Tech Brief

A NATIONAL DRINKING WATER CLEARINGHOUSE FACT SHEET

Membrane Filtration

Summary

A membrane or, more properly, a semipermeable membrane, is a thin layer of material capable of separating substances when a driving force is applied across the membrane.

Once considered a viable technology only for desalination, membrane processes are increasingly employed for removal of bacteria and other microorganisms, particulate material, and natural organic material, which can impart color, tastes, and odors to the water and react with disinfectants to form disinfection byproducts (DBP). As advancements are made in membrane production and module design, capital and operating costs continue to decline.

The pressure-driven membrane processes discussed in this fact sheet are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO).

Membrane Filtration: Alternative to Conventional Filtration

Membrane filtration systems' capital costs, on a basis of dollars per volume of installed treatment capacity, do not escalate rapidly as plant size decreases. This factor makes membranes quite attractive for small systems. In addition, for groundwater sources that do not need pretreatment, membrane technologies are relatively simple to install, and the systems require little more than a feed pump, a cleaning pump, the membrane modules, and some holding tanks. According to a 1997 report by the National Research Council, most experts foresee that membrane filtration will be used with greater frequency in small systems as the complexity of conventional treatment processes for small systems increases.

New Regulations Favor Membrane Technologies

Membrane processes have become more attractive for potable water production in recent years due to the increased stringency of drinking water regulations. Membrane processes have excellent separation capabilities and show promise for meeting many of the existing and anticipated drinking water standards. The Surface Water Treatment Rule (SWTR) and the anticipated Groundwater Disinfection Rule have led to the investigation of UF and MF for turbidity and microbial removal. The new Disinfectants/Disinfection Byproduct (D/DBP) rules have increased interest in NF and UF membranes for DBP precursor removal.

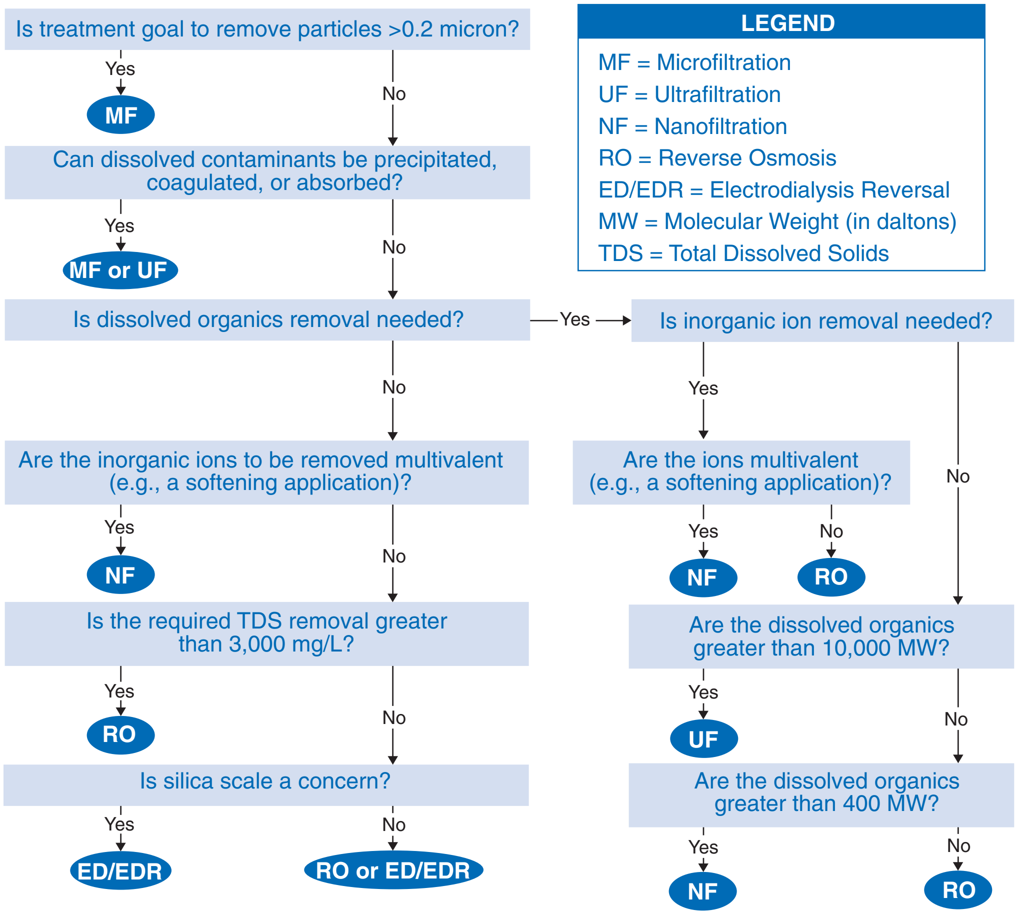
Potable water treatment has traditionally focused on processes for liquid-solid separation rather than on processes for removing dissolved contaminants from water. Thus, the effect of the 1996 Safe Drinking Water Act (SDWA) amendments has been to encourage water treatment professionals to consider the more unconventional treatment processes, such as membrane technologies, alone, or in conjunction with liquid-solid separation, to meet current regulations.

