

TECHNICAL AND COST REVIEW OF COMMERCIALY AVAILABLE MF/UF MEMBRANE PRODUCTS

Authors: Michael Pilutti, PE, Julia E. Nemeth, PE,

Presenter: Julia E. Nemeth, PE

Abstract

Microfiltration (MF) and Ultrafiltration (UF) are low pressure or vacuum membrane filtration processes that are used for pathogen and suspended solids removal. MF/UF membrane processes have gained wide acceptance in the drinking water industry because of their ability to produce a high-quality and consistent product water. More recently MF/UF membrane filtration has gained acceptance as a pretreatment for nanofiltration (NF) and reverse osmosis (RO) for surface water and seawater applications.

Numerous manufacturers of MF/UF membrane systems exist, each with their own proprietary technologies. The differences between proprietary systems can be overwhelming and present significantly varying design considerations. This paper will examine the systems furnished by the major manufacturers and will summarize the following characteristics of each:

- Submerged vs. encased
- Crossflow vs. dead end filtration
- Inside-out vs. outside-in flow
- Materials of construction and oxidant tolerance
- Hollow fiber vs. flat sheet
- Integrity testing
- Cleaning methods
- Performance characteristics (flux, recovery, particle rejection, backwash procedures)
- Pretreatment requirements
- Cost impacts
- Installed capacity summaries

This paper will provide the reader with an overview of the various systems available, their characteristics, capabilities, and limitations to better enable the designer or end user to evaluate available options. Also, this paper will address the feasibility and progress being made in the development of non-proprietary systems that may accept several manufactures' modules.

I. TYPES OF UF/MF MEMBRANE SYSTEMS

1.1 Introduction -- Proprietary vs. Non-proprietary

Virtually all of the UF/MF plants being installed today are proprietary systems. This means the owner is committed to one technology and one system supplier for the life of the plant. This paper summarizes the key differences in the most common systems. The MF/UF industry is in a similar developmental phase as the NF/RO industry was 20 years ago when NF/RO systems were proprietary in nature. The MF/UF industry is showing early signs of moving towards standardization, at least with respect to encased systems.

Non-proprietary systems are designed to accept as many different pressure/encased MF or UF modules as are available. Currently several manufacturers are standardizing on 8-inch diameter by 40-inch or 60-inch long hollow fiber modules, similar to spiral wound RO membranes. As more manufacturers standardize, there will be a greater variety of modules available. A non-proprietary system provides the flexibility to change modules if the raw water quality or finished water goals change. These systems also offer the owner the benefit of competitive purchasing. It is likely the development of non-proprietary MF/UF systems will help advance the industry as the technology will then become more cost-effective and widely accepted. Additionally, the pairing of MF/UF technology with reverse osmosis systems increases the need for custom, non-proprietary systems.

1.2 Submerged Membrane Systems

Submerged membrane systems are proprietary systems with Zenon and US Filter being the most prolific. Although the system components differ slightly between the manufacturers, the mode of operation remains similar regardless of the proprietary equipment used.

Submerged membrane systems are those where the membrane fibers are immersed in an open tank and are exposed to the feed water. Groups of membrane fibers are bundled together in racks or modules. The membrane fibers are slightly longer than the distance between the upper and lower attachment points, allowing the membrane fiber to shake during operation to dislodge accumulated solids. Multiple modules can be submerged in the process tank, depending on the permeate flow required. During normal operation, raw water enters the process tank and completely submerges the membrane modules. The raw water is drawn through the membrane fibers (outside-in) to the inside of the fiber (lumen) by a vacuum pump. Filtered water (permeate or filtrate) exits through the top of the module to the permeate manifold. Generally multiple modules are connected to one permeate pump through a common manifold. Concentrate is continuously withdrawn from the process tank so that the raw water flow is equal to the sum of both permeate and concentrate flow.

Process tanks for submerged membrane systems are designed for a plug flow mode of operation, and recoveries will vary from 50% at the lead module to 99% at the end module. Suspended solids concentration also increases from the raw water inlet to the concentrate outlet. Since the solids concentration and module recovery increases from the lead module to the end module, flux decreases from the lead to the end module. However system recovery and flux is reported as an average of all modules.

Submerged membrane systems can effectively replace clarifiers and multi-media type filters found in conventional water treatment plants and are capable of operating effectively and continuously in high-

solids environments. There is no need to create large flocculated particles for settling in clarifiers or for capture by granular media filters as the membranes are capable of removing pin floc.

Above 5-mgd, capital and operating costs for submerged membrane systems are generally lower than encased membrane systems because of the need for less equipment and lower operating pressures. Additionally, submerged membrane systems can be particularly cost effective if an existing tank/basin can be utilized.

