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The role of membrane technologies in water reuse applications

Peter S. Cartwright

Cartwright Consulting Co., 8324 16th Avenue South, Minneapolis, MN 55425-1742, USA
Tel. +1 952 854-4911, +31 71 5154417; Fax: +1 952 854-6964, +31 71 5156636; email: pscartwright@msn.com
President Kennedylaan, 94, 2343 GT, Oegstgeest, The Netherlands

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ABSTRACT

The world is not running out of water; the relatively fixed quantity is becoming too contaminated for many applications. In many cases, it is possible to collect and treat this contaminated water and reuse it. The crossflow, pressure-driven membrane technologies of microfiltration, ultrafiltration, nanofiltration, and reverse osmosis play an important role in water reuse activities. This study identifies the sources of "used" water (residential, commercial, industrial, and municipal), defines the contaminant parameters, addresses the appropriate membrane treatment technologies, and details system designs necessary to produce water for specific applications, such as potable.

Keywords: Microfiltration; Ultrafiltration; Nanofiltration; Reverse osmosis; Membranes; Reuse; Potable

1. Introduction

Although the total quantity of water on this planet is more or less fixed, its quality is deteriorating, because we have been contaminating it for thousands of years, with little concern for the consequences. The issue that confronts us is the availability of water of sufficient quality.

2. Contamination issues

The contaminants in water supplies which compromise its quality can be organized into the following classes:

Water contaminants

Class	Examples
Suspended solids	Dirt, clay, colloidal materials, silt, dust, insoluble metal oxides, and hydroxides
Dissolved organics	Trihalomethanes, synthetic organic chemicals, humic acids, fulvic acids
Dissolved ionics (salts)	Heavy metals, silica, arsenic, chlorides, sulfates
Microorganisms	Bacteria, viruses, protozoan cysts, fungi, algae, molds, yeast cells
Gases	Hydrogen sulfide, methane, radon, carbon dioxide

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There are not many absolutes in the water treatment industry, but here is one: *it is impossible to make water completely free of all contaminants.*

3. Water reuse

Although still in its infancy, water reuse is growing at an estimated 11% per year in the US. Most of the recovered water is from municipal wastewater treatment plants (reclaimed water) and is used for landscape and agricultural irrigation; however, industrial wastewater reuse is beginning to grow at an even higher rate—over 14% per year, by one estimate.

There are proven technologies available to treat any and all polluted water supplies; it is really a matter of committing financial and engineering resources. For almost all wastewater streams, a comprehensive test is required in order to select the optimum technologies and design the most cost-effective water recovery system.

Due to the extreme variation in the specific kind and concentration of contaminants, industrial wastewater reuse requires the most testing and design expertise; however, with the rapidly increasing discharge regulations on both water quality and quantity, the incentive to recover and reuse is in place.

As the paradigm of water reclamation takes hold throughout the world, the concept of "direct reuse," treating wastewater at the source and reusing it directly will become increasingly common, particularly in residential applications (graywater reuse). In many industrial applications, the incoming water has undergone extensive treatment for a particular process, and, overall, it is often more economical to treat this water for reuse than to simply discharge it, particularly as the cost of municipal water continues to increase.

4. Treatment technologies

The arsenal of treatment technologies available today for industrial and municipal wastewater treatment is extensive.

The traditional technologies are listed in Table 1.

A summary of major industrial treatment technologies is shown in Fig. 1.

As is evident from Fig. 1 and Table 1, a plethora of treatment technologies is available for removing contaminants from water supplies. For water reuse in most industrial and municipal applications, the most versatile and economical technology platform consists of the four crossflow pressure-driven membrane processes of:

- Microfiltration (MF)
- Ultrafiltration (UF)
- Nanofiltration (NF)
- Reverse osmosis (RO)

5. Membrane technologies

Membrane technologies are based on a process known as "pressure-driven crossflow" filtration, which allows for continuous treatment of liquid streams. In this process, the bulk solution flows over and parallel to the membrane surface, and because the system is pressurized, water is forced through the membrane and becomes "permeate". The turbulent flow of the bulk solution over the surface minimizes the accumulation of particulate matter.

