It is most common to add sodium citrate, but sodium phosphate is also used. Addition of citrate and phosphate is essential pretreatment if membranes shall be used to treat blood. The blood should be drawn in a way which secures that there is no contamination. Citrate or phosphate must be added immediately during blood drawing, and the blood should be processed immediately.

Whole blood is difficult to treat with membranes. It is common to remove the red blood cells from whole blood by centrifugation. It is essential that the centrifugation process be relatively gentle in order to prevent cell rupture. Cell rupture releases hemoglobin into the plasma and complicates the membrane filtration process, and complicates the subsequent cleaning of the equipment. The quality of blood plasma is considered to be low if there is too much color from hemoglobin.

CARRAGEENAN

This product is extracted from seaweed at very high pH and contains a high level of suspended solids.

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It is common and mandatory to perform prefiltration, most often with precoat filters prior to ultrafiltration. The prefiltration step removes a certain amount of protein and color together with suspended solids. The use of filter aid, kieselguhr, makes the use of a security filter before the UF system mandatory. If a breakthrough of filter aid occurs, the security filter will be blocked which is preferable to blockage of the membrane filtration equipment.

The filters normally used have a nominal pore size of 200 μ . In reality, the resulting filtration is even better because the filter rapidly blocks up. This result is still a far cry from the 5 or 10 μ demanded in water treatment, but for several reasons it is not realistic or necessary to demand a better prefiltration:

- It is technically almost impossible to perform a better filtration.
- It has been used for years in the industry.
- The flow channel provided by a 90 mil parallel feed spacer corresponds to 2,200 μ , which is 10 times the particle size.

The pre-filtered liquor is close to 14 pH, which is normally adjusted to 8 pH with acetic acid. Without pH adjustment prior to ultrafiltration the membrane life is shortened since membranes tend to become brittle at very high pH. This is aggravated by the fact that the operating temperature is higher than 80°C.

The viscosity of carrageenan is so high that it may be necessary to heat the product to an even higher temperature as a type of pretreatment.

CATIONS

This group of materials (e.g. cationic detergents) are in many cases detrimental to the membrane flux which can drop significantly, sometimes to zero.

The only pretreatment possible is to add enough anionic chemicals to neutralize the cationic materials. This can often be accomplished by adding simple detergents, e.g. lauryl sulfonic acid, which is a common and relatively inexpensive product.

CIP LIQUIDS

CIP liquids represent a special problem in connection with membrane filtration because their composition is not well defined. CIP stands for

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Cleaning-In-Place which is a common procedure for cleaning of processing equipment in food and dairy plants.

The only pretreatment possible is to clarify the liquid, which can be done by many types of filters. Cartridge filters are most commonly used. They are effective but also rather expensive since the cartridges cannot be reused. Another relatively efficient method is to clarify in a centrifuge. This type of equipment is normally used for fat removal from milk, but it will clarify CIP liquids efficiently. Since centrifuges are being used in most food and dairy plants, the availability of this type of equipment does not represent a problem.

COLOR SUBSTANCES

Many naturally occurring or artificial dye stuffs in food products may present problems in connection with membrane filtration, with the naturally occurring colored substances being the most troublesome. The more water soluble a dye stuff is, the less likely is it to cause problems.

It is rarely possible to perform a pretreatment which removes the color since color in most cases forms an important characteristic of the product, for instance the red color of red wine. In the case of waste water treatment from food processing, flocculation has achieved some success in cases where color can be removed without detriment to the product quality, but it is very tricky because the flocculation agent itself may foul the membrane. The best strategy for flocculation is to apply a slight deficit of flocculation agent, leaving a slight amount of color in the product. This will, in most cases, ensure that the product contains no unused flocculation agent, that the permeate has sufficient quality, and that dye precipitation causes only minimal problems.

Color substances are found in numerous foods and food related products, such as waste water from processing peas and carrots, thin juice from sugar production, coffee, fruit juice, beer and wine. Some other troublesome color substances are naturally occurring fulvic and humic acid. All of these color substances have low solubility in water and a pronounced tendency to precipitate on membranes. They have one chemical feature in common, namely one or more benzene rings in their molecular structure, making polysulfone membranes extremely susceptible to fouling. This is because polysulfone contains numerous aromatic rings, which tend to form chemical bonds leading to severe and sometimes often irreversible fouling. Cellulosic, PVDF and other non-aromatic polymers are preferred as membrane materials for these applications.

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There is no such thing as a good, generally accepted pretreatment for removal of color substances. It is a problem one has to learn to live with.

TEXTILE DYEING EFFLUENT

REACTIVE DYEING, DYEING OF POLYAMIDE AND POLYESTER

Dyeing of cotton is the largest dyeing process in the world. Close to 50% of all dyeing is performed with reactive dyes on cotton. Adding dyeing of polyamide and polyester materials to cotton dyeing covers most dyeing operations in the world.

Pretreatment is simple: filter to remove fibers. Usually a conventional 10 to 20 μ filter cloth is sufficient. It seems that enzymatic treatment, e.g. so called stone washing done with enzymes, results in fibers and fiber fragments considerably smaller than usually experienced; even 1 μ filters seem to pass small fibers. In that case, either an extraordinary effort with conventional filters is needed, or the use of inexpensive tubular ultrafiltration membranes is required.

It is a good idea to separate the effluent from the various dyeing baths and other process streams in a textile dyeing operation. This will avoid problems in the treatment of an aggregate stream.

No other pretreatment than filtration is required before the normally used nanofiltration and reverse osmosis membranes.

WASHING WATER

The same comments as above. The main difference is that the membrane process is ultrafiltration, since the waste water can contain oil. A surplus of detergent is needed to emulsify the oil.

EGG PRODUCTS

Chalaza is the two white strings extending from the egg yolk to the opposite ends of the lining membrane of the egg. Membrane filtration is used to de-water egg white, and the chalaza needs to be removed before entering the membrane system. This can be accomplished by conventional filtration, but it is not easy. Chalaza has a spring like character, which means that it may pass through a filter only to curl up again immediately. Therefore, filtration must be performed at a low pressure differential in order not to force the chalaza through.

It is impossible to prevent all chalaza from entering a membrane system, and it is extremely difficult to remove by the daily cleaning. Besides the daily

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alkaline cleaning it is common to soak the system during the weekend in a detergent solution with a large dose of a proteolytic enzyme which can digest the chalaza and thus clean the systems thoroughly.

Egg shells are common and can easily be removed by filtration.

Protein denaturation by heat or shear force is a real danger when treating egg white. Shear forces in pumps or valves can quickly denature soluble egg and turn it into insoluble protein which will foul any membrane system. Use slow action homogenizer type pumps and positive displacement pumps to solve the shear problem. This point does not qualify as pretreatment but is included for the sake of completeness.

Viscosity of egg white is known to be problematic in connection with membrane filtration. The viscosity can be reduced (and glucose removed at the same time) by fermentation. The removal of glucose is desirable to avoid Maillard reaction (browning) in subsequent spray drying. The fermentation typically takes 10-20 hours and may, in fact, be performed while a batch reverse osmosis system is running.

Fermented egg contains a lot of microorganisms, and it may seem problematic to use reverse osmosis for de-watering. However, experience reveals that the reverse osmosis process works fine. The idea of simultaneous fermentation and reverse osmosis is unique from the standpoint that microbial growth in membrane filtration equipment normally should be avoided, but in this case the fermentation does not disturb the function of the membranes. On the contrary, it helps to reduce the viscosity of the product, and since the process operates at ambient temperature, the high count of one microbial species helps subdue the growth of all other species.

FIBROUS MATERIAL

All fibrous materials must be removed before most membrane filtration processes. This can usually be accomplished using one of the many conventional filter types available.

Short fibers can be a nuisance and they are difficult to remove. Very short fibers are found in the textile industry and in the pulp and paper industry. The only totally effective method to produce fiber free liquids is ultrafiltration. This is often the last option to be investigated due to price, but the possibility should not be ruled out all together because the price for ultrafiltration has decreased. Ultrafiltration completely eliminates passage of fibrous material without the use of any filter aid.

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FRUIT JUICE

Color as a general problem is mentioned in another section. Fruit juice represents a special challenge because juice is always colored. Since color is an essential part of the product there is little or nothing that can be done about it except to design membrane filtration equipment with low flux, and to use a membrane and membrane material that works and can be cleaned.

Fines is a less complicated problem. Fines can be removed by conventional filtration or by centrifugation. Prefiltration is only problematic from the point-of-view that it must be consistent and effective.

Pectin and cellulose are always present in the juice in varying amounts. It is common practice to add an enzyme, mostly pectinase, to clarify the juice, and pectinase also effectively prevents precipitation during the membrane filtration process.

Pretreatment by adding enzyme is not absolutely necessary to make a membrane system work, but in many cases it will literally double the membrane flux and thereby make the membrane filtration process more economical. There have been attempts to use membrane filtration to replace de-pectination with enzymes, but the idea never succeeded.

LATEX CONTAINING FEEDS

Pretreatment is in principle very simple: remove all latex prior to membrane filtration. But in reality, this is exceedingly difficult. Centrifuges are used in some cases, but they must be totally dismantled every few hours!

Latex will plug up spiral wound elements, thus the use of spiral wound elements is not possible on feeds containing latex. One half inch or one inch tubular membrane filtration systems will, to some extent, tolerate latex.

LAUNDRY WASTE WATER

Fibers are the real problem when membrane filtrating laundry waste water because fibers, dirt and detergent forms large, loose flocks. Conventional filtration with all kinds of filter types is being used. Experience shows that 20-40 micron filters provide sufficiently good prefiltration, but tighter filters will certainly result in a longer membrane lifetime.

Detergents rarely present a problem for membrane filtration because the detergents used in washing are usually anionic. The only real problem is with the products used for fabric softening because they are cationic. The only possible pretreatment is to ensure that this particular water is mixed well with all the other materials used in a laundry operation. This water contains

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a large surplus of anions, which can effectively neutralize the cations.

Oil, grease and solvent can be present in astonishing amounts in industrial laundry waste water. The best pretreatment method is to strip solvents prior to washing. The only pretreatment possible is to ensure that there is a surplus of detergent, thus securing that fat and grease are emulsified. Adding surplus detergent should not be considered a loss since it will improve the performance of the ultrafiltration system, and may be reused since it passes freely into the permeate.

THE METAL WORKING INDUSTRY

Oil emulsions are used in machining, e.g in cutting and milling. Sedimentation followed by conventional filtration is the only possible pretreatment that will provide adequate pretreatment since the metal particles are heavy and precipitate quickly.

Mineral acid is used extensively in mining and surface treatment of many types of metals. Some examples are:

- H_3PO_4 for surface treatment of aluminum
- H_2SO_4 for etching of copper rods and foil
- H_2SO_4 for heap leaching
- $\text{HCl}/\text{HF}/\text{HNO}_3$ for surface treatment of stainless steel
- HCl for cleaning of iron

Conventional filtration is the only pretreatment possible and necessary.