1.3 Encased Membrane Systems

Encased membrane systems are becoming increasingly non-proprietary in nature. As stated earlier, membrane elements from the various manufacturers are standardizing dimensions to allow for increased flexibility within a particular system. This will allow for relatively simple changes to a system due to alterations in feed water quality, system performance standards, etc. The major manufacturers of UF are Pall, Koch, Norit (X-Flow), Aquasource, and Hydranautics.

A German company called Inge has recently produced a hollow fiber membrane with a multi-bore fiber orientation. The multi-bore design fuses separate capillaries into a single support structure for added stability and reduced fiber damage. The module also incorporates an annular space where permeate is collected. This spacing may optimize backwashing effectiveness. The system is non-proprietary, and can easily be retrofitted into existing systems, as well as vice versa. Membrane specifics can be found in the tables throughout this paper.

Encased membrane systems utilize the same hollow fibers as the submerged systems except that they are packed into a cylindrical casing, usually with a diameter of 8", and a length of 40" or 60". These fiber packages, or elements, are then arranged end-to-end in a pipe, or vessel. Most commonly, in UF applications, the vessels are oriented vertically and each vessel houses one element. For large capacity systems – particularly in Europe – multiple modules can be installed in long vessels in a horizontal configuration similar to reverse osmosis systems. Some manufacturers provide their modules with end structures that are already configured to accept the required piping connections, thus eliminating the need for another housing. This can save a significant amount of capital cost.

An encased system may utilize a cross-flow design, which can allow for a high flux with minimal solids build-up on the membrane surface, or it can operate in "dead-end" mode where all water processed through the filter comes out as filtrate.

II. MEMBRANE MATERIAL PROPERTIES

Membranes can be manufactured in a wide variety of materials. These materials differ in their performance characteristics including mechanical strength, fouling resistance, hydrophobicity, hydrophilicity, and chemical tolerance. This section summarizes the differences in material properties.

2.1.1 Hydrophobicity vs. Hydrophilicity

Membrane materials can be classified as either hydrophilic or hydrophobic. Hydrophilic means water-loving and such materials readily adsorb water. The surface chemistry allows these materials to be wetted forming a water film or coating on their surface. Hydrophobic means water-hating and hydrophobic membrane materials have little or no tendency to adsorb water. Water tends to "bead" on hydrophobic surfaces into discrete droplets.

The hydrophilic and hydrophobic properties of a membrane material are related to the surface tension of the material. The fundamental importance of surface tension comparison is that liquids having lower surface tension values will generally spread on materials of higher surface tension values. Table 1 below summarizes surface tension values of some polymeric membrane materials. The higher the surface tension value of the material, the more hydrophilic the material is.

Table 1
Calculated Surface Tension of Some Polymeric Materials

Chemical Name	Surface Tension (dynes/cm)
Polytetrafluoroethylene (Teflon)	18
Polyvinylidene Fluoride	25
Polypropylene	29
Poly Vinyl Chloride	39
Polysulfone	41
Polycarbonate	42
Polyacrylonitrile	44
Cellulose	44

The degree of hydrophilicity or hydrophobicity influences the wettability and applied pressure requirements for water flow through the membrane. Hydrophilic membranes require less operating pressure than hydrophobic membranes.

Hydrophilic membranes tend to exhibit greater fouling resistance than hydrophobic membranes. Particles that foul in aqueous media tend to be hydrophobic. Hydrophobic particles tend to cluster or group together to form colloidal particles because this lowers the interfacial free energy (surface tension) due to surface area exposure. General tendency will favor particle attachment to any material less hydrophilic than water because less exposure of hydrophobic particles can be achieved by attachment of the particles to the membrane surface. To prevent fouling, a membrane requires a surface chemistry which prefers binding to water over other materials. This implies that the material must be very hydrophilic.

2.1.2 Materials of Construction

Membrane manufacturers offer membranes constructed of a wide variety of materials. These materials vary widely in their chemical and mechanical properties including mechanical strength, burst pressure, oxidant tolerance, VOC tolerance, pH operating range, and so forth. The end user must be aware of the strengths and limitation of each material type and ensure the selected material is compatible with raw water quality, pretreatment requirements, and other operating conditions. Following is a list of commonly available materials and the characteristics of each.

2.1.3 Polypropylene (PP) PP membranes exhibit resistance to a wide operating range of pH (2-14), exhibit good chemical resistance, good mechanical strength (35 psig TMP), but are not oxidant tolerant (<10² ppmh). PP membranes can tolerate limited exposure to chloramines in the feed stream (up to 0.5 ppm).

