Membrane Filtration

A membrane is a thin layer of semi-permeable material that separates substances when a driving force is applied across the membrane. Membrane processes are increasingly used for removal of bacteria, microorganisms, particulates, and natural organic material, which can impart color, tastes, and odors to water and react with disinfectants to form disinfection byproducts.

As advancements are made in membrane production and module design, capital and operating costs continue to decline. The membrane processes discussed here are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO).

MICROFILTRATION

Microfiltration is loosely defined as a membrane separation process using membranes with a pore size of approximately 0.03 to 10 micronas (1 micron = 0.0001 millimeter), a molecular weight cut-off (MWCO) of greater than 1000,000 daltons and a relatively low feed water operating pressure of approximately 100 to 400 kPa (15 to 60psi) Materials removed by MF include sand, silt, clays, Giardia lamblia and Crypotosporidium cysts, algae, and some bacterial species. MF is not an absolute barrier to viruses. However, when used in combination with disinfection, MF appears to control these microorganisms in water.

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 synthetic organic matter to reduce fouling potential. In its normal operation, MF removes little or no organic matter; however, when pretreatment is applied, increased removal of organic material can occur. MF can be used 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.

ULTRAFILTRATION

Ultrafiltration has a 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. Disinfection can provide a second barrier to contamination and is therefore recommended.

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

- No need for chemicals (coagulants, flocculants, disinfectants, pH adjustment)
- Size-exclusion filtration as opposed to media depth filtration

- Constant quality of the treated water in terms of particle and microbial removal
- Process and plant compactness
- Simple automation

However, fouling can cause difficulties in membrane technology for water treatment.

NANOFILTRATION

Nanofiltration 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 operation pressure than either MF or UF. Operating pressures are usually near 600 kPa (90psi) and can be as high as 1,000 kPa (150psi). These systems can remove virtually all cysts, bacteria, viruses, and humic materials. 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. However, more energy is required for NF than MF or UF.

REVERSE OSMOSIS

Reverse osmosis can effectively remove nearly all inorganic contaminants from water. RO can also effectively remove radium, natural organic substances, pesticides, cysts, bacteria and viruses. RO is particularly effective when used in series with multiple units. 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,
- Relatively insensitive to flow and total dissolved solids (TDS level and 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,
- Membranes are prone to fouling and
- Produces the most wastewater at between 25-50 percent of the feed.

MEMBRANE PROCESSES 13.3

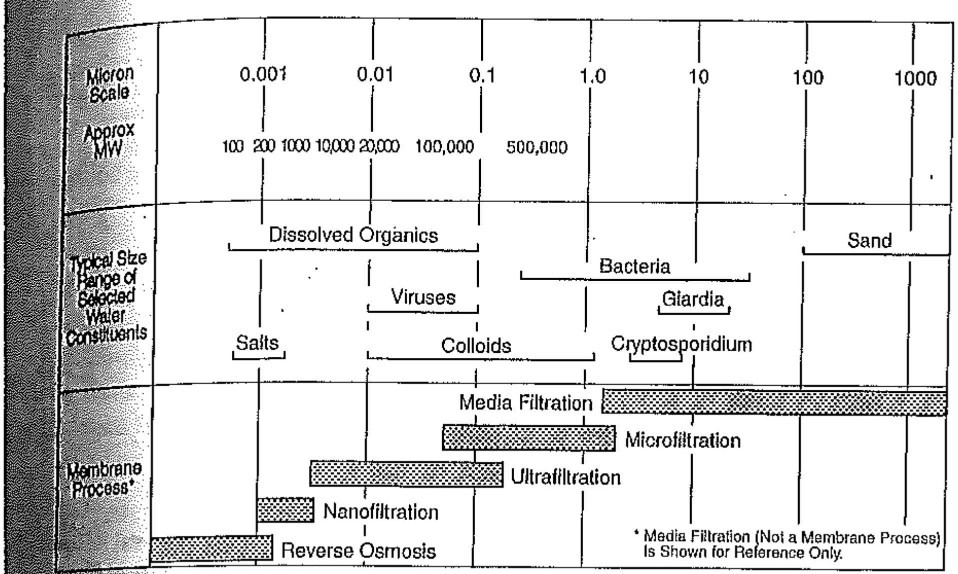


FIGURE 13.2 Pressure-driven membrane process application guide.