DAIRY INDUSTRY

Hair, grass and flies sound like ridiculous things to mention, but in the dairy industry they can present a very real problem. The flies are easy to remove, but hair is much more difficult to see and to remove. When treating dilute raw milk, hair from the cows as well as hairs from brushes are found in a surprising quantity, and grass is often brought in with the milk. Bag filters, which can be washed and sterilized, are commonly used and probably present the best solution to remove this type of impurity.

Casein fines are present in large quantities in cheese whey. It is common to remove the larger particles with a self-cleaning screen. The remainder of casein fines are usually removed by centrifugation. If the centrifuge is run at a relatively low capacity, the fines content is reduced sufficiently for the whey to be treated in a membrane system. Experience has shown that an RO system with 47 mil spacer can handle the quantity of suspended solids passing a casein sieve, and that a centrifuge is not compulsory.

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Milk fat and phospholipids. Milk contains a natural fat content in the 3.0% to 4.5% range. Membrane systems can handle milk fat, but they operate much better when the fat content is below 0.05%. Milk fat can be skimmed off in a centrifuge, which is a very common piece of equipment in dairy plants. Phospholipids stem from the envelope of the fat globules and are liberated when the envelope is disturbed, for instance by homogenization, pumping or churning. They are troublesome because they stick to the surface of membranes, and they require high pH and temperature to be washed off. There is no known method to remove phospholipids from milk and whey.

Pasteurizing prior to membrane filtration is literally an industry standard. Pasteurizing means heating to 72°C and holding for 15-20 seconds, followed by cooling to the operating temperature. There are very few exceptions to this rule. The objective is to reduce bacteriological activity. At the same time calcium phosphate crystals are made (see the section about calcium phosphate). If pasteurizing is not performed, the capacity tends to be lower, and pH in the product will drop after a few hours of operation due to the formation of lactic acid. The drop of pH can very quickly render the product useless. In spite of 25 years of tradition for pasteurizing, there is now a trend to avoid it in order to reduce investment and running costs. If membrane filtration of non-pasteurized products shall be a success, a very careful analysis of the performance requirements must be conducted.

Calcium phosphate, or rather calcium orthophosphate (CaHPO_4), is present in all dairy products. The solubility of calcium phosphate decreases with increasing temperature. This is troublesome since many dairy processes occur at elevated temperature, and since it is next to impossible to remove the calcium phosphate from milk and cheese whey prior to membrane filtration. Pretreatment can help ensure that the amount of precipitation is acceptable, but it will not prevent the phenomenon.

It is common practice to pasteurize dairy products prior to membrane filtration, which means heating to 72°C and holding for 15-20 seconds, followed by cooling to the operating temperature. If cooling of the product is not done immediately, but rather according to the so called “heat-and-hold” method, whereby the temperature of the product (most often sweet cheese whey) is maintained at 55-60°C for an hour, a surprising amount of micro crystals of calcium phosphate will form and precipitate. Some of the crystals formed can be removed as a sludge. They do not interfere with the membrane process, rather, they may even help to prevent further precipitation on the membranes due to the affinity of the solute to an already formed crystal rather than a material alien to the solute. When concentration takes place in a membrane system, and the concentration of calcium phosphate exceeds the solubility, the already formed crystals will continue to grow, thus stripping excess calcium phosphate from the bulk of the liquid.

PRETREATMENT METHODS AND STRATEGIES

This procedure may be compared with crystal seeding techniques known from many other industries. Although it is not totally effective, it does allow 20 hours of operation between cleaning cycles.

Denaturated protein is problematic in feeds to membrane systems. Slight damage will usually reduce the solubility, and total damage will result in a material with the consistency of a hard boiled egg. Slightly damaged proteins which are still soluble cannot be removed by any pretreatment and will lead to reduced flux and increased fouling. Precipitated proteins are removed fairly easily by conventional filtration.

OXIDIZING ENVIRONMENTS

The tolerance of membranes to oxidizing agents varies widely. Thin-film membranes do not tolerate any oxidizing environment with the notable exception of ClO_2 . Integral membranes of polysulfone (Desal E-, F- and P-series), PVDF (Desal J-series), polyacrylonitrile, and modified polyacrylonitrile (Desal M-series) are very resistant to all kinds of oxidizers.

The general rule for thin film membranes is that all oxidizing substances should be removed before a feed enters the membrane system. In the following, only oxidizing agents as they pertain to thin-film membranes will be discussed.

Chlorine (Cl_2), sodium hypochlorite (NaOCl). If one of these are present, de-chlorination is a necessary pretreatment step. The following methods can be used:

- Addition of a reducing agent, e.g. sodium bisulfite (NaHSO_3), is a commonly used method. A drawback to this method is that sulfate will be formed in the system.
- An activated carbon filter is often used. However, there may be a risk that it may be a source of microbial growth and a potentially severe source of biofouling. Another worry is the disposal of the spent carbon.
- Ultraviolet (UV) light is perhaps the best, but also an expensive, method.

Chlorodioxide (ClO_2) has been reported to be harmless to thin-film membranes, but real life experience is lacking. Chlorodioxide is difficult to handle and difficult to produce in a chlorine free quality. It is rarely used in membrane filtration plants.

PRETREATMENT METHODS AND STRATEGIES

Hydrogen peroxide (H_2O_2), peracetic acid (CH_3CO_2OH). Both are relatively weak oxidizing agents which can be used with care for disinfection of thin-film membranes once a week. If they are present in a feed stream, they must be removed by addition of a reducing agent.

Bromine (Br_2) is similar to chlorine and demands an identical pretreatment.

Iodine (I_2) is similar to chlorine and demands an identical pretreatment.

Nitric acid (HNO_3) can be used for cleaning once a day in moderate concentration ($<<0.5\%$) at room temperature. Higher concentration and/or high temperature is not acceptable. It is highly recommended not to use nitric acid if it can be replaced by an acid which is not oxidizing. Good alternatives are phosphoric acid, hydrochloric acid and citric acid.

Chromate (CrO_4^{2-}), Chromium as Cr^{+6} in a feed stream can be a problem since chromate is a quite strong oxidizing agent. The aggressiveness of chromate is pH dependent and is most aggressive at neutral pH. The life time of a thin-film membrane operating at 7 pH and high chromate concentration can be measured in weeks rather than months. If pH can be lowered to less than 2, most membranes will operate satisfactorily. Another pretreatment method is to reduce Cr^{+6} to Cr^{+3} which is harmless to a thin-film membrane. This strategy, however, renders reuse of the chromate impossible.

PAINT

Paint contains inorganic pigments whereas the paint itself is always organic in nature. Paint commonly contains high molecular weight substances of a very sticky nature. Pigments in paint are not considered to be a problem because they literally look and act like small pebbles which roll over the membrane without sticking to it.

Water based traditional paint generates waste water from the washing of tanks and pipes. The only possible pretreatment is conventional filtration, which can be difficult due to soft and sticky precipitates.

In the opinion of the author, a tubular system is probably the best suited for membrane filtration of water based paint since it demands little prefiltration. A sieve will be adequate and foam ball cleaning is possible. All other systems will need prefiltration to be efficient, which is expensive.

Water based paint precipitated by electricity (electrophoretic paint, ED paint) is used in the automotive industry for the first coat of paint. In the context of membrane filtration, the only pretreatment possible is self cleaning sieves for

PRETREATMENT METHODS AND STRATEGIES

the removal of lumps of paint. Filtration is performed anyway in order to secure a smooth surface. The paint and its pigments can pass through almost any membrane module.

Anionic paint is fairly easy to treat.

Cationic paint can be very difficult to treat.

Cellulose acetate membranes work well on the cationic paint, when the pH is around 5 and the temperature below 30°C

PULPING EFFLUENT

There are a number of different effluents from the pulping industry.

A few are:

CTMP Chemical Thermo Mechanical Pulping

KBE Kraft Bleach Effluent

KBL Kraft Black Liquor

MDF Medium Density Fiberboard

NSSC Neutral Sulphite Semi Chemical

SSL Spent Sulphite Liquor

VBL Vanillin Black Liquor

Cellulose fibers. All types of effluent from the pulp and paper industry contain cellulose fibers. Traditional self cleaning filters can most often provide adequate fiber removal. Drum filters with stainless steel mesh is commonly used. The trend to recycle more and more cellulose fibers results in the increase in the amount of very short fibers. This will eventually mean that more sophisticated pre-filters will be needed, e.g. low cost ultrafiltration systems.

Calcium salts can be a real problem in sulphite pulping. The precipitation of calcium sulfite and sulphate is likely in the liquid and, what is worse, in the membrane structure. There is not sufficient knowledge to evaluate the problem. In a major ultrafiltration system, it was necessary after some time to install a Ca-Na ion exchanger to solve the problem of calcium salt precipitation.

PRETREATMENT METHODS AND STRATEGIES

Pitch (Rosin) is a severe problem in sulphite effluents. The product is very sticky and occurs in large quantities. The author is unaware of any effective pretreatment, but it is possible that flotation can be used.

Ultrafiltration has been used for rosin removal but it is not a common process.

SILICON OIL

This substance is poison for membranes. The only effective pretreatment is not to use silicon oil at all. In most cases, silicon oil can be substituted with products which do not harm membranes, e.g. siloxane.

SOLVENTS AND HYDROCARBONS

Table 30. Water Soluble Organic Solvents	
Alcohols	Harmless
Ketones	Keep concentration well below 1000 ppm
Esters Tetra hydro furan Dimethylsulfoxide Dimethylacetamide N-methyl pyrrolidone	Keep concentration well below 10000 ppm

Table 31. Water Insoluble Organic Solvents/Hydrocarbons	
Aromatic Hydrocarbons	Detrimental to polysulfone membranes Detrimental to polysulfone parts Keep out of RO systems <50 ppm in NF systems Good resistance of Desal-J, Q, Y and M
Aliphatic Hydrocarbons	Keep out of RO systems <50 ppm in NF systems Good resistance of most UF systems

Organic solvents, a very broad category of organic chemicals, may or may not cause damage to membranes, thus it is difficult to provide good guidelines. One safeguard is to remove as much solvent as possible, leaving only a few parts per million in the liquid to be treated. It is necessary to distinguish between water soluble and water insoluble solvents. The water insoluble solvents can be treated as hydrocarbons.

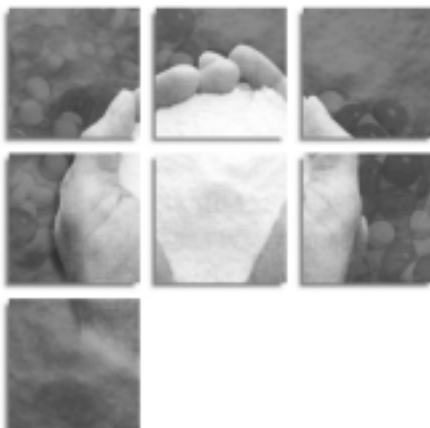
NOTE: Only a few membranes, most notably some Desal membranes, are resistant to organic solvents. A very special element construction is necessary to match the resistance of membrane and support.