These technologies behave differently than filters in that (with some exceptions) the feed stream is pumped at a high flow rate across the surface of the filter media (membrane), with a portion of this stream forced through the membrane to effect separation of the contaminants, producing the permeate, and the concentrated contaminant remaining in the other stream (concentrate) exits the membrane element on a continuous basis. Fig. 2 compares conventional with crossflow filtration.

Crossflow filtration offers the following advantages over traditional filtration technologies:

- Continuous and automatic operation.
- Capable of removing contaminants down into the submicron size range.
- Usually requires no chemical addition.
- Backwashing capabilities.
- Generally can operate in turbulent flow conditions.
- Systems have a very small footprint.

It is important to note that whereas with the media, cartridge and bag filtration technologies, the filtration process must be halted to backwash or replace the medium, crossflow filtration is designed to operate continuously, with the concentrate stream carrying away the contaminants. On the other hand, crossflow filters do become fouled and usually require backwashing or cleaning operations.

By utilizing surface filters of specific membrane construction, very small pore sizes can be obtained, resulting in two submicron technologies: MF and UF.

Microfiltration — is typically used to remove particulate material in the submicron range. Most MF devices in use today are designed as cartridge filters in that the entire solution passes through the filter leaving the particulate material behind, either on the filter surface or down inside the filter medium. The MF devices addressed here use the "crossflow" design, which produces two exiting streams: one

Table 1
Traditional treatment technologies

Treatment technologies	Suspended solids removal	Dissolved organic removal	Dissolved salts removal	Microorganism removal
Biological processes				
MBR (Membrane Bioreactor)	X	–	–	X
Activated sludge	X	X	–	X
Anaerobic digestion	X	X	–	–
Bio-filters	–	X	–	–
Extended aeration				
Bio-denitrification	–	L	–	–
Bio-nitrification	X	X	–	–
Pasveer oxidation ditch	X	X	–	X
Chemical processes				
Chemical oxidation				
Catalytic oxidation	X	X	–	X
Chlorination	X	X	–	X
Ozonation	–	L	–	X
Wet air oxidation	X	X	–	X
Chemical precipitation	–	–	X	–
Chemical reduction	–	–	X	–
Ion exchange	–	–	X	–
Liquid–liquid (solvent)	–	–	X	–
Coagulation				
Inorganic chemicals	X	X	–	X
Polyelectrolytes	X	X	–	X
Electrolytic processes				
Electrodialysis	–	–	X	L
Electrodeionization	–	–	X	–
Electrolysis	–	–	X	–
Ultraviolet irradiation	–	–	–	X
Extractions				
Incineration				
Fluidized-bed	X	X	–	X
Physical processes				
Carbon adsorption				
Granular activated	X	X	–	–
Powdered	X	X	–	X
Specialty resins	–	L	L	–
Filtration				
Diatomaceous-earth filtration	X	–	–	X
Multi-media filtration	X	–	–	X
Microscreening	X	–	–	X
Sand filtration	X	–	–	X
Flocculation–sedimentation	X	–	–	X
DAF (Dissolved air flotation)	X	X	–	–
Foam separation	X	–	X	–
Membrane processes				
Microfiltration	X	–	–	X
Ultrafiltration	X	X	–	X
Nanofiltration	X	X	L	X

(*Continued*)

Table 1 (*Continued*)

Treatment technologies	Suspended solids removal	Dissolved organic removal	Dissolved salts removal	Microorganism removal
Reverse osmosis	X	X	X	X
Stripping (air or steam)	X	X	–	–
Thermal processes				
Distillation	X	X	X	X
Freezing	–	X	X	–

Note: L = under certain conditions there will be limited effectiveness.