MEMBRANE MATERIALS

Normally, membrane material is manufactured from a synthetic polymer, although other forms, including ceramic and metallic "membranes," may be available. Almost all membranes manufactured for drinking water are made of polymeric material, since they are significantly less expensive than membranes constructed of other materials.

Membranes constructed of polymers that react with oxidants used in drinking water treatment should not be used with chlorinated feed water. Mechanical strength is another consideration, since a membrane with greater strength can withstand larger trans-membrane pressure (TMP) levels, allowing for greater operational flexibility and the use of higher pressures.

Membranes with bi-directional strength may allow cleaning operations or integrity testing to be performed from either feed or filtrate side of the membrane. Membranes with a particular surface charge may remove particulate or microbial contaminants of the opposite charge due to electrostatic attraction. Membranes can also be hydrophilic (water attracting) or hydrophobic (water repelling). These terms describe how easily membranes can be wetted, as well as its ability to resist fouling to some degree.

MF and UF membranes may be constructed from a wide variety of materials, including cellulose acetate, polyvinylidene fluoride, polyacrylonitrile, polypropylene, polysulfone, polyethersulfone, or other polymers. Each of these materials has different properties with respect to the surface charge, degree of hydrophobicity, pH and oxidant tolerance, strength and flexibility.

NF and RO membranes are generally manufactured from cellulose acetate or ployamide materials, and their various advantages and disadvantages. Cellulose membranes are susceptible to biodegradation and must be operated within a narrow, pH range of 4 to 8 but they do have some resistance to continuous low-level oxidants.

Chlorine doses of 0.5 mg/L or less may control biodegration and biological fouling without damaging the membrane. Polyamide membranes, by contrast, can be used under a wide range of pH conditions and are not subject to biodegradation. Although these membranes have very limited tolerance for strong oxidants, they are compatible with weaker oxidants such as cholramines. These membranes require significantly less pressure to operate and have become the predominate material used for NF or RO applications.

MEMBRANE MODULES

Membrane filters are usually manufactured as flat sheet stock or as hollow fibers and then formed into on of several different types of membrane modules. Module construction typically involves potting or sealing the membrane material into an assembly, such as with hollow-fiber module. These types of modules are designed for long-term use over the course of a number of years. Spiral-wound modules are also manufactured for long-term use, although these modules are encased in a separate pressure vessel that is independent of the module itself.

Hollow-Fiber Modules

Most hallow-fiber modules used in drinking water treatment applications are manufactured for MF or UF membranes to filter particulate matter. These modules are comprised of hollow-fiber membranes, which are long and very narrow tubes that may be constructed of membrane materials described previously. The fibers may be bundled in one of several different arrangements.

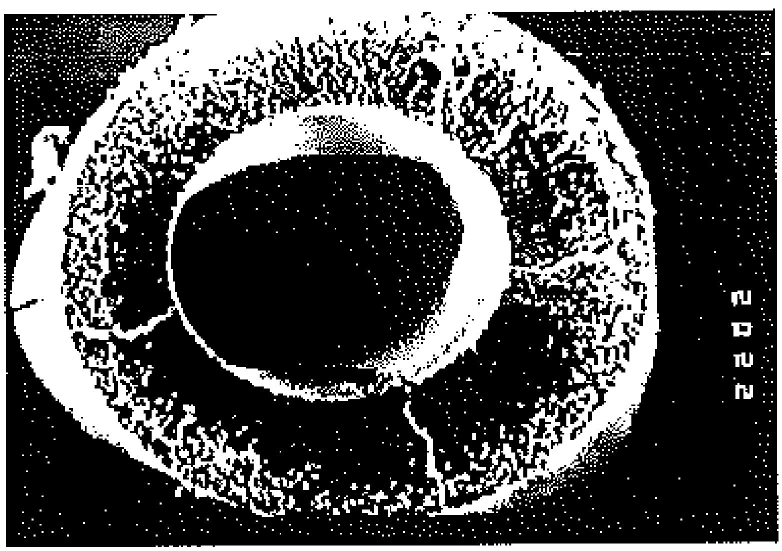
Fibers can be bundled together longitudinally, potted in a resin on both ends, and encased in a pressure vessel. These modules are typically mounted vertically, although horizontal mounting may be used. These fibers can be similar to spiral-wound modules and inserted into pressure vessels independent of the module itself. These modules (and the pressure vessels) are mounted horizontally. Bundled hollow fibers can also be vertically and submerged in a basin that does not need a pressure vessel.