Comparing Membrane Filtration Systems

While all types of membranes work well under proper conditions, choosing the most appropriate membrane for a given application still remains crucial. (See Figure 1.) In many cases, selection is complicated by the availability of new types of membranes, applications, or by site-specific conditions. Bench and pilot tests are powerful tools for situations where process risks and uncertainties exist or the cost impacts from problems are potentially high.

Membrane classification standards vary considerably from one filter supplier to another. What

Figure 1: Generalized Membrane Process Selection Chart



LEGEND

MF = Microfiltration
UF = Ultrafiltration
NF = Nanofiltration
RO = Reverse Osmosis
ED/EDR = Electrodialysis Reversal
MW = Molecular Weight (in daltons)
TDS = Total Dissolved Solids

NOTE: This simplified chart is based on common assumptions and should not be applied to every situation without more detailed analysis.

ASSUMPTIONS

A. Relative Cost
- MF < UF < NF < RO or ED/EDR
- If TDS removal > 3,000 mg/L, RO or ED/EDR may be less costly

B. Removals
- MF–particles > 0.2 Micron
- UF–organics > 10,000 MW, virus, and colloids
- NF–organics > 400 MW and hardness ions
- RO–salts and low MW organics
- ED/EDR–Salts
- Particles include *Giardia*, *Cryptosporidium*, bacteria, and turbidity

Reprinted from Proceedings of the 1993 Membrane Technology Conference, *by permission.*
Copyright ©1993, American Water Works Association.

one supplier sells as a UF product, another manufacturer calls a NF system. It is better to look directly at pore size, molecular weight cutoff (MWCO), and applied pressure needed when comparing two membrane systems. MWCO, which can be regarded as a measure of membrane pore dimensions, is a specification used by membrane suppliers to describe a membrane's retention capabilities.

Microfiltration (MF)

MF is loosely defined as a membrane separation process using membranes with a pore size of approximately 0.03 to 10 microns, a MWCO of greater than 100,000 daltons, and a relatively low feedwater operating pressure of approximately 100 to 400 kPa (15 to 60 psi). Representative materials removed by MF include sand, silt, clays, *Giardia lamblia* and *Cryptosporidium* cysts, algae, and some bacterial species. (See Figure 2 and Table 1.) MF is not an absolute barrier to viruses; however, when used in combination with disinfection, MF appears to control these microorganisms in water.

The primary impetus for the more widespread use of MF has been the increasingly stringent requirements for removing particles and micro-organisms from drinking water supplies. Addi-tionally, there is a growing emphasis on limiting the concentrations and number of chemicals that are applied during water treatment. By physically removing the pathogens, membrane filtration can significantly reduce chemical addition, such as chlorination.

Another application for the technology is for removal of natural or synthetic organic matter to reduce fouling potential. In its normal opera- tion, MF removes little or no organic matter; however, when pretreatment is applied, in-creased removal of organic material, as well as a retardation of membrane fouling can be realized.

Two other applications involve using MF as a pretreatment to RO or NF to reduce fouling potential. Both RO and NF have been traditionally employed to desalt or remove hardness from groundwater.