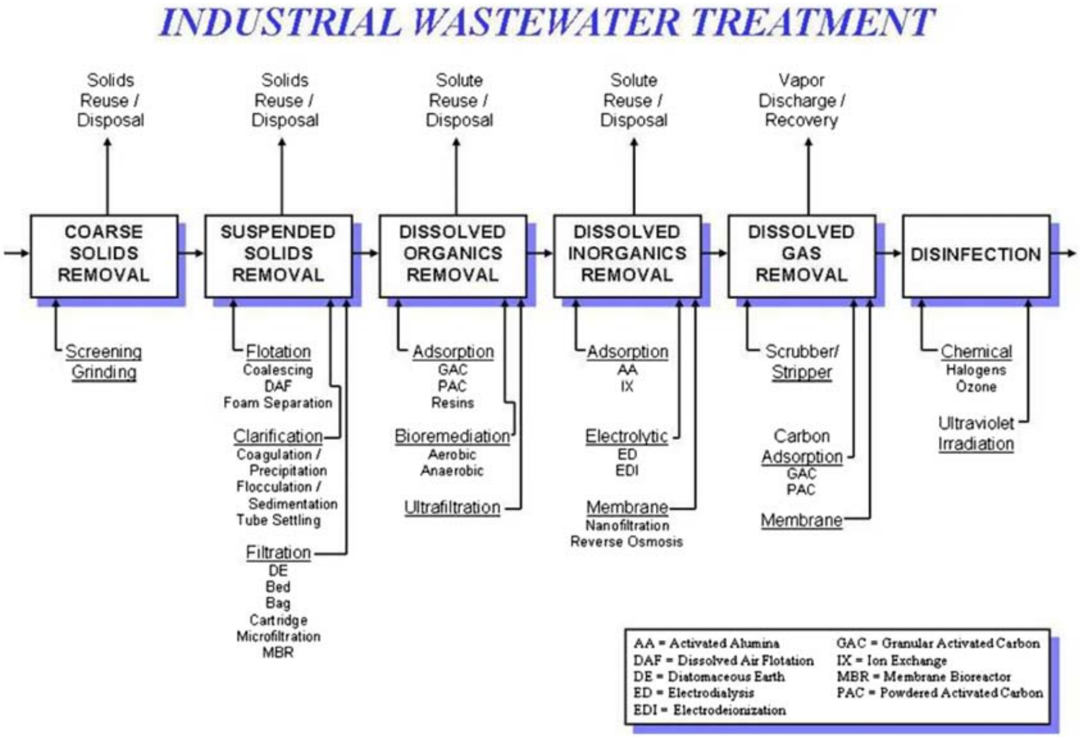


Fig. 1. Summary of major industrial treatment technologies.

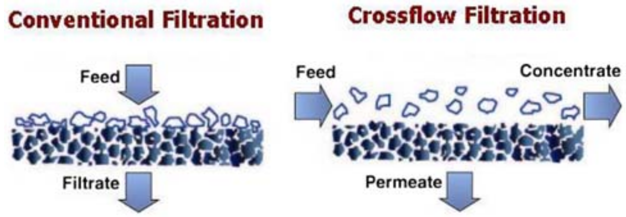


Fig. 2. Conventional vs. crossflow filtration.

which has passed through the membrane media and is purified (permeate), and the other which flows across and parallel to the media surface, continuously removing the contaminants (concentrate).

Generally, MF involves the removal of particulate or suspended materials ranging in size from approximately 0.10 to 1.0 μ (1,000 to 10,000 Å). MF typically operates within a pressure range of 10–30 psi (0.68–2.0 bar).

MF is depicted in Fig. 3.

Ultrafiltration – is used to separate dissolved, non-ionic materials (macromolecules) typically smaller than 0.10 μ (1,000 Å). The removal characteristics of UF membranes can be described in terms of "molecular weight cutoff" (MWCO), the maximum molecular weight of dissolved compounds that will pass through the membrane pores. MWCO terminology is expressed in Daltons (Da). Basically, UF is used to remove dissolved organic contaminants, while suspended solids are removed by MF. UF normally operates in a pressure range of 10–100 psi (0.68–6.8 bar).

Fig. 3. Microfiltration.

Fig. 4. Ultrafiltration.

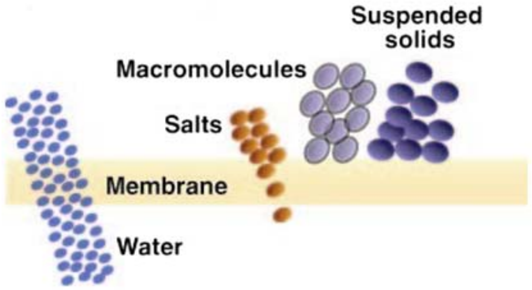


Fig. 5. Nanofiltration.