- 2.1.4 Polyethersulfone (PES) Polyvinylpyrrolidone (PVP) Blends** PES / PVP blends are highly oxidant tolerant (>250,000 ppm hours for chlorine, tolerant to permanganate and ozone), are tolerant to wide pH range (2-12 continuous operation, <1 for cleaning), exhibit resistance to oils and grease, and are highly hydrophilic. The weakness of PES/PVP blends is that they are susceptible to attack from organic solvents such as benzene.
- 2.1.5 Polysulfone** Polysulfone membranes exhibit a wide pH tolerance (continuous exposure range of pH 1-13), high temperature limit (typically 75° C), good oxidant resistance (chlorine exposure: storage 50 mg/L, short-term sanitation 200 mg/L, >10⁶ ppmh).
- 2.1.6 Polyvinylidene fluoride (PVDF)** PVDF membranes are highly oxidant tolerant (up to 5000 ppm chlorine), have a moderate pH operating range (2-10.5), have moderate temperature limits (40° C), and exhibit good mechanical strength (36 psig TMP, 36 psig inlet).
- 2.1.7 Cellulosic Derivatives (CD)** CD membranes exhibit a narrow operating pH range (4-8.5), low temperature limits (<35° C), and moderate oxidant tolerance (>10⁵ ppmh).
- 2.1.8 Polyacrylonitrile (PAN)** PAN membranes have moderate temperature limits (40° C), a moderate pH operating range (2-10), good mechanical strength (44 psig TMP, 44 psig max inlet pressure), moderate oxidant tolerance (up to 1000 ppm during cleaning, <10³ ppmh), and moderate resistance to acids and caustic (acid = 1N, caustic = 0.1N)

The following table summarizes membrane materials of manufacture for some of the more common systems on the market.

Table 2
Membrane Material by System Manufacturer

Manufacturer	Membrane Material of Construction
Aquasource	Polysulfone Cellulose Acetate
Hydranautics	Polyethersulfone
Inge	Polyethersulfone
Koch	Polysulfone
Pall	Polyacrylonitrile Polyvinylidene fluoride
TriSep - SpiraSep	Polyethersulfone
US Filter	Polypropylene Polyvinylidene fluoride
X-Flow	Polyethersulfone / Polyvinylpyrrolidone Blend
Zenon	Laminated Polysulfone

III. MODE OF OPERATION

3.1 Pretreatment

Pretreatment can be employed prior to membrane treatment to control fouling, to provide additional treatment, to meet manufacturer warranty requirements, and to satisfy regulatory requirements. Types of pretreatment employed depend on the nature of the raw water quality and the goal of the pretreatment.

Pretreatment can reduce the solids loading in the membrane feed stream, permitting higher flux rates and in turn reducing initial capital costs by reducing the required membrane area. A reduced solids loading also has the effect of reducing membrane operating costs because of a reduced transmembrane pressure requirement. Reduced solids loading results in benefits including longer runtimes between cleanings, lowered operating costs, and increased membrane longevity.

Pretreatment can also be employed to protect the membranes from constituents in the raw water that could cause damage. Examples of this include large objects and some bacteria that could cause system damage or plug the membrane pores.

Pretreatment may remove raw water contaminants that would not normally be removed by the membrane itself. For example oxidation, coagulation, and sedimentation can be employed to remove dissolved contaminants such as Fe, Mn, or TOC. Coagulation also aids in the agglomeration of microscopic particles that may pass through or plug the membrane into larger particles that will be retained by the membrane.

3.2 Crossflow vs. Dead-end Filtration

The direction of feed water flow, in relation to the membrane surface, determines the type of filtration in a membrane system. In a dead-end filtration system the feed water effectively contacts the membrane surface at a perpendicular angle. In contrast, feed water in a crossflow system flows parallel to the membrane surface. Dead-end flow can also be achieved in a cross-flow system by simply closing the discharge valve. Feed water flow direction accounts for a variety of differences between the two systems. Particularly, the two modes of operation may experience differences in fouling rate, flux and recovery, and finished water quality. Crossflow filtration in MF/UF is the same as in NF/RO: $Q_{\text{feed}} = Q_{\text{permeate}} + Q_{\text{concentrate}}$. In dead end operation $Q_{\text{feed}} = Q_{\text{permeate}}$, just like in conventional multimedia filtration. In crossflow mode solids are continuously flushed from the system resulting in less frequent backpulses and backwashes, and possibly longer membrane life. In dead end operational mode, solids build up in the system, thus more frequent backwashes and backpulses will be required. Some systems are capable of operating in crossflow or deadend mode such as Koch, Norit and Hydranautics. The Zenon and US Filter submerged systems should be considered crossflow since a continuous waste stream is produced.