PRETREATMENT METHODS AND STRATEGIES

STARCH

Membranes are used in some very large starch manufacturing waste water treatment systems. Pretreatment consists of conventional filtration to remove suspended solids.

Sapponins are a problem in waste water from potato processing which is difficult or impossible to solve with pretreatment. The solution is to clean the membranes frequently.



Potato waste water can begin fermenting very quickly. The only pretreatment, if it can be called pretreatment, is to process the effluent immediately and to design and operate the equipment as if treating a high grade food product. If this rule is not observed, acidification and subsequent protein precipitation will result.

SUSPENDED SOLIDS, SLUDGE

The general rule is to reduce the amount of suspended solids to a few parts per million before membrane filtration. That can be achieved by conventional filtration, sedimentation, flocculation or a combination of these processes.

If the suspended material occurs in the form of small, hard particles, it is usually not problematic.

If the suspended material is fibrous, slimy or in any way bulky, it will usually pose problems for membrane filtration equipment, and must be removed. Unfortunately such products are difficult to remove by pretreatment.

WATER TREATMENT

Hardness is observed as the precipitation of calcium carbonate (CaCO_3), calcium sulfate (CaSO_4) and magnesium sulfate (MgSO_4). It is the most common problem in water treatment, and not only in connection with membranes. It is common to calculate the Langelier index or Stiff & Davis index to evaluate the risk of precipitation, and to then evaluate possible pretreatment options. If the Langelier index is positive the water is considered to be scaling.

PRETREATMENT METHODS AND STRATEGIES

Three methods are generally used to prevent precipitation.

- Acidification
- Softening
- Addition of anti-scaling agents

Acidification is an old and proven process.

Sulphuric acid is inexpensive and effective, and it is the acid of choice for most large scale systems. However, sulphuric acid may cause CaSO_4 precipitation if the calcium content is high. Handling of sulphuric acid requires great care. Using sulphuric acid is much less expensive than dosing anti-scaling agents.

Hydrochloric acid is comparatively expensive. It is corrosive, and it is rarely used to prevent precipitation in connection with water treatment.

Organic acids, such as citric acid, are effective but rarely used.

Carbon dioxide (CO_2) injection is, strangely enough, an effective possibility. But it is rarely used since it is difficult to handle.

Addition of acid may cause the release of CO_2 which renders the permeate very aggressive. It may be necessary to remove CO_2 prior to the reverse osmosis plant, and it is certainly necessary to adjust pH with alkali after the reverse osmosis plant to avoid corrosion in the distribution net.

Softening is a more novel process.

An ion exchange medium swaps calcium with sodium. The result is soft water with an increased content of sodium, which will result in an increased sodium content in the permeate. The process requires large amounts of good quality sodium chloride, and it may be a problem to dispose of the volume of very saline water produced in the regeneration of an ion exchanger.

Anti-scalants are used to control precipitation in water.

The product is added in very small amounts, typically a few parts per million. It works by interfering with the crystallization process and allows a high degree of supersaturation. It is a striking fact that, for instance, barium sulfate at 30 times of saturation still does not precipitate. Anti-scaling agents are expensive and must be dosed correctly. Too little means that precipitation can take place. Too much means a waste of money and a potential danger for flux decline.

PRETREATMENT METHODS AND STRATEGIES

Iron, aluminum and manganese hydroxide must be removed from the feed stream since the hydroxides of these metals have very low solubility, typically 0.05 mg/l. In water saturated with oxygen and with a pH-value close to neutral, most types of filtration will remove sufficient amounts of iron, manganese and aluminum. Sand filtration is very commonly used because sand filters can be back washed. Dead end filtration (bag filter, candle filter) is usually used in small systems.

Rust scales are easily removed by almost any type of filter. If rust scales are present in the prefilter, it is always a good idea to find the origin because it indicates a source of dissolved iron, which can cause serious problems.

Humic acid fouling may cause problems for all types of membranes, but given the right working conditions, membranes can be used for the removal of humic acid. It is difficult to remove or destroy humic acid except by liberal dosing of hypochlorite, or energy intensive photo chemical processes. The latter uses UV light and hydrogen peroxide to generate OH-radicals, which attack literally all organic material and oxidize them to water and carbon dioxide. The most common solution to limiting humic acid fouling of membranes is to keep the flux low (<20 lmh) and to clean frequently in order to avoid or limit pretreatment requirements.

Silica (SiO₂) is always present in natural water. The solubility is very temperature dependent. If silica precipitation is a problem, it is common and very effective to increase the temperature slightly. The addition of anti-scaling agents also has an effect, and suppliers of such products claim good results with upward of 300 mg/l SiO₂ in the concentrate.

Calcium, Barium and Strontium has very low solubility as sulphate. Calcium sulphate (gypsum) is a common problem, specially in the Middle East. Barium and Strontium sulphate are more commonly experienced in surface water. It is fairly easy to prevent precipitation using small amounts of an anti-scaling agent which delays or inhibits crystallization, even at concentrations above saturation point, and ensures that precipitation does not take place in the membrane system.

Sand is easily removed by precipitation or filtration. Since sand is very abrasive it must be effectively removed before the feed enters any membrane filtration system.

WATER SUPPLY AND DRAIN

The water demands during the flushing cycle must be met with respect to both flow and quality. The required water flow in UF and MF systems is often in the order of 1,000 lpm, and in most cases 4" water lines are needed to supply this flow to the membrane system in a very short time. A separate water tank may be needed.

The water used during the flushing cycle must be disposed of at the same rate it is being supplied. Therefore, the discharge lines to sewer or any system receiving the flush water must be able to handle the same flow. The existing sewer lines often do not meet this requirement, in which case the operator may need rubber boots during the flushing cycle because there is water everywhere on the floor.

The following are the most common quality demands for the flush water:

Iron	<0.05 ppm
Manganese	<0.02 ppm
Hardness	<20°dH (Softened water is preferable)
Silica	<10 ppm
Humic acid	Not present
Other	The same as for good quality drinking water.
Temperature	No general demands, but in some instances it is necessary for water to be of the same temperature as the product being displaced.

CLEANING CHEMICALS AND CLEANING REGIME

Periodical cleaning is a necessity for membrane systems to insure optimal operation. However, cleaning should only be performed when necessary because of its adverse effect on membrane life, the cost of the chemicals, and the volumes of water required. To avoid cleaning as much as possible and to achieve easy cleaning only when necessary, adopt a strategy of providing good pretreatment of the feed stream, and choose operating parameters that prevent scaling, fouling and precipitation.



If RO permeate is available in quantity, it is usually acceptable for flushing, rinsing and cleaning.

Cleaning of a membrane system is essentially very simple, but there are rules which must be observed and followed.

There are many different cleaning regimens, and the exact procedure for a given membrane system depends on the product treated, the membrane type and the system design. The following is a full fledged cleaning procedure which may have to be modified for specific purposes. Points 5 through 10 can often be avoided.

1. Reduce the pressure. Use 1 - 2 bar for UF/MF and 2 - 8 bar for RO/NF.
2. Flush out the product until the concentrate appears reasonably clean.
3. First alkaline rinse. Recycle permeate and concentrate. Heat to the specified temperature. This can be anything from 45°C to 75°C. Add an alkaline detergent, e.g. DIVOS 100 from Diversey or Ultrasil 90 from Henkel. The concentration is typically 1%. Recycle for 30 - 60 minutes or as specified by the cleaning agent supplier. Check pH carefully.

CHEMICALS FOR CLEANING. PROBLEMATIC CHEMICALS

4. Flush out with tap water.
5. Acid rinse. Recycle permeate and concentrate. Heat to the specified temperature. This can be anything from 45°C to 75°C. Add an acid detergent, such as DIVOS 2 from Diversey or Ultrasil 75 from Henkel. The concentration is typically 1%. Recycle for 20 - 40 minutes or as specified by the cleaning agent supplier. Check pH carefully.
6. Flush out with tap water.
7. Second alkaline rinse. Recycle permeate and concentrate. Heat to the specified temperature. This can be anything from 45°C to 75°C. Add an alkaline detergent such as DIVOS 100 from Diversey or Ultrasil 90 from Henkel. The concentration is typically 0.1%. Recycle for 20 - 30 minutes or as specified by the cleaning agent supplier. Check pH carefully.
8. Flush out with tap water.
9. Recycle permeate and concentrate. Heat to the specified temperature. This can be anything from 20°C to 50°C. Add a disinfectant such as Ultrasil Active from Henkel or DIVOSAN FORTE from Diversey. The concentration is typically 0.1%. Recycle for 10 - 20 minutes or as specified by the cleaning agent supplier. The pressure may need to be increased to achieve a good flow of permeate which is necessary to disinfect the permeate side of the membrane system.
10. Flush out with tap water.
11. Measure water flux at the temperature and pressure specified by the membrane manufacturer. A temperature of 25°C is common.

By now the membrane system should be “squeaky” clean. If not, there is an operational problem which needs to be investigated. In case of problems, it is often a good idea to soak a system for up to 48 hours in a neutral detergent. If the problem is proteins or anything that enzymes can digest, add a liberal dose of a suitable enzyme such as papain, bromelain or Alkalase®.

It is debated whether alkaline-acid-alkaline or acid-alkaline is best. The choice is to a large extent product related. If there are reducing sugars and proteins in the product, then acid is used first. That minimizes the risk that a condensation reaction, similar to the Maillard reaction, can take place in the alkaline environment. The result of a condensation is red-brown sticky

CHEMICALS FOR CLEANING. PROBLEMATIC CHEMICALS

deposits. Such products are difficult to remove from the membranes; oxidizers are the only fast remedy. Alternatively, many cleaning cycles can gradually restore water flux.

Table 32. Main Cleaning Agent Suppliers

Diversey-Lever A/S	Henkel-Ecolab GmbH & CO	Novadan A/S
Smedeholm 3-5 DK-2730 Herlev Denmark	P3-E/Milchwirtschaft Gebäude L34 Ritastrasse 67/Tor 2 D-40554 Dusseldorf Germany	Platinvej 29 DK-6000 Kolding Denmark
Tel +45 7010 6611 Fax +45 7010 6610	Tel +49 211 989 3694 Fax +49 211 7141 709599	Tel +45 7550 3577 Fax +45 7550 4370

The cleaning pressure is also debated. In UF and MF systems there is no doubt that pressure shall be reduced to 1 - 3 bar. In NF and RO systems it may be beneficial to keep the pressure around 10 bar which will ensure that the flow channels remain fully open. At lower pressure, there is a risk that dirt, which is literally filling the flow channels, is kept in position by the membranes. At high pressure, the flow channels remain open enough to allow good flushing of the flow channels.

CLEANING AGENT SUPPLIERS

There are three main suppliers of cleaning agents world wide, directly or through representatives. See Table 32.