PROCESS

MF membranes provide absolute removal of particulate contaminants from a feed stream by separation based on retention of contaminants on a membrane surface. It is the “loosest” of the membrane processes, and as a consequence of its large pore size, it is used primarily for removing particles and microbes and can be operated under ultralow pressure conditions.

In the simplest designs, the MF process involves prescreening raw water and pumping it under pressure onto a membrane. In comparison to conventional water clarification processes, where coagulants and other chemicals are added to the water before filtration, there are few pretreatment requirements for hollow-fiber systems when particles and microorganisms are the target contaminants.

Prefilters are necessary to remove large particles that may plug the inlet to the fibers within the membrane module. More complex pretreatment strategies are sometimes employed either to reduce fouling or enhance the removal of viruses and dissolved organic matter. In such cases, pretreatment by adding coagulants or powdered activated carbon (PAC), has been employed. In some cases, the cake layer built up on the membrane during the water production cycle can remove some organic materials.

It may be necessary to adjust the feedwater pH by chemical dosing prior to membrane filtration in order to maintain the pH within the recommended operating range for the membrane material employed. It should be noted that pH adjustment is not required for scaling control, since MF membranes do not remove uncomplexed dissolved ions.

MF membranes, under the most conservative conditions, appear to act as an absolute barrier to selected bacteria and protozoan cysts and oocysts. Unlike UF however, MF does not remove appreciable densities of viruses. Therefore, it is necessary to complement MF with a post-membrane disinfection process. Chemical disinfection may be employed by applying chlorine, chlorine dioxide, or chloramines; however, long contact times are required to inactivate viruses.

EQUIPMENT

For municipal-scale drinking water applications, the commercially available membrane geometries that are the most commonly em-ployed are spiral wound, tubular, and hollow capillary fiber. However, spiral-wound configurations are not normally employed for MF due to the flat-sheet nature of the membrane, which presents difficulties in keeping the membrane surface clean. Unlike spiral-wound membranes, hollow-fiber and tubular configurations allow the membrane to be backwashed, a process by which fouling due to particulate and organic materials is controlled.

Membrane “package” plants are normally employed for plants treating less than one million gallons per day (mgd). The components of the plant may include prescreens, a feed pump, a cleaning tank, an automatic gas backwash system, an air compressor, a membrane integrity monitor, a backwash water transfer tank, a pressure break reservoir, an air filter for the gas backwash, controls for the programmable logic controller, and a coalescer.

OPERATION AND MAINTENANCE

In MF, there are two methods for maintaining or re-establishing permeate flux after the membranes are fouled:

- Membrane backwashing: In order to prevent the continuous accumulation of solids on the membrane surface, the membrane is backwashed. Unlike backwashing for conventional media filtration, the backwashing cycle takes only a few minutes. Both liquid and gas backwashing are employed with MF technology. For most systems, backwashing is fully automatic. If backwashing is incapable of restoring the flux, then membranes are chemically cleaned. The variables that

should be considered in cleaning MF membranes include: frequency and duration of cleaning, chemicals and their concentrations, cleaning and rinse volumes, temperature of cleaning, recovery and reuse of cleaning chemicals, neutralization and disposal of cleaning chemicals.

- Membrane pretreatment: Feedwater pretreatment can be employed to improve the level of removal of various natural water constituents. It is also used to increase or maintain transmembrane flux rates and/or to retard fouling. The two most common types of pretreatment are coagulant and PAC addition.

Ultrafiltration (UF)

UF involves the pressure-driven separation of materials from water using a membrane pore size of approximately 0.002 to 0.1 microns, an MWCO of approximately 10,000 to 100,000 daltons, and an operating pressure of approximately 200 to 700 kPa (30 to 100 psi). UF will remove all microbiological species removed by MF (partial removal of bacteria), as well as some viruses (but not an absolute barrier to viruses) and humic materials. (See Figure 2 and Table 1.) Disinfection can provide a second barrier to contamination and is therefore recommended.

The primary advantages of low-pressure UF membrane processes compared with conventional clarification and disinfection (postchlorination) processes are:

- No need for chemicals (coagulants, flocculants, disinfectants, pH adjustment);
- Size-exclusion filtration as opposed to media depth filtration;
- Good and constant quality of the treated water in terms of particle and microbial removal;
- Process and plant compactness; and
- Simple automation.