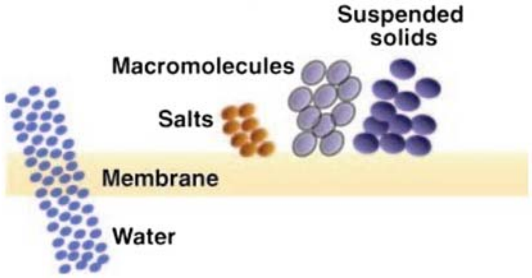


Fig. 6. Reverse osmosis.

UF membranes are available over a wide range of MWCO removal properties, from about 1,000 to over 100,000 Da.

UF technology is illustrated in Fig. 4.

The above processes (MF and UF) separate contaminants based on a "sieving" process; that is, any contaminant too large to pass through the pore is rejected and exits in the concentrate stream.

Nanofiltration can be considered "loose" reverse osmosis. It rejects dissolved ionic contaminants but to a lesser degree than RO. NF membranes reject a higher percentage of multivalent salts than monovalent salts (e.g. 99 vs. 20%). These membranes have MWCOs for nonionic solids below 1,000 Da. NF is illustrated in Fig. 5.

Reverse osmosis produces the highest quality permeate of any pressure-driven membrane technology. Certain polymers will reject over 99% of all ionic solids and have MWCOs in the range of 50–100 Da. RO is illustrated in Fig. 6.

Both NF and RO membranes reject salts utilizing a mechanism that is not fully understood. Some experts endorse the theory of pure water preferentially passing through the membrane; others attribute it to the effect of surface charges of the membrane polymer on the polarity of the water. Monovalent salts are not as highly rejected from the membrane surface as multivalent salts; however, the high rejection properties of the newer thin film composite RO membranes exhibit very little differences in salt rejection characteristics as a function of ionic valance. As indicated earlier, this difference is significant with NF membranes.

In all cases, the greater the degree of contaminant removal, the higher the pressure requirement to effect this separation. In other words, reverse osmosis, which separates the widest range of contaminants, requires an operating pressure typically an order of magnitude higher than MF, which removes only suspended solids.

Table 2 summarizes the various properties and other features of these technologies.

5.1. Device configurations

To be effective, membrane polymers must be packaged into a configuration commonly called a "device" or "element". The most common element configurations are: tubular, hollow (capillary) fiber, spiral wound, and plate and frame.

The element configurations are described and illustrated in Fig. 7.

5.1.1. Plate and frame

Sheet membranes are stretched over a frame to separate the layers and facilitate collection of the permeate, which is directed to a collection tube.

Table 2
Membrane technologies compared

Feature	Microfiltration	Ultrafiltration	Nanofiltration	Reverse osmosis
Materials of construction	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride, Polytetralluoroethyfiene	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride	Thin film composites, Cellulosics	Thin film composites, Cellulosics
Pore size range (micrometers)	0.1–1.0	0.001–0.1	0.0001–0.001	<0.0001
Molecular weight cutoff range (Da)	>100,000	1,000–100,000	300–1,000	50–300
Operating pressure range	<30	20–100	50–300	225–1,000
Suspended solids removal	Yes	Yes	Yes	Yes
Dissolved organics removal	None	Yes	Yes	Yes
Dissolved inorganics removal	None	None	20–95%	95–99 + %
Microorganism removal	Protozoan cysts, algae, bacteria*	Protozoan cysts, algae, bacteria*, viruses	All*	All*
Osmotic pressure effects	None	Slight	Moderate	High
Concentration capabilities	High	High	Moderate	Moderate
Permeate purity (overall)	Low	Moderate	Moderate-high	High
Energy usage	Low	Low	Low-moderate	Moderate
Membrane stability	High	High	Moderate	Moderate

*Under certain conditions, bacteria may grow through the membrane.