Recovery is a term that describes the amount of water that is treated versus the amount of filtrate that is produced: $\text{Recovery} = Q_{\text{filtrate}}/Q_{\text{feed}}$. Even systems operating in dead-end mode should not be considered as 100% recovery systems. Water that is used up during backwashes and flushes to drain must be considered when calculating system recovery. Recovery is discussed further in Section IV.

3.3 Inside-out vs. Outside-in flow

Inside-out flow and outside-in flow refers to the direction of feed water passing through the membrane, as well as the orientation of the feed water in relation to the membrane surface. For example, in an outside-in system, the feed water surrounds the membrane, and the filtrate is collected from inside of the hollow tube fibers (lumen). The outside-in scheme has the advantage of a larger membrane surface area, which allows for a slightly higher flow than the inside-out model while still maintaining the same flux rate and solids concentration.

An inside-out system places the feed water inside the fibers, and the filtrate is collected on the outside of the membranes. The feed water enters the fibers at one end of the membrane element, and the discharge passes through the element and exits the fibers on the other side. The filtrate is collected inside the element on the outside of the fibers.

Both methods have been shown to operate successfully by different manufacturers. What the user should consider in evaluating the best options for a particular situation are the backwashing implications of the two different configurations. The backwash cycle for virtually all systems consists of introducing clean filtrate back into the modules through the filtrate conduit within the module. Thus the inside-out modules backwash from outside-in and vice versa. Depending on the water quality, the configuration of the modules and the water treatment goal, one type of configuration and backwash scheme may be more suited than another. It may only be determined by pilot studying which may be the most effective for a particular application.

3.4 Cleaning Methods

Cleaning MF and UF systems is very similar in nature to RO and NF cleanings. However, the MF/UF systems have the added advantage of backwash and backpulse during the cleaning cycle. MF/UF membranes, depending on the material of construction can be cleaned with caustic solutions to remove organics. Citric acid or other acid solutions are used to remove scalants, and oxidants may be used to remove biological or inorganic foulants, if the membrane material is tolerant of oxidants. The chemicals to be used depend on the type of fouling and the material of membrane construction. Cleaning cycles can be automated and implemented into the system design. A typical cleaning cycle can last for anywhere from 10 minutes to 2 to 3 hours per bank, including soaking and rinsing times. Cleaning frequency for surface water applications can again vary tremendously, from once per day to about 4 to 6 weeks. Cleaning procedures, durations, and frequencies will vary significantly depending on feedwater quality, system design and operation, flux rates, and recovery rates. Cleanings may be automated and performed in place or they may be manual with the modules actually being removed from operation and cleaned in a special cleaning area. Submerged systems have the ability to remove cartridges service and clean them in a special tank. Encased modules are usually cleaned in place, but can be removed to a special cleaning rack.

3.5 Backwash Procedures

All UF/MF systems incorporate a backwash cycle, whether operating in dead-end or cross-flow modes. A backwash cycle commonly operates on a preset timeframe, usually about every 15 to 60 minutes and is initiated by the PLC controlling the system. A typical backwash lasts around one to two minutes. The flow rate can range from lower than the feed flow to as much as ten times as high as the feed flow. All elements in a given array are backwashed together. The backwash water is typically collected in a backwash tank. The tank ensures the backwash fluid is released to atmospheric pressure. Backwashes can also be initiated when the transmembrane pressure reaches a predetermined limit as recommended by the system manufacturer.

Typically, filtrate water is used for the backwash. The filtrate flows out of a tank and through the filtrate end of the membrane, then to discharge. The backwash releases solids that are attached to the feed side of the membrane surface. Backwashing improves the operational flux of the system to maintain desired performance. It is recommend to include a forward flush to drain to ensure that solids dislodged during backwashing are thoroughly flushed out of the system prior to directing filtrate to the filtrate tank.

Experience has shown that this will greatly reduce turbidity spikes that may be seen after backwash cycles.

Compressed air, as in the Memcor (US Filter) system, can also be used for backwash purposes. The compressed air, usually less than 100 psi, is introduced on the filtrate side to remove accumulated suspended solids. Many systems also have the ability to have a continuous gas stream flowing through the membrane. This provides added protection against solids build-up.

The membrane systems that employ outside-in flow during normal operation generally use a backpulse feature to dislodge solids from the outside surface of the membrane fibers. During a backpulse, membrane permeate is drawn from a holding tank and is pumped in reverse direction, from the inside of the fiber out effectively dislodging solids from the outside of the membrane. The backpulse water can be chemically conditioned with acid, caustic, or biocide to further clean the membrane fiber. Backpulses typically are initiated automatically by the PLC controlling the system and occur at 15-30 minute intervals with a duration of 10-30 seconds.