A typical hollow-fiber module may consist of several hundred to over 10,000 fibers. Although dimensions vary by manufacturer, approximate ranges for hollow-fiber construction are:

- Outside diameter 0.5 – 2.0 mm
- Inside diameter 0.3-1.0 mm
- Fiber wall thickness 0.1-0.6 mm
- Fiber length 1-2 meters

Hollow-fiber membrane modules may operate in an "inside-out" or "outside-in" mode. In inside-out mode, feed water enters the center of the fiber (lumen) and is filtered radially through the fiber wall. Filtrate is then collected from outside the fiber. During outside-in operation, feed water passes from outside the fiber to the inside, where filtrate is collected in the center of the fiber.

Hollow Fiber Cross-Section Photomicrograph



When a hollow-fiber module is operated in an inside-out mode, pressurized feed water may enter the center of the fiber at either end of the module, while filtrate exits through a port located at the center or end of the module. In outside-in mode, feed water typically enters the module through an inlet port located in the center and is filtered into the center of the fiber, where the filtrate exits through a port at one end of the module. Most hollow-fiber systems operate in direct filtration mode and are periodically backwashed to remove the accumulated solids.

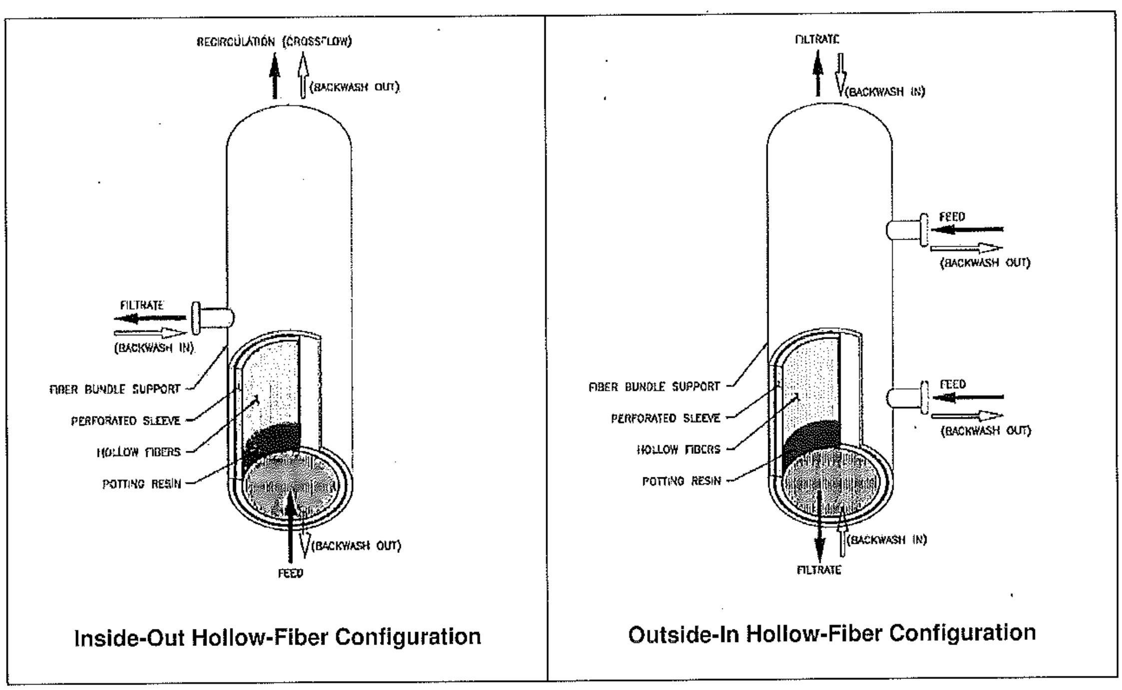