CHEMICALS - PROBLEMS

Do not test new or different cleaning chemicals since it may cause major problems. Companies like Henkel and Diversey have gone through a long learning process and have paid their dues to learn how to clean membranes. There are many smaller, local suppliers of cleaning chemicals who want to enter this market, but be very careful in an attempt to save a little money on cleaning chemicals. The price may well be a complete set of membranes.

Rules of thumb for cleaning chemicals:

- **cat-ionic** = cat-astrophe
- **non-ionic** = non-problematic
- **an-ionic** = applicable

CHEMICALS FOR CLEANING. PROBLEMATIC CHEMICALS

However, there are exceptions to these rules of thumb. For instance, non-ionic cleaners can damage some polymers, such as polysulfone, where they may cause stress corrosion.

ANTI-FOAM AGENTS

There are many different types of anti-foam agents. They work by changing the surface tension, and thereby destroy foam's ability to make bubbles. This can be achieved by adding hydrophobic compounds, which is the most common and lasts the longest, or by adding hydrophilic compounds, which usually last only a short time. A very common hydrophobic compound is silicon oil. A common hydrophilic type is alcohols.

Bear in mind that a membrane process is totally dependent on the membrane surface.

- The more hydrophilic the membrane surface is, the easier it is for water to permeate.
- As the membrane surface becomes more and more hydrophobic it will essentially cease to provide permeate flux, and the process will come to a standstill.

There are anti-foam agents which only lower the permeate flux slightly and where the flux drop is reversible. An example is siloxanes.

There are also anti-foam agents which cause the flux to drop to zero and where the flux drop is irreversible. The best known example is silicon oil.

The rule is that all anti-foam agents have an effect on membranes: it is only the extent of the effect which differs. It is a good idea to test all chemicals coming into contact with the membrane surface, and this goes double for anti-foam agents. Always test anti-foam agents in a membrane test cell. Otherwise a major membrane disaster may occur where only a new set of membranes can correct the problem.

FLOCCULATING AGENTS

There are no firm rules for the use of flocculating agents. Many flocculating agents are cationic in nature, and as mentioned in the section about cleaning chemicals, this can be dangerous. Flocculating agents may also be high molecular weight polymers, and if they are used in excess, they may have a detrimental effect on membranes, too.

PASTEURIZATION, DISINFECTION, STERILIZATION

HEAT STERILIZATION

Sterilizing is defined in the Pharmacopeia as heating to 121°C for 20 minutes with wet steam. If dry steam is used, a longer duration or higher temperature is needed. Very few membrane systems can be sterilized in this way. Ceramic systems alone claim to be compatible with such sterilization procedures, and this is even questionable.

All membrane systems described here are designed to handle liquids. Gases, in which category steam falls, are handled only with difficulty, and this concept is certainly outside the specifications for membrane systems as discussed here.

It is possible to heat several types of membrane systems to well over 80°C. This is not truly sterilization, but rather pasteurization. This type of heat treatment is quite adequate in the dairy industry which uses pasteurization in several unit operations to prevent bacterial growth. It is a fact that pasteurization is adequate for sterilization in several other non-dairy processes and industries as well. The author believes that pasteurization is adequate in all but the most demanding membrane applications in the pharmaceutical industry. In the experience of the author, all membrane systems which can tolerate heating to 80°C are “sterilized” to the point where it is “good enough.” It is extremely important that not only the membrane plant but also pipes, pumps, tanks, etc., before and after the membrane plant, are heated to 80°C for an adequate length of time.

CHEMICAL STERILIZATION

For many years, membrane filtration systems have been “sterilized” by chemical means. The goal of achieving chemical sterilization has often proved to be difficult because microorganisms are very adaptable when it comes to protecting themselves. They develop new resistant strains, even in extremely harsh chemical environments.

Formaldehyde has been used with good results for many years. It is very effective, but due to legislation it is rarely used now.

Sodium hypochlorite is effective but not very popular. It is a very aggressive chemical which most people prefer not to handle, and it causes pollution indirectly because quicksilver - still - is a vital chemical in the manufacture of sodium hypochlorite. It can also form trihalomethane (THM) precursors, which are carcinogenous. Thin-film membranes do not, in general, tolerate sodium hypochlorite in any quantity. In short, sodium hypochlorite is very effective, but rarely used.

PASTEURIZATION, DISINFECTION, STERILIZATION

Ozone is effective but quite expensive. It is in reality never used for membrane systems. No thin-film membranes can tolerate any quantity.

Sodium hydrogen sulphite and **sodium hydro sulphite** are weak reducing agents which have some effect on microorganisms. They are popular because all thin-film membranes can tolerate these chemicals, but they are not very effective.

Hydrogen peroxide and peracetic acid is used extensively in the dairy industry. Peracetic acid is quite an effective chemical, but TFC membranes have limited resistance to it, thus the use of these chemicals must be strictly controlled.

Chlorine dioxide can be used on TFM, but only if it is free from chlorine which tends to be present in small quantities.

MEASURING DEVICES, FLOW, PRESSURE, TDS.

An automatic control system requires input from the parameters it is supposed to control. This input can come from several different devices and in several different forms.

FLOW

Flow is probably the most commonly measured parameter. There are a number of flow meters on the market. The fast development of microprocessors makes it difficult to keep track of the capabilities of the flow meters. However, the following are considered by the author to be valid 2001.

The Rotameter is the only purely mechanical type of flow meter used in quantity, but today it is considered to be old-fashioned. Some are supplied with a transmitter, but this is not common. Rotameters are excellent for local indication, but are almost useless for data transmission. Flow is shown with some accuracy, but rotameters are sensitive to viscosity and density of the liquid. If the float or the transparent housing get worn, the flow indication can be completely wrong.

The Magnetic Flow Meter is the only flow meter which gives good and reliable flow data on all products encountered in a membrane filtration plant. The only fluid it is not compatible with is ultrapure water. The magnetic flow meter usually transmits a 4 to 20 mA signal.

There are several advantages of the magnetic flow meter:

- The flow channel is completely free from obstacles
- There is virtually no pressure drop
- The diameter is the same as the tube through which the liquid flows
- It has a larger measuring range than most other flow meters

There are a number of manufacturers of magnetic flow meters. The following are commonly used in Europe, but the list is by no means complete.

- Siemens (Germany)
- Rosemount (USA)
- F&P (United Kingdom)
- Bürkert (Germany)
- Endress & Hauser (Germany)
- Process Data (Denmark)

It may be difficult to obtain a flowmeter that can operate under the pressures in an RO system. Another problem is sourcing magnetic flow meters for the dairy industry since sanitary connections are required.

MEASURING DEVICES, FLOW, PRESSURE, TDS.

Process Data and Danfoss can supply this design.

Flow meters can be delivered with a local display as well as a display in a control panel. Features like display of temperature and a flow totalizer are commonly available.

The Turbine Flow Meter will in principle do the same job as a magnetic flow meter at a much lower price. Turbine flow meter bearings are often so weak that they are rendered unsuitable for use in membrane filtration systems.

The Ultrasonic Flow Meter has for several years been promoted as a good, inexpensive flow meter. That may be correct, but the measuring principle can only work well when there are particles in the liquid (solids or air bubbles) to reflect the sound waves. In membrane filtration systems there are few suspended solids and very little air. Thus, these meters are rarely used in the membrane world.

Mass Flow Meters are sophisticated instruments used to measure flow, density and mass simultaneously. They are used to control evaporators. The measuring principle involves inertia, mass and resonance damping. From the exterior they appear as a long U-tube, often close to one meter long. The concentrate is sent through the tube which is connected through a flexible joint to the evaporator. The weight of the product in the tube is measured by a weighing cell, and the density of the product is calculated. The faster the liquid flows, the more the tube will flex due to the force necessary to change the flow direction 180°. This flexing is measured, and based on the density of the liquid, the flow velocity is calculated. Knowing speed and density allows calculation of the mass flow. Viscosity can indirectly be determined by introducing a high frequency tone generator.

Mass flow meters are excellent for fluids containing high solids. The reading is more questionable in membrane plants treating low-solid fluids.

The five types of flow meters mentioned rely on linear velocity, magnetic properties of the liquid, the flow velocity, the reflection of sound waves, the density of the liquid and the inertia of the liquid. There are many ingenious flow meters on the market using these and other principles.

It is the author's opinion that it is risky to use flow meters containing moving parts. Suspended solids can foul the mechanism, floats can get stuck, bearings can wear out and gears can get worn stuck. The author's advice is to use magnetic flow meters and thus avoid endless problems.

MEASURING DEVICES, FLOW, PRESSURE, TDS.

PRESSURE

Electronic pressure transmitters are fairly new. They can, in contrast to the traditional Bourdon type, easily provide readings with 0.1% accuracy, which is actually necessary and very beneficial in a membrane system. Another virtue of electronic pressure transmitters is that the meters can be electronically zeroed. The older Bourdon type meters cannot be zeroed.

Electronic pressure devices can be delivered with local display as well as with display in a control panel.

With a measuring error of less than 0.1 bar on a 100 bar meter, it is possible to get a good indication of pressure drop across a housing without buying the very expensive and complicated differential pressure transmitters.

Bourdon type meters can be used, but only for local indication and only to give the operator a visual estimation of the pressure rather than an accurate reading. The ability to obtain a visual estimation of the pressure with a glance from a distance, without actually making a reading, is often valuable. It is similar to driving an automobile and glancing at gauges to check water temperature and oil pressure: one does not need to know the actual value; the position of the indicator suffices.

If a Bourdon type meter is used, it is necessary to use a gauge which employs a diaphragm to separate the meter from the product.

OTHER TRANSMITTERS

Electronic temperature transmitters are the industry standard while traditional thermometers are hardly used any more. Electronic temperature transmitter signals are usually 4 to 20 mA.

Amp meters are only used in systems where the product tends to be very viscous, and where the viscosity is used to regulate the system. It is very simple to measure the current consumed by a motor, and the outgoing signal may be digital as well as analog.

Industrial refractometers are used for in-line measuring and control of dissolved solids. They are usually used in the dairy industry for special processes. The system works well in most cases, although a refractometer in reality measures the refractive index and not total solids. It is possible, however, to establish a good relationship between the refractive index and the dissolved solids.

MEASURING DEVICES, FLOW, PRESSURE, TDS.

The measuring unit most often used is degree Brix ($^{\circ}\text{Bx}$). 1°Bx is defined as the refractive index of 1 W/W % sucrose at 25°C . Water has 0°Bx . For many dairy products, dissolved solids is obtained by multiplying $^{\circ}\text{Bx}$ by 0.82. For pulp and paper effluents, the multiplication factor is 0.78. It is highly recommended to develop a calibration curve for the actual product treated since the relation between $^{\circ}\text{Bx}$ and true solids may not be constant in the whole range.

Suspended solids pose a special problem because they are not “seen” by a refractometer. This is a challenge in the dairy industry where UF of whole milk is a common process. In order to obtain a correct reading, it is necessary to establish the actual composition of the feed before it enters the UF system. This comment is, of course, valid for all other feeds containing suspended solids.