Fouling is the limiting phenomenon responsible for most difficulties encountered in membrane technology for water treatment. UF is certainly not exempt from this fouling control problem. Therefore, membrane productivity is still an important subject, which should be thoroughly researched in order to have a better understanding of this phenomenon and its mechanisms.

PROCESS

UF is a pressure-driven process by which colloids, particulates, and high molecular mass soluble species are retained by a process of size exclusion, and, as such, provides means for concentrating, separating into parts, or filtering dissolved or suspended species. UF allows most ionic inorganic species to pass through the membrane and retains discrete particulate matter and nonionic and ionic organic species.

UF is a single process that removes many water-soluble organic materials, as well as microbiological contaminants. Since all UF membranes are capable of effectively straining protozoa, bacteria, and most viruses from water, the process offers a disinfected filtered product with little load on any post-treatment sterilization method, such as UV radiation, ozone treatment, or even chlorination.

Unlike RO, the pretreatment requirement for UF is normally quite low. Fortunately, due to the chemical and hydrolytic stability of UF membrane materials, some of the pretreatments essential for RO membranes, such as adjustment of pH or chlorine concentration levels, do not apply. However, it may be necessary to adjust the pH to decrease the solubility of a solute in the feed so that it may be filtered out.

UF is designed to remove suspended and dissolved macromolecular solids from fluids. The commercially available modules are therefore designed to accept feedwaters that carry high loads of solids. Because of the many uses for UF membranes, pilot studies are normally conducted to test how suitable a given stream is for direct UF.

Water containing dissolved or chelated iron and manganese ions needs to be treated by an adequate oxidation process in order to precipitate these ions prior to UF membrane filtration, as with all membrane processes. This is recommended to avoid precipitation of iron and manganese in the membrane, or even worse, on the permeate side of the membrane (membrane fouling during the backwash procedure). Preoxidation processes generally used include aeration, pH adjustment to a value greater than eight, or addition of strong oxidants, such as chlorine, chlorine dioxide, ozone, or potassium permanganate.

Natural Organic Matter (NOM) is of great importance in potential fouling of the UF membrane and, consequently, in permeate flux that can be used under normal operating conditions. Thus, it is an interesting design option to use PAC or coagulants to pretreat the water to remove NOM and, consequently, decrease the surface of membrane needed.

EQUIPMENT

UF membranes can be fabricated essentially in one of two forms: tubular or flat-sheet.

Package plants, skid-mounted standard units that allow significant cost savings, are usually employed for plants treating less than 1.5 mgd. The primary skid-mounted system components may include an auto-cleaning prefilter, raw water pump, recirculation pump, backwash pump, chlorine dosing pump for the backwash water, air compressor (valve actuation), chlorine tank, chemical tank (detergent), programmable logic controller with program and security sensor (high pressure, low level, etc.)

OPERATION AND MAINTENANCE

The UF membrane plant may be divided into several subcategories:

- Raw water intake and pressure pumps;
- Pretreatment, which includes prescreening, prefiltration, and pH adjustment (if required) or any of the needed pretreatments;
- UF units;
- Chemical cleaning station, backwash station (which uses chlorinated product water), chlorine station, conditioner/preservative station; and
- Line for discharging or treatment of back wash water.

Operation and performance of a UF membrane plant are greatly influenced by raw water quality variations. Turbidity as well as Total Organic Carbon (TOC) of the raw water are water quality parameters of major importance that drive operation mode and membrane flux for all the UF plants presently in operation worldwide.

Nanofiltration (NF)

NF membranes have a nominal pore size of approximately 0.001 microns and an MWCO of 1,000 to 100,000 daltons. Pushing water through these smaller membrane pores requires a higher operating pressure than either MF or UF. Operating pressures are usually near 600 kPa (90 psi) and can be as high as 1,000 kPa (150 psi). These systems can remove virtually all cysts, bacteria, viruses, and humic materials. (See Figure 2 and Table 1.) They provide excellent protection from DBP formation if the disinfectant residual is added after the membrane

filtration step. Because NF membranes also remove alkalinity, the product water can be corrosive, and measures, such as blending raw water and product water or adding alkalinity, may be needed to reduce corrosivity. NF also removes hardness from water, which accounts for NF membranes sometimes being called “softening membranes.” Hard water treated by NF will need pretreatment to avoid precipitation of hardness ions on the membrane.