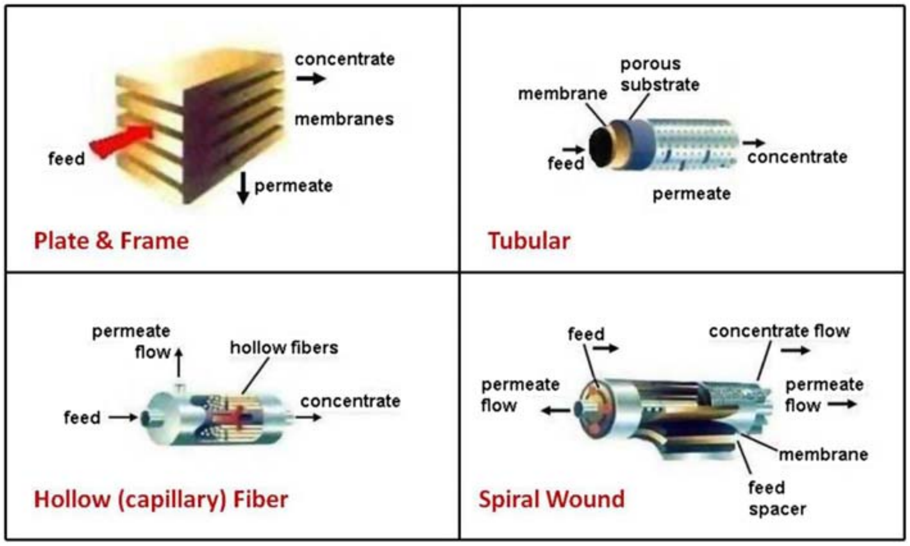


Fig. 7. Membrane element configurations.

5.1.2. Tubular

Manufactured from ceramics, carbon, stainless steel, or a number of thermoplastics, these tubes have inside diameters ranging from one-fourth inch up to approximately 1 inch (6–25 mm). The membrane is typically coated on the inside of the tube and the feed solution flows under pressure through the interior (lumen) from one end to the other, with the permeate passing through the wall and collected outside of the tube.

Table 3
Membrane element configuration comparison

Element configuration	Packing density*	Fouling resistance**
Plate & frame	Low	High
Tubular	Low	Very high
Hollow (Capillary) fiber	High	Medium
Spiral wound	Medium	Low

*Membrane area per unit volume.
**Tolerance to suspended solids.

5.1.3. Hollow (capillary) fiber

These elements are similar to the tubular element in design, but are smaller in diameter and are usually unsupported membrane polymers or ceramics. In the case of polymeric capillary fibers, they require rigid support on each end provided by an epoxy "potting" of a bundle of the fibers inside a cylinder. Feed flow is either down the interior of the fiber (lumen feed) or around the outside of the fiber (outside-in).

5.1.4. Spiral wound

This element is constructed from an envelope of sheet membrane wound around a permeate tube that is perforated to allow collection of the permeate. Water is purified by passing through one layer of the membrane and, following a spiral path, flows into the permeate tube. It is by far the most common configuration in water purification applications, but generally requires extensive pretreatment in wastewater applications.

Table 4
Microfiltration (MF) & Ultrafiltration (UF)

Materials of construction	Device configuration			
	Hollow fiber	Tubular	Plate & frame	Spiral wound
Polymeric				
PS	X	X	X	X
PES	X	X	X	X
PAN	X	X	X	X
PE	–	X	–	–
PP	X	X	X	–
PVC	–	X	–	–
PVDF	X	X	–	–
PTFE	X	–	X	–
PVP	X	X	–	–
CA	X	–	–	–
Non-Polymeric				
Coated 316LSS	–	X	–	None
α-alumina	–	X	X	None
Titanium dioxide	–	X	–	None
Silicon dioxide	–	X	–	None

Note: PS = Polysulfone, PVDF = Polyvinylidene fluoride, PES = Polyethersulfone, PTFE = Polytetrafluoroethylene, PE = Polyethylene, CA = Cellulose acetate, PP = Polypropylene, PVP = Polyvinylpyrrolidone, PAN = Polyacrylonitrile, TF = Thin film composite.