The refractometer must be placed in such a way that a reasonable and constant flow over the prism is ensured in all production phases. In a recirculation loop the flow is very high, but then the loop must always be in operation. If the refractometer is placed in the concentrate line, flushing of the prism can be secured by connecting a very thin tube from the pressure side of the last recirculation pump to the refractometer, as shown in Figure 16.

PLC, PC AND MAIN FRAME CONTROL SYSTEMS

This century has experienced a rapid development of control devices. The development spans from purely mechanical control systems to the computers which are so prominent today in many forms.

The transition from analog to digital signals is not complete. The 4 to 20 mA signal range from a measuring device is still a commonly used standard. However, there is a clear trend towards digital signals.

The old fashioned pneumatic controllers and relays have one virtue: they can literally be repaired with a pocket knife. Consequently, there are quite a few places in this world where simple technology is preferable to the most up-to-date technology. It seems that the human mind works against a simple solution since most end-users want the latest and greatest in the form of computer based control systems, and that the producers love to sell them.

PLCs have been around for quite some years, and there are many manufacturers. The author does not have any specific preferences, but strongly advises the selection of a well known brand. A little money can be saved by buying little known brands, but there may only be a few people who can service it or re-program it. That, of course, is not satisfactory for an industrial operation.

PLC programming has progressed greatly without becoming decidedly user-friendly. The author believes that it may be slowly surpassed, or merged, with normal PC programming.

PC based controllers are not used very often, but there are a few suppliers offering powerful and yet simple systems which can be easily programmed.

Main frame computers for control purposes have been around for many years. They are used in very large operations like refineries and pulp mills. Siemens and Allen Bradley have very good reputations in this field. These types of control systems also have a hefty price tag, but worldwide, locally available service is a bonus. Very few end-users are able to program such computers themselves.

The type and brand name of the control system is often determined by the end user who may have an existing system and understandably wants to use the same type and brand again.

**Do not try to save a few pennies buying a cheap control system.
The savings can be quickly lost by problems before the system is even delivered!**

HOW TO CONTROL MEMBRANE PLANTS

Basically, there are only a few different ways to control membrane filtration systems, at least when one considers the major overall control system. The control method is mainly chosen based on the product treated, but also with consideration for the plant design. On the other hand, alarms and set points depend more upon the plant design and less on the product treated.

The main control methods are:

- Pressure control
- Ratio control
- Total solids (TS) control
- Viscosity control
- Manual control

Looking at membrane filtration system based on shear numbers, the pressure control method is the most common due to its widespread use in water desalination plants.

For industrial applications, the ratio control method is by far the most commonly used.

System controls based on total solids are used in a few dairy systems.

The viscosity control method is found in a few rare systems operating on polysaccharides.

Manual control is rarely used for systems of industrial size.

GENERAL REMARKS

Several of the control methods can be combined to obtain a more constant end product. In this context there are a few simple rules that must be observed.

	Ratio controller	TS controller	Plus Constant Flow controller
RO	Yes	Yes	Yes
NF	Yes	Yes	Yes
UF	Yes	Yes	No
MF	Yes	Yes	No

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

PRESSURE CONTROLLER

The pressure in the system is controlled and varied in order to achieve a set point.

The pressure control system is almost exclusively found in NF and RO water desalination systems where the operating parameters remain constant for very long periods of time. In RO and NF, there is a linear relationship between pressure and flux, making the control system simple and straight forward. Pressure control may be applied to UF and MF, but then the objective becomes membrane protection and constant capacity is not achieved at all.

FLOW RATIO CONTROLLER

The function of a flow ratio controller is to secure that the ratio between the volume entering the plant and the volume of concentrate leaving the plant has a constant predetermined value set by the operator, the volumetric concentration ratio or degree. It is necessary to have a flow meter in the feed line and one in the concentrate line. The actual control function is performed by a pneumatically or electrically driven concentrate valve with actuator and positioner. The signals from the flow meters travel to the controller which, based on the information received, sends a signal to the concentrate valve specifying the desired position. See Figure 13.

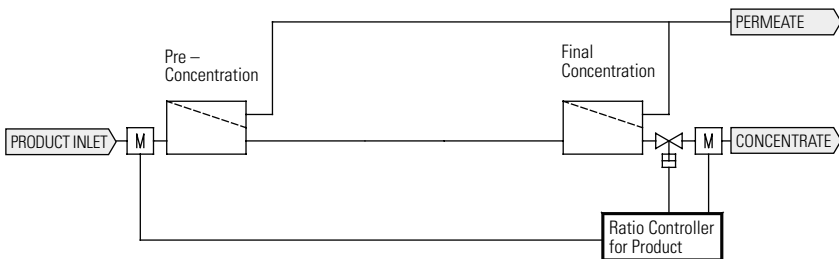


Figure 13. Ratio Controller

A ratio controller is comparatively simple to design and operate. When the composition of the feed is fairly constant the control function is satisfactory.

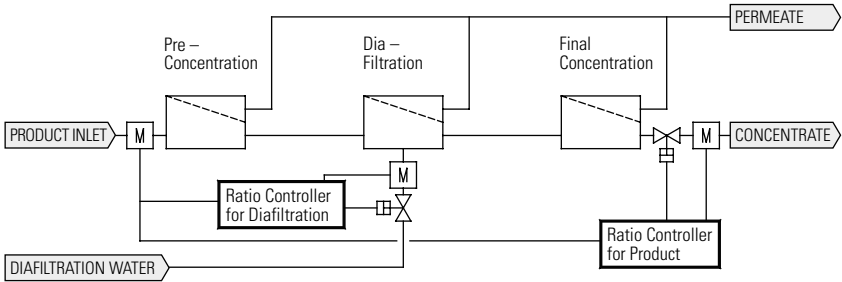
It has been suggested many times to use the permeate flow for regulation instead of the concentrate flow. This scheme will work in some cases, but not always, and it has several inherent problems. Sometimes water is added during the filtration process to reduce the content of one of the species which passes through the membrane (diafiltration). In this case a control system based upon the permeate flow will not work. Also, when the

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

concentration ratio is high, even a small adjustment error may lead to disastrous results.

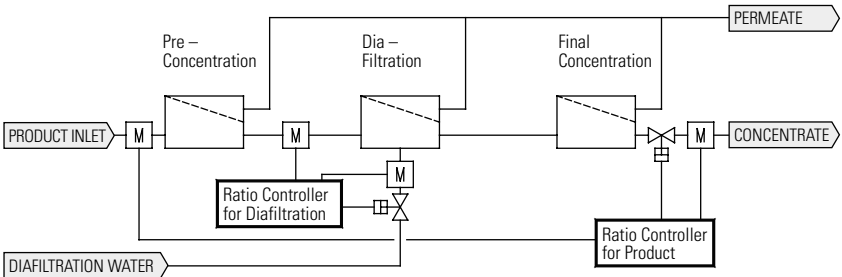
It is preferable to measure the concentrate flow, and it always works.

When diafiltration is involved, there are two flow ratios to control: the volumetric concentration ratio, and the ratio water to concentrate. It is tempting to build a system with only three flow meters as shown in Figure 14. The diafiltration volume is determined by the feed flow, but this is distinctly dangerous. Adjustment errors or operator error can lead to situations where the diafiltration volume exceeds the flow of concentrate from the previous loop, with the result that there is no concentrate flow. This leads to the build up of solids and subsequent blocking of the membranes.



**Figure 14. Ratio Controlled System with Diafiltration.
Three Magnetic Flow Meters.**

A safely operating system has four flow meters as shown in Figure 15. This design assures that the flow of diafiltration water never exceeds the flow of concentrate from the previous loop.



**Figure 15. Ratio Controlled System with Diafiltration.
Four Magnetic Flow Meters.**

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

TOTAL SOLIDS CONTROLLERS

Total solids (TS) or total dissolved solids (TDS) are parameters that are not often used to control membrane filtration systems. An exception is in UF of whole milk where this method is used consistently. The reason is that the UF milk concentrate most often is used for production of cheese and therefore it is essential that TS is correct. Another exception is the pulp and paper industry where refractometers are sometimes used.

Refractometers may be placed in two correct positions. First, they may be placed in the concentrate line. However, it is quite difficult to start the system up, and very careful engineering is needed to ensure that the concentrate valve is never completely closed (See Figure 16). Second, they be placed in the last recirculation loop (See Figure 16). The drawback is that this loop must always be in operation.

An attractive feature of refractometers is that they contain no moving parts. A less attractive feature is that the reading can be distorted by fouling of the prism which is in contact with the liquid. Fouling of the prism is a distinct possibility because a rather powerful light source is needed to obtain a signal which can be detected. Local heating of the product takes place and that can cause the product to precipitate and adhere to the prism. One fairly simple method to minimize the problem to a manageable extent is to draw a very thin tube from the pressure side of the recirculation pump in the last loop of the plant to the refractometer. This creates a small but quite powerful jet of product flushing the prism.

Another serious problem is that the lamp in the refractometer can burn out. Alarms are needed for that situation and a quick response is essential. Otherwise the system can become completely out of control.

The reading can be very diffuse, and it tends to become more diffuse at higher solids levels, especially on dairy products containing fat. Industrial refractometers have capabilities that the human eye does not. The electronic sensor integrates the diffuse signal simply because that is the nature of the sensor. A very diffuse signal is therefore in most cases not a problem for the refractometer, although it can become a substantial problem for the human operator.

An industrial refractometer cannot tolerate high pressure. The pressure limitation is not serious in a UF system, but it presents a serious problem in NF and RO.

Viscosity has no influence on the reading of a refractometer.

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

Temperature has some influence on the reading. Therefore, calibration at the operating temperature is necessary.

It is common to control plants using diafiltration with refractometers (See Figures 16 and 17). The control system is similar to the diafiltration explained earlier.

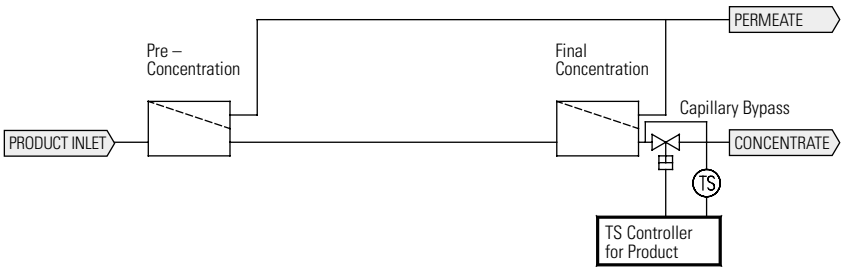
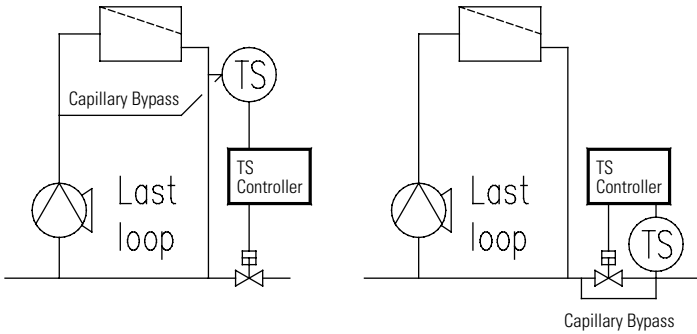


Figure 16.
Plant with TS Controller. No Diafiltration.
Above the Possible Positions of the Refractometer.