Spiral-Wound Modules

Spiral-wound modules were developed to remove dissolved solids, and are most often associated with NF/RO processes. The basic unit is a sandwich of flat membrane sheets called a "leaf" wound around a central perforated tube. One leaf consists of two membrane sheets placed back to back and separated by a spacer called permeate carrier. Layers of the leaf are glued along three edges, while the unglued edge is sealed around the perforated central tube.

Feed water enters the spacer channels at the end of the spiral-wound element in a path parallel to the central tube. As feed water flows through the spacers, a portion permeates through either of the two surrounding membrane layers and into the permeate carrier, leaving behind any dissolved and particulate contaminates that are rejected by the membrane.

Filtered water in the permeate carrier travels spirally inward toward the central collector tube, while water in the feed spacer that does not permeate through the membrane continues to flow across the membrane surface, becoming increasingly concentrated with rejected contaminates. This concentrate stream exits the element parallel to the central tube through the opposite end from which the feed water entered.

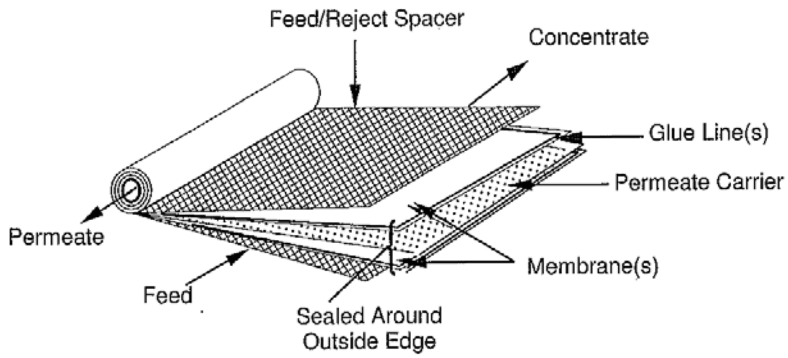
Inside-Out and Outside-In Modes of Operation (Using Pressure Vessels)