Table 5
Nanofiltration (NF) and reverse osmosis (RO)

Materials of construction	Device configuration			
	Hollow fiber	Tubular	Plate & frame	Spiral wound
Polymeric				
PS*	–	X	X	X
PES*	–	X	X	X
CA	–	X	X	X
TF	–	X	X	X
Non-Polymeric				
None				

*Base polymer below TF polymer, PS = Polysulphone, CA = Cellulose acetate, PES = Polyethersulfone, TF = Thin film composite.

From the perspective of cost and convenience, it is beneficial to pack as much membrane area into as small a volume as possible. This is known as "packing density." The greater the packing density, the greater the membrane area enclosed in a certain sized device, and generally the lower its cost. The downside of the high packing density membrane elements is their greater propensity for fouling. Table 3 compares the element configurations with regard to their packing densities.

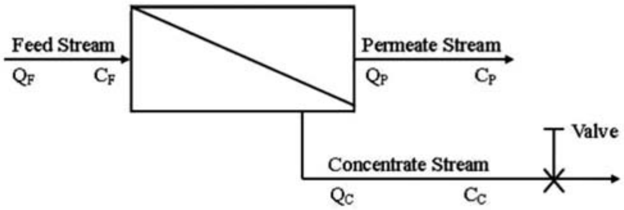
To clarify the membrane materials used for the various element configurations, Tables 4 and 5 are provided.

6. System design

Fig. 8 is a schematic of a complete membrane processing system (or a single membrane element).

The feed stream enters the system (or membrane element), and as the stream passes along and parallel to the surface of the membrane under pressure, a percentage of the water is forced through the membrane polymer producing the permeate stream. Contaminants are prevented from passing through the membrane based on the polymer characteristics. This contaminant-laden stream exits the membrane system (or element) as the "concentrate" stream, also known as "brine" or "reject."

The permeate rate of a given membrane element cannot be changed without varying the applied pressure or temperature. Recovery, however, can be easily



Q_F - Feed Flow Rate
C_F - Solute Concentration in Feed
Q_P - Permeate Flow Rate
C_P - Solute Concentration in Permeate
Q_C - Concentrate Flow Rate
C_C - Solute Concentration in Concentrate

$$\text{Recovery} = \frac{Q_P}{Q_F}$$

(Expressed as Percent)

TDS = Total Dissolved Solids: Usually considered the total of the ionic contaminants (salts) in solution.

mg/L (milligrams per liter) is the same as ppm (parts per million)

Fig. 8. Membrane system schematic.

changed by varying the feed flow rate to the element, and this is one of the variables that are controlled by the system designer.

For wastewater treatment and water reuse applications, the minimum recovery is usually no less than 90%.

The relationship between recovery and concentration of solute in the concentrate stream is illustrated by the data in the table and plotted in the Fig. 9 below. The concentration effect resulting from pumping a certain percentage of the solvent through the membrane is represented mathematically by the term:

$\frac{1}{1-\text{recovery}}$ also known as "concentration factor" (X).

One way to understand "concentration factor" is to think about the evaporation or distillation process. If half of a given volume of water is distilled and the condensate recovered as pure water (permeate), this is the same concept as operating a membrane system at 50% recovery. Evaporating three-fourths of the water is 75% recovery, and so on.

The advantage of operating systems at high recoveries is that the volume of concentrate is small and the flow rate of the feed pump is smaller; the potential disadvantages are numerous:

- The higher concentration of contaminants is likely to result in fouling. In NF and RO applications, the concentrated salts solution results in high osmotic pressure, requiring a high-pressure pump and a more pressure tolerant system.
- As higher recoveries reduce the quantity of concentrate to be discharged, the higher concentration of the concentrate stream may present regulatory discharge problems.