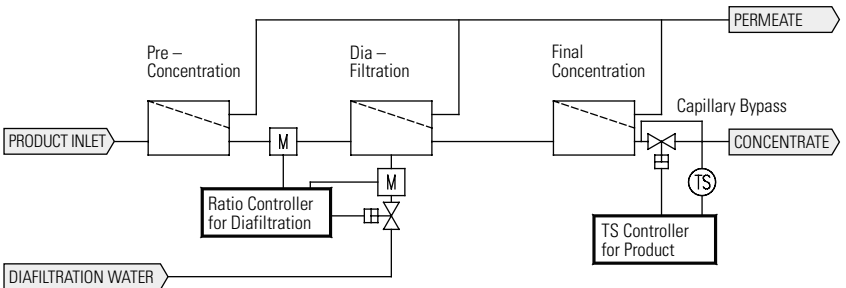


Figure 17.
Plant with TS Controller Diafiltration with Ratio Controller.

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

There are only a few manufacturers of refractometers used in the membrane industry. Those known to the author are:

- Anacon
- The Electron Machine Company
- Siegrist
- X-Control

PRESSURE CONTROLLERS AND FEED FLOW CONTROLLERS

Pressure is a value which most often needs to remain constant or adjusted slightly for a membrane filtration plant to provide a certain level of performance. That is very common for water desalination plants. In water desalination it is, as a matter of fact, almost the only control method used and the only one needed. The same is the case for industrial RO and NF plants, but in these cases pressure control is rarely the only control function.

For RO and NF plants a pressure controller is in reality identical to a feed flow controller and can just as well be seen as a plant capacity control device.

For UF plants, feed pressure control is used as a way to ensure that the pressure does not rise above the maximum allowed or maximum desired value. It is also used to minimize the inevitable high flux occurring at production startup with clean membranes.

It is shown in Figure 23 that pressure cannot be used to control the capacity in UF and MF systems. The capacity is determined by the nature of the product and by the characteristics of the membrane. The operating pressure is literally irrelevant.

The feed flow can only be indirectly controlled in UF and MF systems. It is common in a multi-stage system not to start all loops at the beginning of the production cycle. In a five stage system, three loops are typically started up at first. After a short time, maybe 30 to 60 minutes, the fourth stage is needed to reach plant capacity, and after a few hours the fifth stage is needed.

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

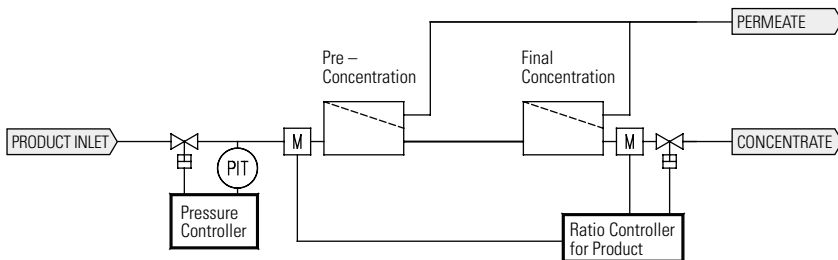


Figure 18.
Constant Pressure and Concentration Ratio. Variable Flow.

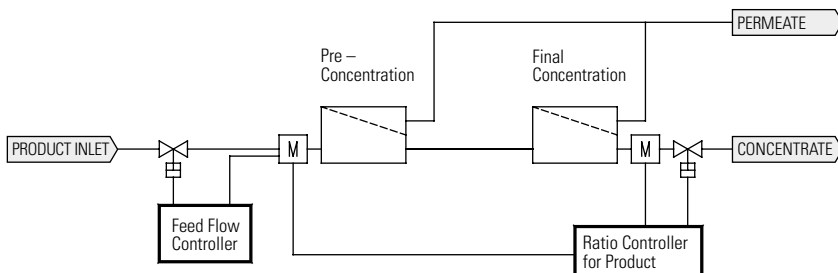


Figure 19.
Constant Flow and Concentration Ratio. Variable Pressure.

PERMEATE FLOW CONTROLLERS

Constant permeate flow is often desired, and can be achieved in NF and RO processes. It is accomplished by installing a flow meter in the permeate line and using the signal to control the feed pressure. This is done by (1) varying the RPM of the feed pump, which is best achieved using a frequency converter, or (2) using the signal to open or close the throttle valve between the feed pump and the plant.

Batch system. If the feed pump is a positive displacement pump, the net result is that the concentration ratio is kept constant. If the feed pump is a centrifugal pump, the concentration ratio is un-determined which does not really matter.

Continuous system. If the feed pump is a positive displacement pump the net result is that the concentration ratio is kept constant. If the feed pump is a centrifugal pump a ratio controller is needed.

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

Permeate flow control is somewhat controversial since there are several possible sources of error. Permeate flow control is, for instance, hardly useful in systems with diafiltration. However, it seems to work very satisfactorily in NF and RO systems with relatively non-fouling feeds, and in batch systems.

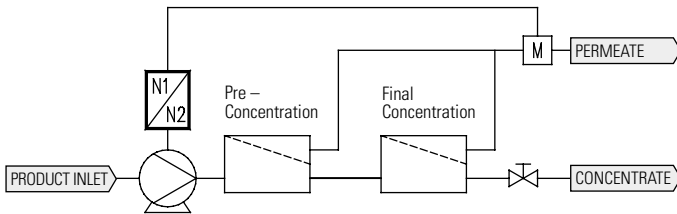


Figure 20.
Constant Permeate Flow Controller.

VISCOSITY CONTROLLERS

Viscosity can be a serious problem or challenge when concentrating products like carrageenan and xantan. It makes very little sense to use solids, as indicated by a refractometer or concentration ratio, for control of the plant because these parameters have little or no correlation to the viscosity. Consequently, a very indirect control method has been designed.

A positive displacement pump installed in the last loop will provide a flow which is almost independent of the pressure the pump is operating against, and there is a clear relationship between the pressure drop in the membrane element and the viscosity. When the viscosity increases, the pressure drop increases, thereby increasing the pressure which the pump has to deliver. The electrical current consumed by the motor is directly related, although not as a linear function, to the pressure provided by the pump when the flow is constant. Consequently, there is a clear relationship between the viscosity and the electrical current used by the motor. The information about the current consumed can be used via a controller to set the concentrate outlet valve and make sure that the viscosity of the concentrate remains constant. Centrifugal pumps cannot be used in the last loop.

COMMON CONTROL LOOPS IN MEMBRANE SYSTEMS

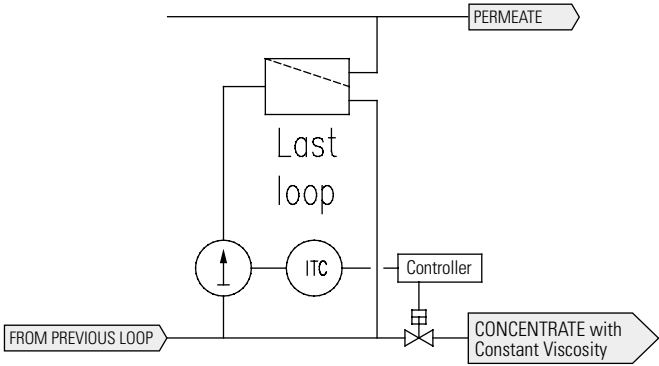


Figure 21. Constant Viscosity Controller.

HOW TO AVOID TS SURGES ON STARTUP

Starting up a large multi-stage UF or MF system is not easy. Traditionally, the operator will start loop 1, then loop 2 and so on in quick succession. A few disasters where UF systems were blocked by precipitated protein or other matter lead to a careful analysis of the profile of the solids buildup taking place from the time of startup of a water filled plant to the time a steady state has been reached, and several interesting discoveries were made which, in retrospect, are quite logical.

For example a 5-stage system with an internal volume of 800 liters is shown in the figure symbolizing an industrial size system designed to treat 30,000 lph cheese whey. It is assumed that it has a volumetric concentration ratio of 30:1. For the sake of simplicity there is no diafiltration. This means that at steady state the plant will produce 1,000 lph of concentrate and 29,000 lph of permeate. It is assumed that the system is controlled by a ratio controller and a feed pressure regulator. Under ideal conditions $15 \times 800 = 12,000$ liters need to be fed into the plant before a steady state is reached, but conditions are never ideal and therefore the required volume is somewhat larger.

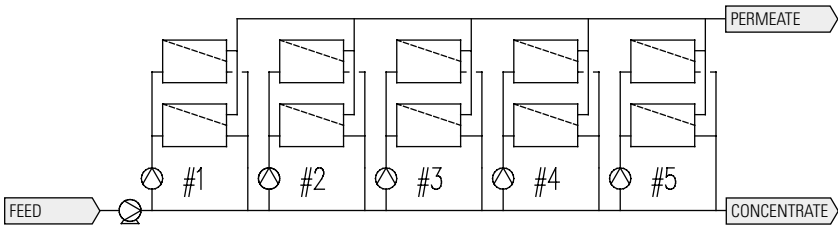


Figure 22. Five Stage Feed and Bleed System.

Here is an example how not to start a plant: A lazy operator in a plant placed nails in a piece of wood to coincide with the placement of all of the pumps' start buttons such that, using this device, all pumps could be started at the same time. Among others things, this procedure resulted in a spectacular power surge because 8 motors were started at once, each drawing 18.5 kW.

Even with a gentler startup procedure a large flow of product will start flowing into the plant. The water contained in the plant starts mixing with product, and the result is that the solids in the plant will be very pure protein which is pushed from the first stage to the subsequent stages.

Due to the high initial flux, the concentration in the first loops will be higher than normal. When this over-concentrated product moves further through

HOW TO AVOID TS SURGES ON STARTUP

the plant and reaches the last stage there is a good chance that the protein level gets so high that gelling occurs which can lead to a disastrous situation. Total blocking of all or the majority of the flow channels can occur, and it can prove to be impossible to clean the elements properly. This leaves the total change out of elements as the only possibility to get the plant up and running again.

Through the years a number of plants have suffered from this problem. It took quite a while and a lot of speculation and calculation to understand why and suggest a solution.

The best way to start a multi-stage plant is as follows, using a 5-stage system as an example. Loop #5 is started first while loops 1 through 4 are valved off. When the flux in loop #5 gets close to the normal production value, loop #4 is started. When the flux in loop #4 gets close to the normal production value loop #3 is started and so on. The idea is to get the buildup of solids to exactly the point where it should be under normal production, particularly in the last stage.