3.6 Integrity Testing

Membrane integrity testing ensures the membrane is still intact. These tests check the membrane structure for wear or damage which would result in a pore size that is larger than permitted. It is important that these tests be carried out regularly since finished water quality can be adversely affected by damage to the membrane surface. All tests are non-destructive, and are designed to isolate the problem area, should the need arise. Such tests include bubble point, diffusive flow and pressure hold. The tests are characterized as direct or indirect. Direct tests challenge the physical structure of the membrane utilizing air or pressure hold tests. Indirect tests monitor filtrate water quality parameters such as turbidity or particle counts to determine membrane integrity.

One of the more popular tests is the “bubble point” test. The bubble point test uses capillary properties, of the membrane, to locate any problems. According to capillary theory, the smaller the pore size, the higher the pressure is required to expel water from the pore. Pressurized air hits the filtrate side of the membrane, while feed water covers the feed side. The feed side is at atmospheric pressure via an open backwash valve. The test is successful when, at a specified air pressure, no air is released into the feed end for a specified time period. Therefore, the membrane passes the test when the feed water remains in the pores of the membrane at a specified air pressure. This ensures the pores of the membrane are intact.

Table 3, below presents a summary of the types of integrity tests currently practiced and a discussion of their applicability.

Table 3 ^[1]
Advantages and Disadvantages of Existing Integrity Monitoring Tests

Method	Advantages	Disadvantages
Direct Methods		
Bubble Point Test	Identifies individual compromised fibers Reliable and easy to interpret Follows a relatively standard procedure	Time consuming and labor intensive Has to be performed offline Cannot monitor integrity of the entire system Can be subject to operator error Has to be used in conjunction with other direct methods

Method	Advantages	Disadvantages
Pressure Decay Test	<ul style="list-style-type: none"> Can be used to monitor the integrity of a number of modules at once Is highly automated Is an accepted standard test for most membrane suppliers Can detect small breaches of membrane integrity Can be performed relatively quickly Can reveal leaks in downstream plumbing 	<ul style="list-style-type: none"> Must be performed offline Lacks a standard procedure Requires a fully wetted membrane Lacks a reliable baseline value Difficult to correlate with log-removal values Is not continuous Results affected by many factors including temperature, instrument sensitivity, upstream volume Is prone to dilution effects
Vacuum Decay Test	<ul style="list-style-type: none"> Similar to the pressure decay test although not widely used by membrane suppliers 	<ul style="list-style-type: none"> Similar disadvantages to the pressure decay test Is not fully developed and proven Requires additional tank for water trap More difficult to conduct
Diffusive Flow Test	<ul style="list-style-type: none"> Similar to pressure decay test Can be more accurate if volume displacement measured Is reportedly more sensitive than pressure decay test 	<ul style="list-style-type: none"> Similar to pressure decay test Currently not fully automated Currently not supplied as standard equipment
Sonic Sensing Test	<ul style="list-style-type: none"> Can identify compromised modules Could be developed into a continuous test Relatively easy to use 	<ul style="list-style-type: none"> Not automated May be affected by background noise or mode of operation Interpretation of results may be subjective Not widely used Time consuming and labor intensive Cannot be used with submerged systems
Spiked Integrity Monitoring Method	<ul style="list-style-type: none"> Can be performed more frequently than other direct methods May provide relatively good indication of log reduction values Relatively easy to use Has shown reasonable sensitivities 	<ul style="list-style-type: none"> Still under development Not widely used Requires addition of a surrogate Continuous tests may be difficult and expensive Relatively difficult to establish a baseline value Prone to interference from other particles naturally present in the water
Indirect Methods		
Particle Counting	<ul style="list-style-type: none"> Performed continuously Widely used and usually a standard equipment Shown to be more sensitive than other indirect methods May be used in multiple channel configuration to save cost 	<ul style="list-style-type: none"> May not detect minor breaches of membrane integrity Affected by changes in raw water particle counts (difficult to establish a baseline value) Requires difficult and frequent calibration Can produce false positives because of microbubbles present in the permeate or particle shedding in the plumbing Requires regular maintenance and cleaning of the sensor Test results depend on the resolution

Method	Advantages	Disadvantages
		of the instruments Precision varies with different instruments Can be relatively expensive, especially for larger plants
Particle Monitoring	Performed continuously Has lower costs than particle counters Requires little to no calibration Has higher sensitivity than conventional	Less sensitive than particle counters Can produce false positives because of microbubbles present in the permeate or particle shedding in the plumbing Provides neither particle counts nor sizes but only a relative index Results harder to interpret than particle counters Sensor may clog
Turbidity Monitoring	Performed continuously Standard equipment in nearly all surface water treatment plants Lower cost than particle counters New laser units may provide increased sensitivity	Relatively insensitive to small breaches in membrane integrity Requires regular maintenance and calibration Can produce false positives because of microbubbles present in the permeate or particle shedding in the plumbing