Inside-Out Hollow-Fiber Configuration

Outside-In Hollow-Fiber Configuration

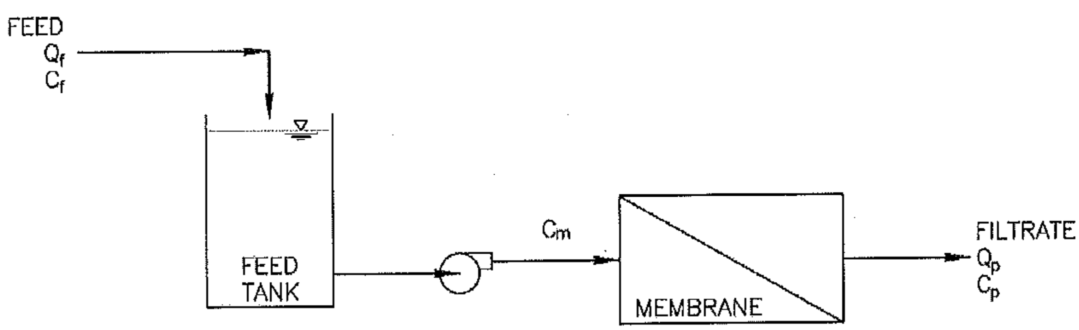
Spiral-Wound Membrane Module



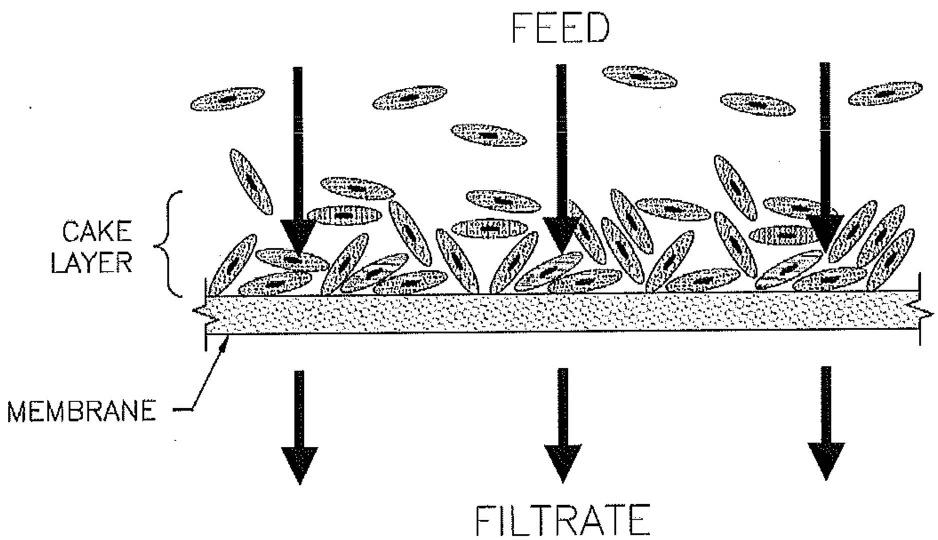
DEPOSITION MODE

Membrane filtration systems operating in deposition have one influent (feed) and one effluent (filtrate) stream. These systems are also commonly called “dead-end” or “direct” filtration systems and are similar to conventional granular media filters in terms of hydraulic configuration. In deposition mode, contaminates suspended in the feed stream accumulate on the membrane surface and are held in place by hydraulic forces acting perpendicular to the membrane, forming a cake layer.

Schematic of a System Operating in Deposition Mode



Deposition Mode



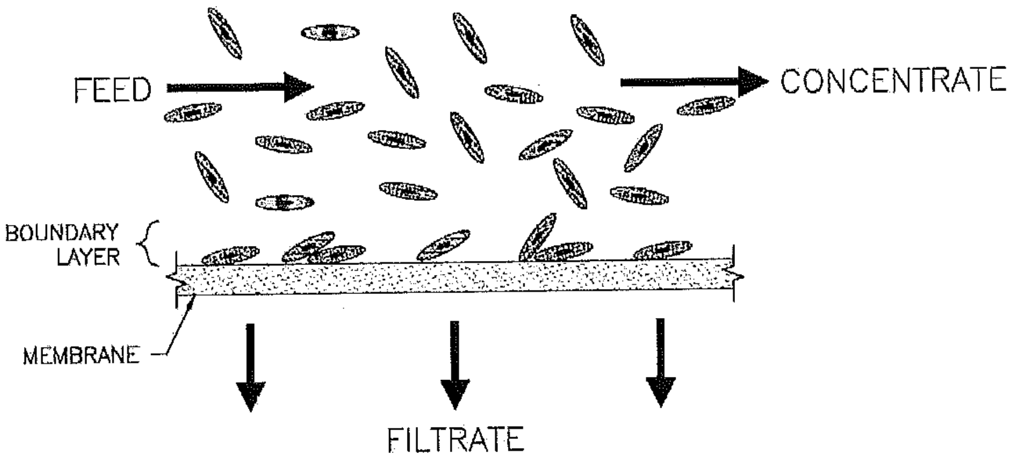
Most hollow-fiber MF and UF systems operate in deposition mode. Typically, accumulated solids are removed from MF/UF systems by backwashing. However, some systems operate until accumulated solids reduce the flow and/or TMP to an unacceptable level, at which point the membrane cartridge is replaced.