Using the traditional startup method results in a 5 fold higher feed flow than during normal production. The pretreatment equipment, by the way, can rarely handle this much flow and still function properly. It typically takes about 30 minutes until everything settles down to the normal flow conditions.

The latter method requires a feed flow close to the normal value because the membrane area first activated is small. There will obviously still be rapid variations in flow when a new loop is started, but it occurs with a comparatively small membrane area under activation at any one time. Consequently, the surge in feed flow is manageable.

The latter method provides an asymptotic approach from the low side to the correct TS in the concentrate, possibly with a small tendency to over-concentrate. The traditional method will overshoot considerably, and then approach the correct TS from the high side.

ELECTRICALLY AND PNEUMATICALLY OPERATED VALVES

Much has been said in the debate about electrically versus pneumatically operated valves. The author has by far the best experience with pneumatically operated valves for the following reasons:

- They do not stop functioning if they get wet.
- They do not burn out if they are stuck for a while.
- They are simple to repair.
- Most types are explosion proof.

Still, the choice is a matter of taste and a matter of which type is already in use in a manufacturing facility.

A pump almost never delivers the exact flow and pressure needed, so it has to be controlled in some fashion.

It is necessary to distinguish between centrifugal pumps and positive displacement pumps. The following table provides information about the most important characteristics for the two types of pumps.

	Single-stage Centrifugal Pump	Multi-stage Centrifugal Pump	Positive Displacement Pump
Pressure	Almost constant	Varies considerably	Varies from 0 to infinity
Flow	Varies from 0 to infinity	Varies considerably	Almost constant

A positive displacement pump provides, as the name says, almost the same volume of liquid independent of the pressure. Well known pump types are the piston pump and the diaphragm pump.

A single-stage centrifugal pump will tend to deliver almost constant pressure which is largely independent of the flow it delivers when it operates close to its maximum efficiency.

A multi-stage pump is somewhere between the first two mentioned. The more stages a pump has, the steeper the pump characteristic. Consequently, the pressure varies significantly if flow changes.

These statements are only correct in principle. For a thorough description of pumps, a textbook on the subject should be consulted.

With the above mentioned characteristics in mind, the following possibilities can be listed for controlling a pump. The list represents what is done rather than what is theoretically possible.

	Single-stage Centrifugal Pump	Multi-stage Centrifugal Pump	Positive Displacement Pump
Throttling valve	x	x	
Frequency converter	x	x	x
Mechanical variator			x

CONTROL OF PUMPS

When using a positive displacement pump, never place a fully closable valve after the pump because if the valve closes, something will break. For many years, the only means to control flow and pressure were by mechanical variators by which the RPM of the pump can be changed. In later years, frequency converters have become more common and they offer an excellent way to control a positive displacement pump. Mechanical variators wear out faster than electronic converters.

Centrifugal pumps are simple and easy to control using a throttling valve. This method is very traditional. It is simple and inexpensive, but it has several drawbacks:

- It is noisy to the extent that the noise can be physically harmful.
- It is a waste of energy. Two kWh every hour can easily be lost, and in one year the money wasted could have purchased a frequency converter.
- It generates heat which may have to be removed by cooling, which is an expensive process.
- Severe shear forces occur which can harm the product being treated.

Frequency converters do not have any of these limitations. The only drawback in using a frequency converter is the cost, but it is certainly the technology of the future. Frequency converters have dropped in price, and it seems that they continue to become less expensive. There are even pumps on the market with built in frequency converters.

OPTIMIZING PARAMETERS AND PLANT OPERATION

A well operating membrane filtration system must have a reasonable and stable flux and the energy consumption should be as low as possible. In order to achieve these goals, the process must be optimized with respect to product flux, pressure and temperature. As stated previously, extremely high permeate flux is not a goal in itself, and can lead to unstable operation.

Flux as a function of pressure is shown in Figure 23. It is a very generalized drawing, but nevertheless basically correct.

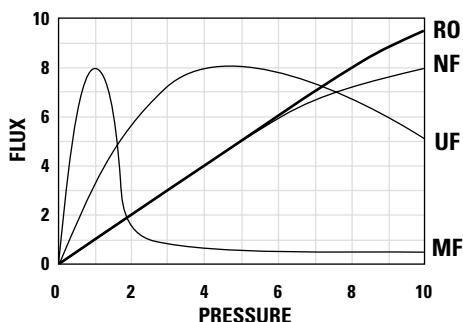


Figure 23. Flux as a Function of Pressure

FLUX AS FUNCTION OF PRESSURE

The general rule for RO is simple: when the NDP pressure is doubled, the flux doubles.

NF is similar to RO but the relation between flux and NDP is not as linear as with RO.

UF is more difficult. The flux actually drops if the feed pressure is increased above a few bars. For most products, the maximum useful pressure is 3 to 5 bar with very few exceptions. This means in reality that a UF plant has a capacity which depends more on the product than on the membrane. There is little the user can do except observe the flux and choose the most advantageous operating pressure.

From the standpoint of choosing the operating pressure, MF is the most difficult membrane process. Over approximately 0.5 bar the flux decreases! It is almost impossible to operate an MF system under pressure and flow conditions which are ideal. This is one of the reasons that MF suppliers for the last 15 years have been declaring that “next year MF sales will really

OPTIMIZING PARAMETERS AND PLANT OPERATION

boom". The reality is that MF systems represent <1% of the membrane area sold in 1995.

The conclusions of the above are:

- Pressure can be used as a variable in RO and NF processes to optimize permeate flux
- Pressure does not determine the permeate flux in UF and MF processes

FLUX AS FUNCTION OF TEMPERATURE

If it is at all possible to change the temperature of the product, it is mostly recommended to increase temperature as much as possible simply because the flux increases with temperature. But the nature of the product or the volume or the economy may make it impossible to do anything but accept the product at whatever temperature it comes.

The water flux for most membranes increases by 3.3% per °C, and a temperature increase of 30°C will therefore double the water flux. This is unfortunately only true for very few products, because chemical and bacteriological phenomena tend to limit the flux in a number of ways. The full potential flux increase based on temperature is only realized on very pure water, or on effluents from the pulp and paper industry. In most other cases it is more realistic to calculate with 1% increase per °C.

Increased operating temperature can cause:

- Precipitation of Ca-salts, e.g. CaHPO_4
- Precipitation of proteins, e.g. egg white
- Growth of microorganisms, resulting in slime formation

For many dairy and pharmaceutical products it is therefore true to state that "less is more" meaning that if one starts the operation at low temperature and low flux, the result may be a higher permeate flux at the end of the day than if one started the operation at high temperature and high flux.

Only when the product is viscous, for instance when working with gelling agents, is high operating temperature a true advantage. It will perhaps not provide a high flux, but it will prevent the system from being blocked by the product.

The calculation of the change of flux is easy.

OPTIMIZING PARAMETERS AND PLANT OPERATION

Below 25°C Coefficient = $(1 + TC/100)^{(\text{Temperature} - T_{\text{test}})}$

Above 25°C Coefficient = $1 + (TC/100)^*(\text{Temperature} - T_{\text{test}})$

where

Coefficient is the factor with which to multiply flux at 25°C

TC = temperature coefficient is % flux increase per °C.

Water	TFM	3.3% per °C
Water	PSO, CA	2.7% per °C
Most products	All membranes	1% per °C

OPTIMIZATION OF PLANT OPERATION

First the operating temperature is chosen. Then one must find or select the optimum pressure.

RO and NF optimization is relatively simple. The feed flow should be chosen as recommended by the membrane supplier, and pressure should be increased until the permeate flux is suitable, usually in the 20 - 35 l/mh range.

For UF it is somewhat more difficult. An example of the flux curve as a function of pressure has been mentioned earlier. If the flux curve has been established based on the results from a cell test, it should be used as a guideline.

Optimization of the operation of a UF plant can be done as follows:

1. Select the flow recommended by the membrane supplier.
2. Set the pressure to a low value, e.g. concentrate pressure 0.5 bar, and operate for at least one half hour, and preferably for a few hours, at that pressure.
3. Increase the pressure to 1.0 bar and operate for a period of time again.
4. Continue to increase the pressure by 0.5 bar at a time until no further flux increase occurs.

Under industrial conditions a system should be operated at a slightly lower pressure than the optimum found because flux may decrease substantially over long periods of operation, and the lower the start flux is, the smaller the flux drop is likely to be over time.

Optimization of MF systems will not be discussed here due to the complexity and the totally different nature compared to the other membrane processes.

DO NOT . . .

Table 36. Do Not . . .

A	<p>- force a system to deliver high permeate flux. It is only possible with very few products and rarely possible for a long time. It will increase membrane fouling in all cases. The flux should, in spiral wound elements, be restricted to #35 l/mh. For most other systems 50 - 70 l/mh is a practical maximum.</p>																		
B	<p>- believe promises of >>100 l/mh permeate flux when treating industrial feed streams - unless you can get a bullet proof guarantee in writing. Until this day only the CR filter from Valmet Flootek has consistently exceeded 100 l/mh for extended periods of time and been able operate >24 hours per day without cleaning.</p>																		
C	<p>- exceed limits set by membrane manufacturer. There are certainly rules that can be broken, but it takes a lot of experience, insight or knowledge to get away with it where membranes are involved.</p>																		
D	<p>- expect to exceed the following TS by concentration of:</p> <table border="0" data-bbox="238 646 732 857"> <thead> <tr> <th data-bbox="238 646 453 667">TYPE OF SOLUTE</th> <th data-bbox="453 646 543 667">EXAMPLE</th> </tr> </thead> <tbody> <tr> <td data-bbox="238 667 453 688">polysaccharide</td> <td data-bbox="453 667 543 688">4% Xantan</td> </tr> <tr> <td data-bbox="238 688 453 709">low MW ionic solute</td> <td data-bbox="453 688 543 709">5% NaCl</td> </tr> <tr> <td data-bbox="238 709 453 730">divalent solute</td> <td data-bbox="453 709 543 730">15% NiSO₄</td> </tr> <tr> <td data-bbox="238 730 453 751">monosaccharide</td> <td data-bbox="453 730 543 751">15% glucose</td> </tr> <tr> <td data-bbox="238 751 453 773">protein</td> <td data-bbox="453 751 543 773">22% egg white or whey protein</td> </tr> <tr> <td data-bbox="238 773 453 794">disaccharide</td> <td data-bbox="453 773 543 794">25% ordinary sugar</td> </tr> <tr> <td data-bbox="238 794 453 815">milk concentrate</td> <td data-bbox="453 794 543 815">42%, for feta cheese production</td> </tr> <tr> <td data-bbox="238 815 453 836">oil emulsion</td> <td data-bbox="453 815 543 836">70% mineral oil in water</td> </tr> </tbody> </table> <p data-bbox="181 885 923 954">The literature often quotes values higher than those stated here. It may be possible in laboratory tests or for short periods of time for industrial applications, but most of this kind of information can be categorized as pure fiction.</p>	TYPE OF SOLUTE	EXAMPLE	polysaccharide	4% Xantan	low MW ionic solute	5% NaCl	divalent solute	15% NiSO ₄	monosaccharide	15% glucose	protein	22% egg white or whey protein	disaccharide	25% ordinary sugar	milk concentrate	42%, for feta cheese production	oil emulsion	70% mineral oil in water
TYPE OF SOLUTE	EXAMPLE																		
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disaccharide	25% ordinary sugar																		
milk concentrate	42%, for feta cheese production																		
oil emulsion	70% mineral oil in water																		
E	<p>- expect or ask for unreasonable production guarantees. A guarantee is a kind of insurance, and insurance costs money. It is better to first run thorough pilot tests and work with the membrane and system supplier to optimize the design and operation of a membrane system before assuming the responsibility for the operation.</p>																		

PRICE, SYSTEMS AND MEMBRANES

The prices mentioned in this section are prices for complete systems. By this it is meant complete systems, typically skid mounted, with membrane elements, internal piping and tubing, valves, pumps and control equipment. The prices mentioned do not include buildings, installation of the system or auxiliary facilities like water, drain, electric power and pressurized air.