More energy is required for NF than MF or UF, which has hindered its advancement as a treatment alternative.

PROCESS

NF membranes have been observed to operate on the principle of diffusion rather than sieving as with MF and UF membranes.

OPERATION AND MAINTENANCE

Operational parameters of membranes include the physical and chemical properties of the membrane, the pore size or molecular weight cut-off (MWCO), and configuration.

Reverse Osmosis (RO)

RO systems are compact, simple to operate, and require minimal labor, making them suitable for small systems. They are also suitable for systems where there is a high degree of seasonal fluc-tuation in water demand.

RO can effectively remove nearly all inorganic contaminants from water. RO can also effectively remove radium, natural organic substances, pesticides, cysts, bacteria, and viruses. (See Figure 2 and Table 1.) RO is particularly effective when used in series. Water passing through multiple units can achieve near zero effluent contaminant concentrations. Disinfection is also recommended to ensure the safety of water.

Some of the advantages of RO are:

- Removes nearly all contaminant ions and most dissolved non-ions,

Table 1. Surface Water Treatment Compliance Technology: Membrane Filtration

Unit Technologies	Removals: Log Giardia & Log Virus	Raw Water, Pretreatment & Other Water Quality Issues
Microfiltration (MF)	Very effective Giardia, >5-6 log; Partial removal of viruses (disinfect for virus credit).	High quality or pretreatment required. Same note regarding TOC.
Ultrafiltration (UF)	Very effective Giardia, >5-6 log; Partial removal of viruses (disinfect for virus credit).	High quality or pretreatment required (e.g., MF). TOC rejection generally low, so if DBP precursors are a concern, NF may be preferable.
Nanofiltration (NF)	Very effective, absolute barrier (cysts and viruses).	Very high quality or pretreatment required (e.g., MF or UF to reduce fouling/extend cleaning intervals). See also RO pretreatments, below.
Reverse Osmosis (RO)	Very effective, absolute barrier (cysts and viruses).	May require conventional or other pretreatment for surface water to protect membrane surfaces: may include turbidity or Fe/Mn removal; stabilization to prevent scaling; reduction of dissolved solids or hardness; pH adjustment.

Source: U.S. Environmental Protection Agency, 1998.

Table 2. Surface Water Treatment Compliance Technology: Membrane Filtration

Unit Technologies	Complexity: Ease of Operation (Operator Skill Level)	Secondary Waste Generation	Other Limitations/ Drawbacks
Microfiltration	Basic: increases with pre/post-treatment and membrane cleaning needs.	Low-volume waste may include sand, silt, clay, cysts, and algae.	Disinfection required for viral inactivation.
Ultrafiltration	Basic: increases with pre/post-treatment and membrane cleaning needs.	Concentrated waste: 5 to 20 percent volume. Waste may include sand, silt, clays, cysts, algae, viruses, and humic material	Disinfection required for for viral inactivation.
Nanofiltration	Intermediate: increases with pre/post-treatment and membrane cleaning needs.	Concentrated waste: 5 to 20 percent volume.	Disinfection required under regulation, and recommended as a safety measure and residual protection.
Reverse Osmosis	Intermediate: increases with pre/post-treatment and membrane cleaning needs.	Briney waste. High volume, e.g., 25 to 50 percent. May be toxic to some species.	Bypassing of water (to provide blended/stabilized distributed water) cannot be practiced at risk of increasing microbial concentrations in finished water. Post-disinfection required under regulation, is recommended as a safety measure and for residual maintenance. Other post-treatments may include degassing of CO2 or H2S, and pH adjustment.