IV. PERFORMANCE CHARACTERISTICS

4.1 Flux

Flux in a MF/UF membrane system is not a characteristic of a specific manufacturer so much as it is limited by the following parameters:

- Raw water quality (temperature, solids content, NOM content, etc.).
- Efficiency or existence of the pretreatment process.
- Maximum transmembrane pressure as dictated by the physical properties of the membrane polymer and limitations of manufacturer's equipment.
- Acceptability of the resulting cleaning frequency

All of these factors are interrelated and will therefore dictate the flux rate achievable on a case by case basis. Flux rates though can be as low as 5 gfd for challenging waters, and flux rates have been documented over 90 gfd for very clean feed waters. Average flux rates range from 25-40 gfd.

4.2 Recovery

Similar to flux, recovery rates in a MF/UF membrane system are not a characteristic of a specific manufacturer so much as recovery is limited by the following parameters:

- Raw water quality (temperature, solids content, NOM content, etc.).
- Efficiency or existence of the pretreatment process.
- Maximum transmembrane pressure as dictated by the physical properties of the membrane polymer and limitations of manufacturer's equipment.
- Acceptability of the resulting cleaning frequency

High recovery rates generally require high transmembrane pressures to operate higher cleaning frequencies because the membranes are forced to run in a higher solids environment. All of the above factors are interrelated and will therefore dictate the recovery rate achievable on a case by case basis. Recovery rates can be as low as 50% for challenging waters, while recovery rates have been documented at up to 99% for very clean feed waters. Average recovery rates range from 92% to 95%.

4.3 Particle Rejection

The main difference between membrane filtration and conventional filtration is that membranes reject particles based on size exclusion as opposed to media depth filtration. For all practical purposes, MF/UF membranes will produce a constant permeate water quality regardless of feedwater conditions because they act as an absolute barrier. This can be expected since most suspended solids present in raw water streams are larger than the pore size of most MF/UF elements. Permeate turbidity can be expected to be less than 0.1 NTU or lower and SDI less than 0.4. However, breaches in integrity such as a broken fiber or ruptured seal, or imperfections in the membrane due to the manufacturing process can allow particles to enter the permeate stream.

While it has been said that MF/UF membranes pose an absolute barrier to suspended solids, it is more appropriate to express solids removal in terms of log removal. Most membranes are capable of up to 6-log pathogen (protozoan cysts and bacteria) removal, though this will vary depending on the membrane manufacturer. Virus rejection varies significantly between manufacturers with some systems removing virtually no appreciable amount of viruses while others report greater than 6-log removal.

4.4 Factors Affecting Fouling and Cleaning Frequency

Fouling is the most serious disadvantage of pressure-driven membrane separation processes. Membrane fouling results in a decrease in flux and an increase in energy consumption and feed pressure. Fouling will occur in any MF/UF system, regardless of the membrane polymer, system manufacturer, and mode of operation. Fortunately, fouling can be effectively controlled through the proper use of pretreatment processes, chemical additions, and proper system design and operation. The following factors are the most common causes of membrane fouling and can be controlled by proper design and operation.

Equipment Malfunctions. Malfunctioning equipment can increase cleaning frequencies. For example, malfunctioning level control equipment in a submerged membrane system can allow membranes to operate in partially full tanks, thus accelerating membrane fouling.

Pretreatment Chemicals. Pretreatment chemicals must be evaluated for their compatibility with the membrane materials. For example, oxidants such as chlorine or potassium permanganate used for iron and manganese removal may cause permanent damage to some membrane materials, such as PP. Polymers that are used in conventional treatment processes to enhance coagulation may create a slime layer on membrane fibers resulting in accelerated fouling. Coagulants must also be evaluated and approved by membrane suppliers. Furthermore, feeding excess amounts of coagulant in a pretreatment process results in no significant fouling impacts as long as the coagulant is compatible with the membrane material. However, the membranes can rapidly foul during coagulant underfeeds. The coagulation process produces a pin floc that is substantially larger than the membrane pores. When the size of the suspended solids is approximately the same as the membrane pores, membrane fouling increases because it becomes more difficult to dislodge the solids from the membrane surface.

Temperature. The effect of temperature on permeate flux is well documented in the membrane industry. Decreases in temperature decrease flux, increase TMP, and increase fouling rates. Cleaning frequencies can double with a 15-degree C change in water temperature.

Flux. Increasing flux increases cleaning frequency.