Effect of recovery on concentration

$$C_c \approx \frac{C_F}{1 - \text{Recovery}} = XC_F$$

$$X = \frac{1}{1 - \text{Recovery}} = \text{Concentration Factor}$$

Percent Recovery	Concentration Factor
33%	1.5
50%	2
67%	3
75%	4
80%	5
90%	10
95%	20
97.5%	40
98%	50
99%	100

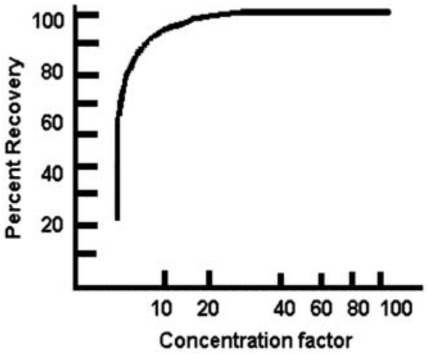


Fig. 9. Effect of recovery on concentration factor.

7. Testing

In general, every stream must be tested to develop the following design factors:

- Optimum membrane element configuration
- Total membrane area
- Specific membrane polymer
- Optimum pressure
- Maximum system recovery
- Flow conditions
- Membrane element array
- Pretreatment requirements

To generate the necessary design data, several testing options are available.

7.1. Cell testing

A typical cell testing device is illustrated in Fig. 10.

Cell test devices are available for purchase (or through a consulting engineering firm skilled in the art), which evaluate small sheets of membranes on the stream to be processed. Typically, the sheet is placed between two stainless steel plates, and the test stream

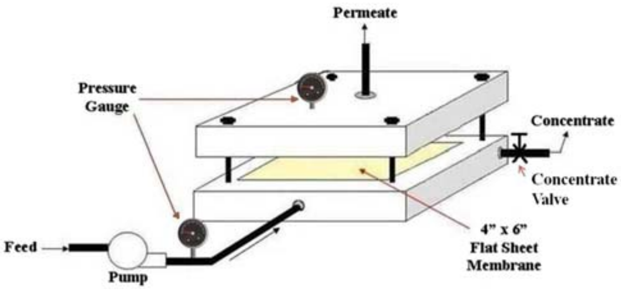


Fig. 10. Cell test unit.

pumped across the membrane surface at a selected pressure and flow rate. The permeate is collected and analyzed for the degree of separation, possible effect of the stream on the test membrane, and other properties.

The cell test offers a number of *advantages*:

- Only small areas of membranes are needed; excellent for screening membrane polymer candidates.
- Can be run on small volumes of test stream.
- Takes very little time.
- Unit is simple to operate.

The *disadvantages* of this testing approach are as follows:

- Cannot obtain engineering design data.
- Cannot be used for long-term fouling study.
- Is only useful with membranes available as flat sheet.
- The cell test approach is useful as an initial step, primarily to select one or more membrane candidates for further evaluation.

7.2. Application testing

Fig. 11 illustrates an application test schematic.

Application testing utilizes a membrane element in a test unit capable of operating similar to a production unit. Since the data from this testing will be used to scale up the design to full size, it is essential that the membrane element manufacturer supplies an element capable of this scale up.

The application test equipment should be designed so that very high recoveries can be achieved without compromising the flow rates required to produce turbulent flow, for example. This requires that the pump be capable of not only producing the desired pressure, but also the flow rate to accomplish the minimum crossflow velocity across the membrane surface.

Because the system must be capable of testing at very high recoveries, the concentrate valving must be adjustable to accurately produce extremely low flow rates. This typically involves the assembly of a "valve nest" using micrometer valves. Additionally, the recycle line should be equipped with a diaphragm valve for adjustment of flow and pressure.

The most important feature for application testing equipment is versatility. Different membrane elements have very specific operating parameters, and the equipment must accommodate these. To cover the entire gamut of membrane technologies, two different pieces of application testing equipment are generally required: one for MF and UF, and the other for NF and RO.

The latter must be capable of pressures up to 1,000 psi (68 bar), and it is virtually impossible to find a single pump capable of supplying the flows and pressures required for all four technologies. For MF and UF applications, a variable speed drive centrifugal pump works fine, although the variable speed feature makes it expensive.