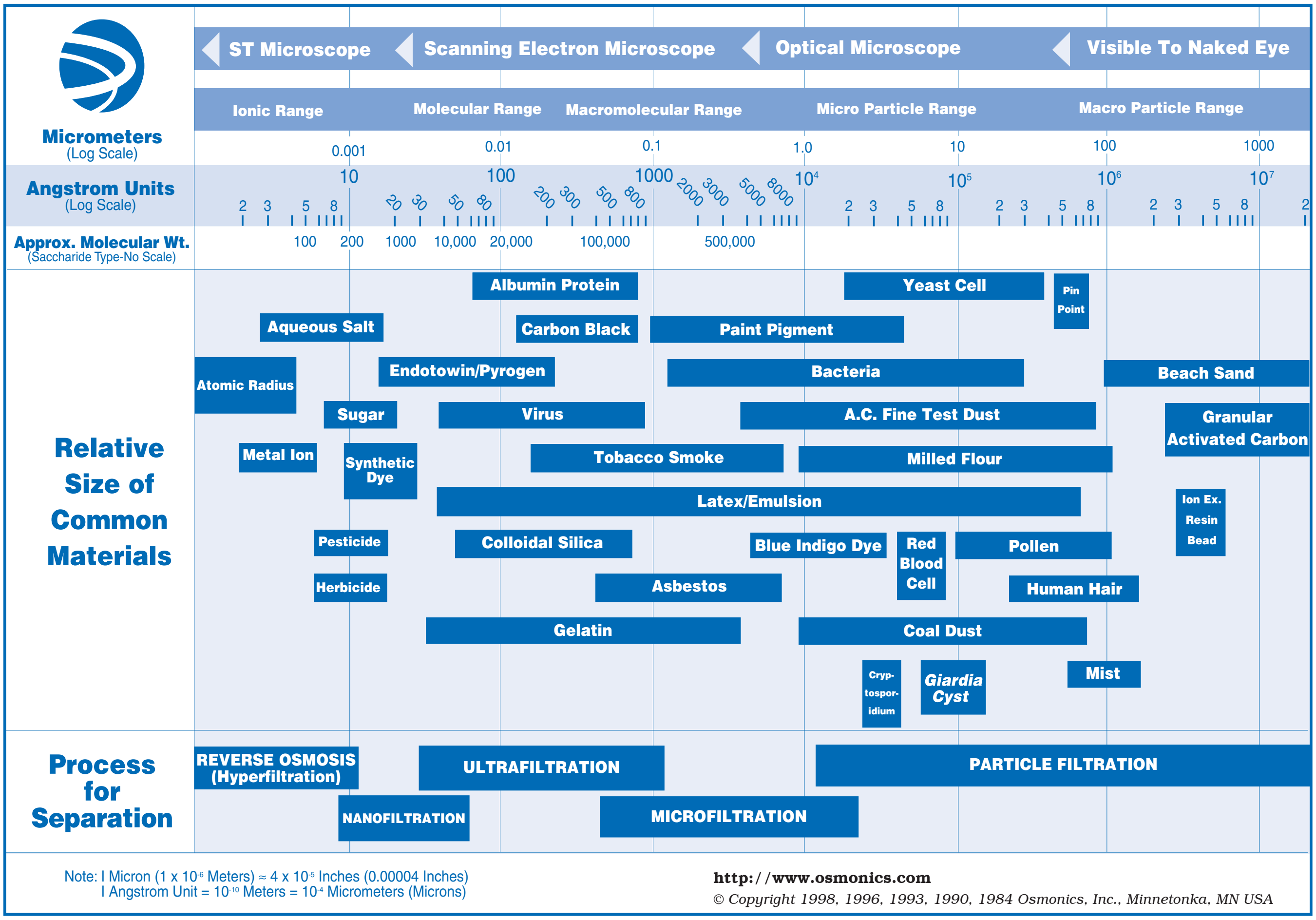
Source: U.S. Environmental Protection Agency, 1998.

- Relatively insensitive to flow and total dissolved solids (TDS) level, and thus suitable for small systems with a high degree of seasonal fluctuation in water demand,
- RO operates immediately, without any minimum break-in period,
- Low effluent concentration possible,
- Bacteria and particles are also removed, and
- Operational simplicity and automation allow for less operator attention and make RO suitable for small system applications.