Prices for membrane systems were stable in Europe from the mid 1970s to 1989. In the same period, prices in the USA were declining until the difference was out of proportion. In 1989, spiral wound elements were massively introduced into the dairy industry, which reduced the price for complete systems by a factor of three, from around US\$ 1,400 per m² to as low as US\$ 370 per m² membrane area installed. This price drop occurred within a few months. Since 1989 the prices have declined further. In early 2001 the price for a pharmaceutical system was typically US\$ 200 to 300 per m². Dairy systems typically sold for US\$ 150 to 250 per m² and water systems for US\$ 70 to 150 per m².

While this may attract more end users, the system supplier's low profit margin will make it more difficult for end users to get service and warranties.

SPIRAL WOUND ELEMENTS

For many years, spiral wound elements have been the least expensive on the market per m² of membrane area. Prices have slowly but surely declined until, in early 2000, they reached a point where it was difficult to reduce price further. This is due to the simple fact that sales price was uncomfortably close to the production price.

Replacement spiral wound element price. Note that price varies from country to country. It also depends on the number of elements and element construction.

Thin-film RO sells for	US\$ 15 - 25 per m ² membrane area
Thin-film NF sells for	US\$ 20 - 40 per m ² membrane area
Polysulfone UF sells for	US\$ 25 - 50 per m ² membrane area
Specialty elements sells for	US\$ 35 - 70 per m ² membrane area

The installation costs for a plant with spirals is typically in the range US\$ 300 to 500 per m² membrane area installed.

TUBULAR SYSTEMS

This membrane configuration is available, as previously mentioned, at two price levels.

PRICE, SYSTEMS AND MEMBRANES

There are a few low priced tubular systems on the market, selling for approximately the same price as spiral wound elements. They have some severe temperature and pressure limitations and can hardly compete except for a few unusual and undemanding applications.

The higher priced tubular systems sell for well over \$1,000 per m² membrane area installed, and although the market is limited, there are niche applications for highly priced tubular systems. Membrane replacement typically costs around US\$ 120 per m² membrane.

FLAT SHEET SYSTEMS

When the price for flat sheet membranes was highest, it was in the range US\$ 200 - 300 per m², but nobody loses money when spare membranes are sold today at approximately US\$ 130 to 180 per m².

Complete plate-and-frame systems can, in fact, be manufactured and sold profitably at a price close to that of systems with spiral wound elements. In the infancy of membrane filtration, plate-and-frame systems were sold at prices in the range of US\$ 2,000 to US\$ 3,000 per m² membrane installed based on political decisions. Instead of flooding the market with plate-and-frame systems in the early days of membrane filtration when competition was scarce, this system maintained a Rolls Royce status in the market and became almost extinct.

FIBER SYSTEMS

This membrane configuration sells at a high price, typically >US\$ 1,700 per m² membrane area installed, for treatment of oil emulsions and whole milk. Fibre configurations are rarely used in other applications.

The replacement membrane price is typically >US\$ 700 per m².

There are new fiber systems emerging, selling for close to US\$ 300 per m². It remains to be seen whether this new development will succeed. If they do, they will give the spirals real competition.

CERAMIC SYSTEMS

These are very, very expensive. They can cost >US\$ 10,000 per m². For years, manufacturers of ceramic membrane systems have been promising that next year the sale will boom, and they keep promising. The users of ceramic systems are either rich or have a very, very special product to treat. Even though ceramic systems are getting cheaper, they have a long way to go before they can start competing on price.

Choosing the system design for a given membrane filtration application is essentially easy and can be done in a few minutes, but preparing a detailed and well documented system design is a comprehensive task. However, some general rules and shortcuts which can help determine the first price estimate will be provided in the following, which is usually sufficient to determine whether a membrane filtration project is economically viable or not.

The following information is necessary:

- Volume to be treated, expressed in liters per hour for instance
- Concentration ratio or volume of permeate
(typically 75 - 95% of the feed volume)
- Expected permeate flux, expressed in liters per hour for instance

Either there are flux data available, or a guess must be made. It is not too difficult to make an educated guess on flux if the following rules are followed.

- RO: 15 to 25 lmh
- NF: 20 to 30 lmh
- UF: 25 to 50 lmh
- MF: No general rule

If in doubt, a low flux value should be used.

The Christmas tree design is totally dependent on the available flow, and there is not much flexibility for choosing design parameters. The following comments are valid for multi-stage recirculation systems.

(see next page)

DESIGNING A SYSTEM

Table 37. Necessary Steps for Designing a System

#1	Select, guess or measure flux in l/mh.
#2	Calculate the number of m ² membrane area by dividing permeate volume by flux.
#3	Select a membrane element and find the m ² membrane area per element.
#4	Calculate the number of membrane elements: (membrane area) / (membrane area per module)
#5	Is the number of modules reasonable? If NO : go back to # 4 If YES : continue to # 6
#6	Is there more than one membrane element per housing, e.g. spiral wound elements? If YES : select the number of modules per housing and calculate number of housings. If NO : continue to #7
#7	Calculating the number of recirculation loops is a bit tricky, because several parameters are involved in making a decision. If the flux curve is steep, select relatively many loops. If the flux curve flat, select relatively few loops. Select a number of loops and distribute the membrane elements evenly. Are the number of housings/modules big enough to justify the number of loops chosen? (The more expensive a system is, the more loops can be justified in order to increase efficiency and decrease membrane costs.)
#8	Find the specified feed flow and typical pressure drop per module. Since all modules/housings in a loop are in parallel, the type of recirculation pump can be chosen. Knowing the volume to be treated and (hopefully) the operating pressure, a feed pump can be chosen.
#9	Having selected flow, pressure and pumps, the kW consumed can be calculated.
#10	With respect to the cost of a membrane system, only a broad guideline can be provided. For industrial applications: Most spiral wound element systems will cost between US\$ 400 and US\$ 600 per m ² installed. These numbers can be doubled for more expensive tubular or fiber systems. For water desalination: Somewhat less expensive than industrial systems.
#11	The internal volume is typically 1.5 liters per m ² membrane area. This figure is important in order to calculate the amount of water used for flushing.
#12	Water for flushing is three times the internal volume per flush.
#13	Variable costs are mostly US\$ 0.4 - 1.0 per m ³ permeate. Interest and amortization is the same number as the variable costs. US\$ 1 per m ³ permeate in total is a good figure.

Table 37. Necessary Steps for Designing a System (continued)

#14	<p>There are no good rules of thumb for floor space. A lab system will usually take 2 -3 m². A production system with 1,000 m² membrane as spiral wound elements needs 30 square meters of floor space. Compared to most other processes, membrane filtration equipment does not take up much floor space.</p>																																											
#15	<p>Membranes are a consumable item. All users want to know how long membranes last, but it varies widely from application to application. The following is typical for polymer membranes, but even small variations in product composition can have a big impact on the life time, and so can the plant operator.</p> <table style="margin-left: auto; margin-right: auto; border: none;"> <tr> <td style="padding-right: 10px;">Water</td> <td style="padding-right: 10px;">RO, NF</td> <td style="padding-right: 10px;">3</td> <td style="padding-right: 10px;">to</td> <td style="padding-right: 10px;">6</td> <td style="padding-right: 10px;">years</td> </tr> <tr> <td>Water</td> <td>UF</td> <td>2</td> <td>to</td> <td>4</td> <td>years</td> </tr> <tr> <td>Dairy</td> <td>whhey</td> <td>1.5</td> <td>to</td> <td>2.5</td> <td>years</td> </tr> <tr> <td>Dairy</td> <td>whole milk</td> <td>1</td> <td>to</td> <td>2</td> <td>years</td> </tr> <tr> <td>Pharmaceutical</td> <td></td> <td>0.5</td> <td>to</td> <td>1.5</td> <td>years</td> </tr> <tr> <td>Oil emulsions</td> <td></td> <td>0.5</td> <td>to</td> <td>3</td> <td>years</td> </tr> <tr> <td>Pectin, etc</td> <td></td> <td>0.5</td> <td>to</td> <td>1.5</td> <td>years</td> </tr> </table>		Water	RO, NF	3	to	6	years	Water	UF	2	to	4	years	Dairy	whhey	1.5	to	2.5	years	Dairy	whole milk	1	to	2	years	Pharmaceutical		0.5	to	1.5	years	Oil emulsions		0.5	to	3	years	Pectin, etc		0.5	to	1.5	years
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#16	<p>Typical investment in a complete system, incl. pumps, tubes, membranes and controls</p> <table style="margin-left: auto; margin-right: auto; border: none;"> <tr> <td></td> <td style="text-align: center;">US\$ per m²</td> </tr> <tr> <td>Spiral wound element</td> <td style="text-align: center;">water 150</td> </tr> <tr> <td>Spiral wound element</td> <td style="text-align: center;">industrial 350</td> </tr> <tr> <td>Tubular</td> <td style="text-align: center;">1400</td> </tr> <tr> <td>Plate and frame</td> <td style="text-align: center;">>1700</td> </tr> <tr> <td>Fiber system</td> <td style="text-align: center;">>1700</td> </tr> <tr> <td>Ceramic</td> <td style="text-align: center;">>3000</td> </tr> </table>		US\$ per m²	Spiral wound element	water 150	Spiral wound element	industrial 350	Tubular	1400	Plate and frame	>1700	Fiber system	>1700	Ceramic	>3000	<p>Prices based on exchange rates January 2000.</p>																												
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It seems that price is often the only competitive parameter considered in many industries. It is the authors opinion that many end-users error when they buy a low-cost system. Subsequent problems with service, loss of valuable product, shut-down of process lines, change of process parameters and expansion of the system will often cost a lot more than the initial investment. It is possible that water desalination RO systems have become so standardized that low-cost systems are an acceptable choice. However, it is still necessary to use high quality components and good technical designs for process and waste water membrane systems. This is the only way to assure satisfactory, reliable and successful operation.

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