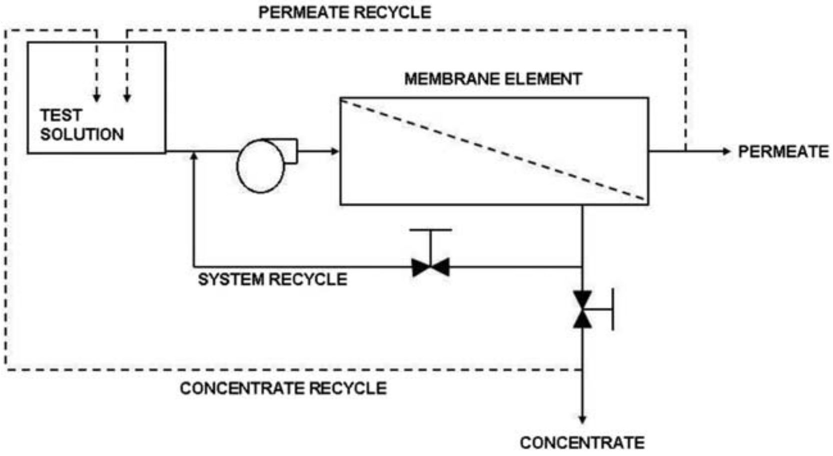


Fig. 11. Applications test schematic.

Materials of construction are an important consideration in testing considerations: 316 L stainless steel is essential for applications requiring pressures in excess of 60 psi (4 bar); below that, schedule 80 PVC is sufficient.

Application testing is capable of generating complete design data for the full-sized system. An applications test can be run on as little as 50 gallons (200 L) of test stream, and after setup, can be completed in one hour or less, for each membrane element tested.

A typical applications test is run as follows:

(1) To establish "control conditions", high-quality water (tap water or water treated with RO or DI) is run into the system at low recovery to minimize any possible contaminant concentration effects. Take data.
(2) Feedwater is then run into the unit set at low recovery, and after stabilization (usually less than 5 min), the following data are taken:

(a) Pressures

  (1) Prefilter
  (2) Primary (feed)
  (3) Final (concentrate line)

(b) Flow Rate

  (1) Recycle
  (2) Permeate
  (3) Concentrate

(c) Temperature (recycle)
(d) Quality (conductivity)

  (1) Feed
  (2) Permeate
  (3) Concentrate

(e) The system recovery is then increased incrementally while adjusting the recycle valve to ensure that the correct crossflow velocity is maintained.

(1) At the conclusion of the testing, high-quality water is again run through the system to determine whether the permeate rate or other operating characteristics have been affected.

At each recovery, in addition to the collection of flow and pressure data, analytical samples should be taken for performance evaluation. Of course, the choice of parameters to be measured depends upon the separation goals of the test. It is unusual for system recoveries to exceed 95%; however, that also depends upon the goals of the testing, and it is possible to run a well designed test unit up to 99% recovery.

Once the optimum conditions have been established, such as operating pressure and maximum system recovery, the normalized performance data will enable the test engineer to determine the total membrane area required for the full-sized system.

Application testing provides the following advantages and disadvantages:

(i) Advantages

- Fast.
- Provides scale-up data (flow, osmotic pressure as a function of recovery, pressure requirements, etc.).
- Can provide an indication of membrane stability.

(ii) Disadvantages

- Does not reveal long-term chemical effects.
- Does not provide data on long-term fouling effects.

7.3. Pilot testing

Usually, this involves placing a test machine (such as that used for the applications test) in the process, operating continuously on a "side-stream" for a minimum of 30 days.

(i) Advantages

- Accomplishes all of the functions of the applications test plus provides long-term membrane fouling and stability data.

(ii) Disadvantages

- Expensive in terms of monitoring and time requirements.

8. Conclusions

With the exception of the oxygen we breathe, there is no substance more critical to life than water, and no substitute for it.

Many experts feel that there is no other product whose real value so far exceeds its price, and whose price is so often unrelated to its actual cost of production and delivery.

As the world's population continues to grow, as this expanding population tends to relocate to water-short regions, and as climate changes create areas of drought, stress on the quality of our fixed water quantity will become very, very critical. This problem can only be addressed by aggressively and constructively employing such innovative conservation and water reuse.

Solutions are there, but the entire world must give water quality issues high priority and be willing to commit the investments of money, education, and commitment to make these solutions a reality.