Recovery. Increasing recovery increases cleaning frequency due to higher solids concentrations in the feed water. For example, the solids concentration factor is 12.5 at 92% recovery and is 100 at 99% recovery.

Cake Formation. Accumulation of particles near the surface of the membrane form a cake layer which can be considered a second membrane. The cake layer can enhance the particle rejection characteristics of the membrane by depth filtration and adsorption. However, the cake layer increases the resistance to flux and leads to higher transmembrane pressures. This type of fouling is reversible and can be removed by cleaning and backpulsing.

Adsorption. Organic matter present in the feedwater can lead to membrane fouling either by adsorbing into the cake formation or by adsorbing into the membrane itself. Some membrane polymers exhibit higher adsorptive rates than others, depending on the hydrophilicity of the polymer. Pretreatment can be optimized to remove as much organic matter from the feed to extend membrane life, and chemical cleaning can be optimized to remove adsorbed foulants.

Metals Precipitation. Though metals precipitation in MF/UF membranes is not as prevalent as in NF/RO processes, fouling due to metals precipitation has been documented. Calcium carbonate scale can form on the permeate side of membranes in scaling waters where carbon dioxide is driven off as part of the process. In operations using membrane filtration for iron and manganese removal, precipitation of these metals on the concentrate and permeate side can occur. Postprecipitation of iron and aluminum associated with metallic-based coagulants has been observed and can lead to fouling on the permeate side and increased particle counts in the permeate.

V. SUMMARY OF MEMBRANE SYSTEM PARAMETERS

The table below lists a summary of several of the major UF/MF manufacturers and information about their products.

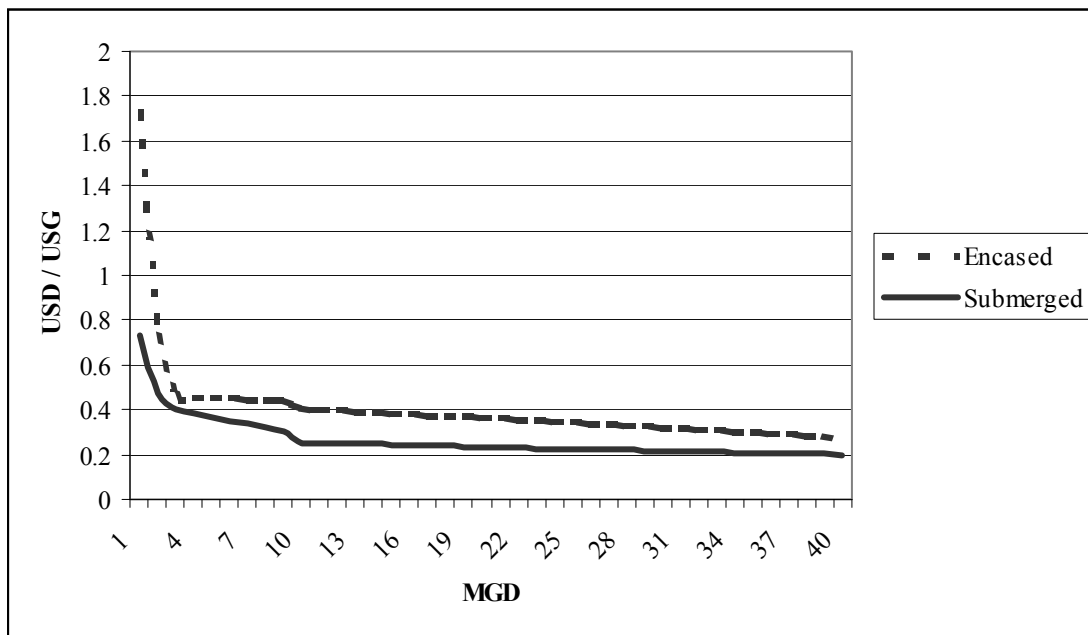
System Manufacturer and Model	System Type	Pore Size	Mode of Operation	Cleaning Method(s)	Flux (gfd)	Recovery (%)
Legend	S --- Submerged E – Encased MF – Microfiltration UF – Ultrafiltration	All sizes listed are in microns (μm) or Daltons (mol. wt. cut-off)	I/O – Inside-out O/I – Outside-in CF – Crossflow DE – Deadend		GFD x 1.7 = LMH	
Aquasource	E New large diameter (18") module available UF	0.01 μm	I/O DE and CF	Chemical soak	N/A	N/A
Hydranautics	E 8" x 40" or 8" x 60" UF	150,000 daltons (0.9 μm)	I/O DE and CF	Chemical soak	35-85 gfd	95%-98%
Hydranautics	S 17,550 sf per 10 bundle module MF	N/A introduced March 2003	O/I	Chemical Soak and Air Scrub	N/A yet	N/A yet
Inge	E 485 m ² per el 8" x 40" or 8" x 60" UF	100,000 daltons	I/O Annular permeate collection DE and CF	Chemical soak and flush LP air scour	40–90 gfd	85%-98%
Koch	E 8" x 48" (32 m ²) or 8" x 72" (50 m ²) UF	100,000 daltons	I/O DE and CF	Chemical Soak	N/A	N/A
Pall	E UF – 5" x 80" MF – 6" x 80"	UF -- 13,000 or 80,000 daltons MF – 0.1 μm	Double skin – I/O and O/I	Chemical and air scrub	UF --57-100 gfd MF – 259 gfd	>95%
TriSep - SpiraSep	S Spiral wound 8" x 40" UF	.05 μm	O/I	Chemical backwash and air scour	Up to 80 gfd	> 90%
US Filter	S, E 5" x 40" 372 sf	MF - .1 μm	O/I DE	Chemical – caustic and acid air scour	15-40 gfd	90% - 98.5%+
X-Flow	E 8" x 60" primarily, but many other dim. available UF – 80% MF – 20%	UF – 50,000 daltons (0.2 μm) MF – 150,000 daltons (0.9 μm)	I/O CF and DE	Backwash and soak only – no air	42-84 gfd	90% - 96%