Some MF/UF systems utilize a periodic “backpulse” or a short interval of reverse flow (which may include air and/or addition of small doses of oxidants) designed to dislodge particles from the membrane surface without removing these solids from the system. This process re-suspends particles, effectively concentrating the suspended solids in the feed near the membrane surface and increasing the potential for pathogens or other particulate to pass through an integrity breach and contaminate the filtrate.

SUSPENSION MODE

In membrane filtration systems that operate in suspension mode, a scouring force using water and/or air is applied parallel to the membrane during production of the filtrate in a continuous or intermittent manner. The objective of operating in this mode is to minimize the accumulation of contaminants at the membrane surface or boundary layer, thus reducing fouling.

Suspension Mode



BACKWASHING

The backwash process is designed to remove contaminants accumulated on the membrane. Each membrane unit is backwashed separately and in a staggered pattern to minimize the number of units in simultaneous backwash at any given time. During backwash, the direction of flow is reverse for 30 seconds to 3 minutes. The force and direction of the flow dislodge the contaminants at the membrane surface and wash accumulated solids out through the discharge line. Membrane filtration systems are 15 to 60 minutes between backwash events. The backwash process reduces system productivity 5 to 10 percent due to the volume of filtrate used during backwash. Backwashing is almost exclusively associated with hollow-fiber MF and UF processes.

Backwashing is conducted according to manufacturer specifications and site-specific considerations. Although more frequent backwashing allows for higher fluxes, this is counterbalanced by the decrease in system productivity. In general, a backwash cycle is triggered when a performance-based benchmark is exceeded, such as operating time, volume, increase in TMP, and/or flux decline. Ideally, the backwash process restores the TMP to its clean level; however, most membranes exhibit a gradual increase in TMP after each backwash, indicating accumulation of foulants that cannot be removed by the backwash process alone. These foulants are addressed through chemical cleaning.

Some systems also utilize pressurized air and/or chlorine in combination with filtered water to remove solids, provide pathogen inactivation and biofouling control, and improve backwash effectiveness. A disinfectant such as chlorine may be added at every backwash to once per day.

Some MF/UF membranes use chemicals other than chlorine (such as acids, bases, surfactants, or other proprietary chemicals). These strategies are used to enhance membrane flux and extend intervals between chemical cleanings, thus lowering the cost of operation. State regulators may require enhanced cross-connection control measures for backwash piping and special provisions for rinsing the membranes after backwash be required.

Because spiral-wound membranes generally do not permit reverse flow, NF and RO membrane systems are not backwashed. For these systems, membrane fouling is controlled with chemical cleaning, flux control, and crossflow velocity. The inability of spiral-wound membranes to be backwashed is one reason NF and RO membranes are seldom applied to directly treat water with high turbidity and/or suspended solids.

CHEMICAL CLEANING

Chemical cleaning also controls membrane fouling, particularly inorganic scaling and organic and befouling that is not removed with backwash. Chemical cleaning is conducted for each membrane unit separately and is typically staggered to minimize the number of units undergoing cleaning at any time.

While chemical cleaning is conducted on both MF/UF and NF/RO systems chemical cleaning is the primary mean of removing foulants in NF/RO systems. Although cleaning intervals may vary on a system-by-system basis, gradual accumulation of foulants makes chemical cleaning necessary. Membrane cartridge filters are an exception, however, in that cartridge filters are usually designed to be disposable and are not subject to chemical cleaning.

The goal of chemical cleaning is to restore the TMP of the system to its clean level. Any foulant that is removed by either the backwash or chemical cleaning process is known as reversible fouling. Over time, membrane processes also experience some degree of irreversible fouling which cannot be removed through chemical cleaning or backwashing. Irreversible fouling occurs in all membrane systems, and eventually requires membrane replacement.

There are a variety of different chemicals that may be used for membrane cleaning, and each is targeted to remove a specific form of fouling. For example, citric acid is used to dissolve inorganic scaling. Strong bases such as caustic are typically used to dissolve organic material. Detergents and surfactants may also be used to remove organic and particulate foulants, particularly those that are difficult to dissolve. Chemical cleaning may also use a strong chlorine solution to control biofouling. Due to the variety of foulants present in source waters, it is often necessary to use a combination of different chemicals in series to address multiple types of fouling.