Some of the limitations of RO are:

- High capital and operating costs,
- Managing the wastewater (brine solution) is a potential problem,
- High level of pretreatment is required in some cases,

Figure 2. The Filtration Spectrum



Note: I Micron (1 x 10⁻⁶ Meters) ≈ 4 x 10⁻⁵ Inches (0.00004 Inches)
I Angstrom Unit = 10⁻¹⁰ Meters = 10⁻⁴ Micrometers (Microns)

http://www.osmonics.com

Reprinted courtesy of Osmonics, Inc., Minnetonka, MN.

- Membranes are prone to fouling, and
- Produces the most wastewater at between 25–50 percent of the feed.

PROCESS

RO removes contaminants from water using a semipermeable membrane that permits only water, and not dissolved ions (such as sodium and chloride), to pass through its pores. Contaminated water is subject to a high pressure that forces pure water through the membrane, leaving contaminants behind in a brine solution. Membranes are available with a variety of pore sizes and characteristics.

EQUIPMENT

Typical RO units include raw water pumps, pretreatment, membranes, disinfection, storage, and distribution elements. These units are able to process virtually any desired quantity or quality of water by configuring units sequentially to reprocess waste brine from the earlier stages of the process. The principal design considerations for reverse osmosis units are:

- operating pressure,
- membrane type and pore size,
- pretreatment requirements, and
- product conversion rate (the ratio of the influent recovered as waste brine water to the finished water).

Waste Stream Disposal

Waste stream disposal is a significant problem in many areas. Unlike conventional treatment processes, in which approximately 5 to 10 percent of the influent water is discharged as waste, membrane processes produce waste streams amounting to as much as 15 percent of the total treated water volume. (See Table 2.) Because little or no chemical treatment is used in a membrane system, the concentrate stream usually contains only the contaminants found in the source water (although at much higher concentrations), and for this reason the concentrate can sometimes be disposed of in the source water. Other alternatives include deep well injection, dilution and spray irrigation, or disposal in the municipal sewer. These alternatives are usually necessary for NF wastes, which usually contain concentrated organic and inorganic compounds. Regardless of the type of membrane, disposal must be carefully considered in decisions about the use of membrane technology. Applicable local discharge regulations must be respected.

Membrane Integrity Testing

One of the most critical aspects of employing membrane technology is ensuring that the membranes are intact and continuing to provide a barrier between the feedwater and the permeate or product water. There are several different methods that can be employed to monitor membrane integrity, including:

- Turbidity monitoring,
- Particle counting or monitoring,
- Air pressure testing,
- Bubble point testing,
- Sonic wave sensing, and
- Biological monitoring.

Where can I find more information?

(1) American Water Works Association and American Society of Civil Engineers. 1998. *Water Treatment Plant Design.* New York: McGraw-Hill.

(2) Bergman, A.R. and J.C. Lozier. 1993. “Membrane Process Selection and the Use of Bench and Pilot Tests.” *Membrane Technology Conference Proceedings.* Baltimore: American Water Works Association.

(3) Jacangelo, J. G., J-M. Laine, E.W. Cummings, A. Deutschmann, J. Mallevialle, M.R. Wiesner. 1994. *Evaluation of Ultrafiltration Membrane Pretreatment and Nanofiltration of Surface Waters.* Denver: American Water Works Association and AWWA Research Foundation.

(4) Jacangelo, J. G., S. Adham, J-M. Laine. 1997. *Membrane Filtration for Microbial Removal.* Denver: American Water Works Association Research Foundation and American Water Works Association.

(5) Mallevialle, J., P.E. Odendaal, and M.R. Wiesner, 1996. *Water Treatment Membrane Processes.* New York: McGraw-Hill.

(6) National Research Council. 1997. *Safe Water From Every Tap.* Washington, D.C.: National Academy Press.

(7) U.S. Environmental Protection Agency. 1990. *Environmental Pollution Control Alternatives: Drinking Water Treatment for Small Communities.* Washington, D.C.: Office of Water. EPA/625/5-90/025.

(8) U.S. Environmental Protection Agency. 1989. *Technologies for Upgrading Existing or Designing New Drinking Water Treatment Facilities.*Washington, D.C.: Office of Water. EPA/625/4-89/023.

(9) U.S. Environmental Protection Agency. 1998. *Small System Compliance Technology List for the Surface Water Treatment Rule and Total Coliform Rule.* Washington, D.C.: Office of Water. EPA/815/R/98/001.