System Manufacturer and Model	System Type	Pore Size	Mode of Operation	Cleaning Method(s)	Flux (gfd)	Recovery (%)
Zenon ZeeWeed 500	S	0.04 μm	O/I CF	Continuous air scour, air and water backwash	10-40 gfd	85-99%
Zenon ZeeWeed 1000	S	0.04 μm	O/I DE	Continuous air scour, air and water backwash	10-40 gfd	85-99%

VI. COST IMPACTS AND INSTALLED CAPACITY INFORMATION

6.1 Capital and Operating Costs

Capital costs of membrane system vary depending on the manufacturer, the scope of supply, the design capacity of the system, and the level of competition during bidding. The capital costs discussed in this section include the membranes, skids, racks, compressors, blowers, pumps, piping, instrumentation, controls, and other components necessary for a complete and operable system. The capital costs for the submerged membranes do not include costs for tanks. The capital costs are for systems bid and constructed from 1999 to 2002 and are presented in US Dollars (USD) per US Gallon (USG) of capacity. The data is presented in summary in the figure below. The information clearly shows that capital costs are very competitive for systems up to 10 mgd, and submerged systems are more cost-effective for systems larger than 10 mgd.



Operating costs of membrane systems depend on numerous factors including water quality, flux, recovery, pretreatment, and cost of labor and consumables. Due to space constraints, it is beyond the scope of this paper to provide operating cost information. Additionally, operating costs are site specific and are best predicted individually based on pilot information or detailed design information.

6.2 Installed Capacity Summaries

Information was requested from the various manufacturers regarding the combined capacities of their installations. Several manufacturers provided this information, their responses are summarized below:

- Hydranautics states their encased UF has 55 MGD installed capacity as of beginning of 2003, 25 MGD under contract.
- Norit Membrane Technologies – X-Flow currently has more than 200 MGD of installed MF and UF capacity, and approximately another 200 MGD of anticipated backlog upcoming.
- Aquasource cites nearly 100 installations have gone on-line since 1988, with individual installation capacities ranging from 0.01 MGD to 20 MGD.

NOTE: some suppliers included only municipal US installations, others included all installations worldwide.

6.3 Summary

Membrane treatment is one of the most rapidly advancing water treatment technologies. MF/UF membrane processes have gained wide acceptance in the drinking water industry because of their ability to produce a high-quality and consistent product water. More recently MF/UF membrane filtration has gained acceptance as a pretreatment for nanofiltration (NF) and reverse osmosis (RO) for surface water and seawater applications. The engineer or end user may be overwhelmed by the variety of technologies that exist. The variety is especially imposing when the reviewer considers that most applicable technologies are proprietary, and the end user is locked into their particular process for the life of the plant, with little flexibility for modification in the future. Non-proprietary systems will likely become more popular as the industry grows and matures.

There are advantages and disadvantages for the many various technologies that are available in MF/UF systems. With proper study and review of data versus available membrane capabilities, the engineer should be able to design a system for the end user that will be tailored to the application and will operate efficiently and cost-effectively for years.

VII. REFERENCES

Note: this paper was designed to provide the reader with a summary of the basics necessary to compare commercially available UF/MF technologies, most of the information presented herein was compiled from published manufacturer's literature.

[1] Farahbakahsh, Khosrow, et. al., 2003. *Monitoring the Integrity of Low Pressure Membranes*, AWWA Journal June 2003, 95:107