Chemical Cleaning Agents

Category	Chemicals Commonly Used	Typical Target Contaminant(s)
Acid	• Citric Acid ($C_6H_8O_7$) • Hydrochloric Acid (HCl)	Inorganic scale
Base	• Caustic (NaOH)	Organics
Oxidants / Disinfectants	• Sodium Hypochlorite (NaOCl) • Chlorine (Cl_2) Gas • Hydrogen Peroxide (H_2O_2)	Organics; Biofilms
Surfactants	• Various	Organics; Inert particles

Proprietary cleaning chemicals are available, and these specialty cleaning agents may be useful when more conventional chemicals are ineffective. For example, enzymatic cleaners have been effective at dissolving organic contaminants. Chemical cleaning options are limited for membranes that cannot tolerate oxidants and/or extreme pH levels. A chemical cleaning regimen may be specified by the manufacturer based on site-specific source water quality.

Clean-in-place (CIP) is often used to describe chemical cleaning since it is typically conducted while the membrane modules remain within the membrane unit (in-situ). The cleaning process re-circulates a cleaning solution through the membrane system at high velocities (to generate scouring action) and elevated temperature (to enhance the solubility of the foulants).

A soak cycle follows the recirculation phase. After the soak cycle, the membrane system is flushed to remove residual traces of the cleaning solution(s). The processes may be repeated using a different cleaning solution to target different types of foulants until the membranes have been successfully cleaned. Softened or de-mineralized water may be required for the cleaning solution, or as rinse water.

While backwashing may be conducted at more regular intervals, chemical cleaning is done only when necessary. Chemical cleaning is generally necessary for MF and UF systems when periodic backwashing to restore system productivity reaches a point of diminishing returns. For NF and RO systems, a 10 to 15 percent decline in flux or a 50 percent increase in differential pressure may indicate the need for chemical cleaning.

Delaying necessary chemical cleaning can accelerate irreversible fouling, reduce production capacity, and shorten membrane life. A benchmark of 30 days is commonly used as a minimum required interval between chemical cleanings for MF/UF systems, although a well-designed system may operate for much longer between cleanings. NF/RO systems are normally designed to operate for much longer periods between chemical cleanings, from 3 months to 1 year.

In addition to a CIP when a point of diminishing productivity is reached, some MF/UF membrane system manufacturers recommend a routine, short duration chemical cleaning to minimize the accumulation of foulants. These processes are referred to "chemical washes" or "maintenance cleans," and are implemented on preset intervals ranging from several times pre day to once every several days, depending on the propensity of the water to cause membrane fouling.

Isolating cleaning chemicals from the treated (filtered) water is an important consideration. In addition, it is important to properly flush the membrane unit after the cleaning process and before restarting the filtration cycle. The flushed water should be diverted to waste until filtrate water quality parameters (turbidity for MF/UF systems and pH for NF/RO systems) return to normal levels. The volume of flushed water can be significant when surfactants are used.

For MF/US systems, it is common to recycle as much as 90 percent of the cleaning chemicals for reuse, thus reducing the volume of chemical waste as well as the cost associated with cleaning. Recycling cleaning solutions is less common with NF/RO systems, since used cleaning solutions accumulate dissolved constituents with repeated use, diminishing effectiveness of the cleaning agents.

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 as much as 15 percent of the total treated water volume. Because little or no chemical treatment is used in a membrane system, the concentrate stream usually contains only the contaminates found in source water (although at much higher concentrations), and concentrate can sometimes be disposed of in the source water. Other alternatives include deep well injection, dilution and spray irrigation, or disposal in municipal sewer. These alternatives are usually necessary for NF wastes, which usually contain concentrated organic and inorganic compounds. Disposal must be carefully considered and applicable 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 permanent 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.

Adapted from PA website, dated November 2005, and National Drinking Water Clearing House Web site, dated March 1999