

Microfiltration and Ultrafiltration Membranes for Drinking Water

Second Edition



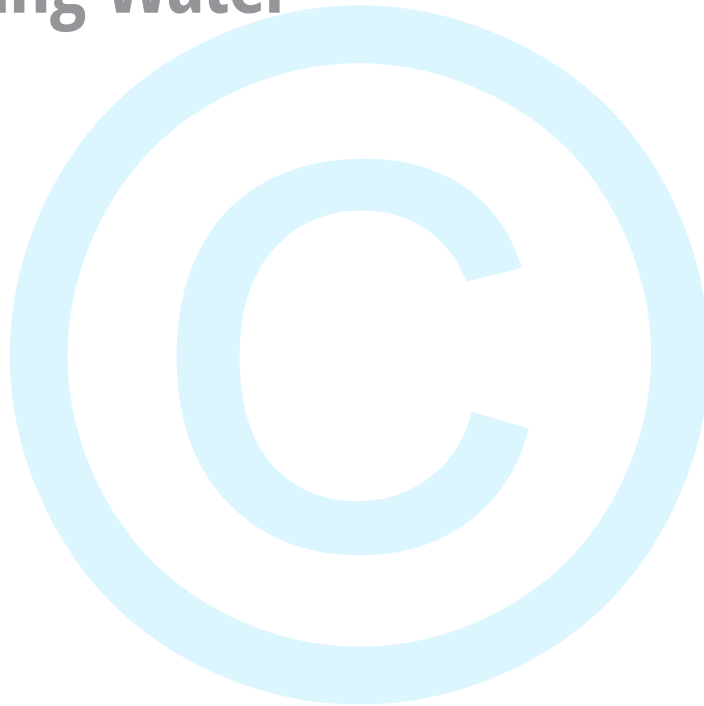
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Microfiltration and Ultrafiltration Membranes for Drinking Water

Second Edition



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Manual of Water Supply Practices—M53, Second Edition

Microfiltration and Ultrafiltration Membranes for Drinking Water

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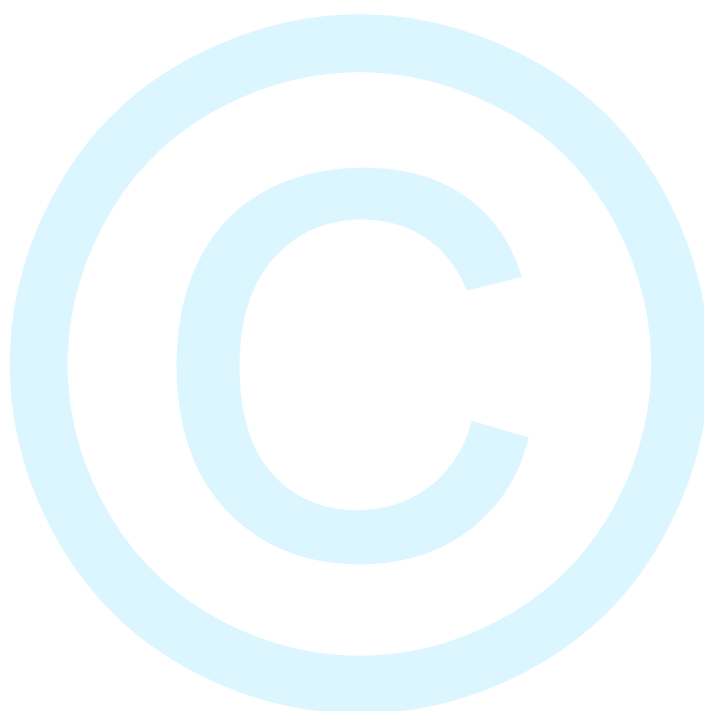
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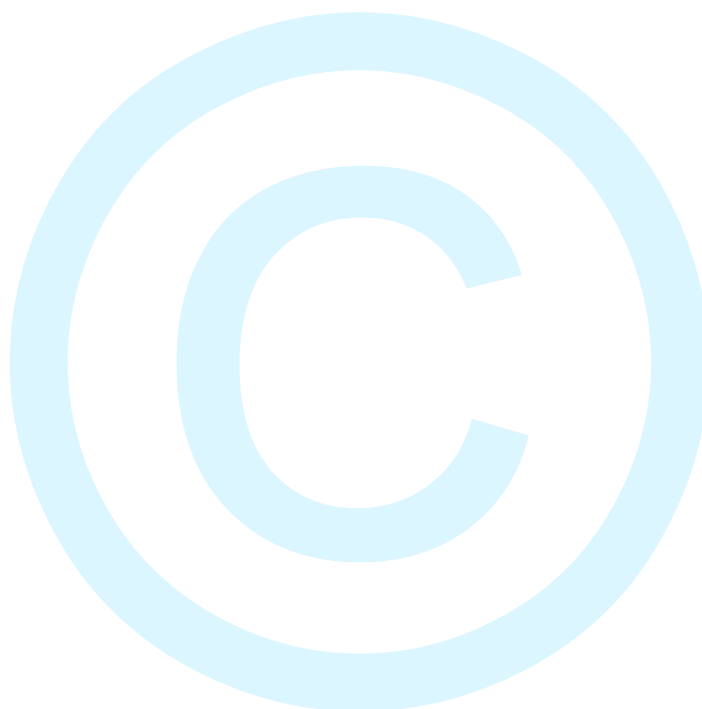
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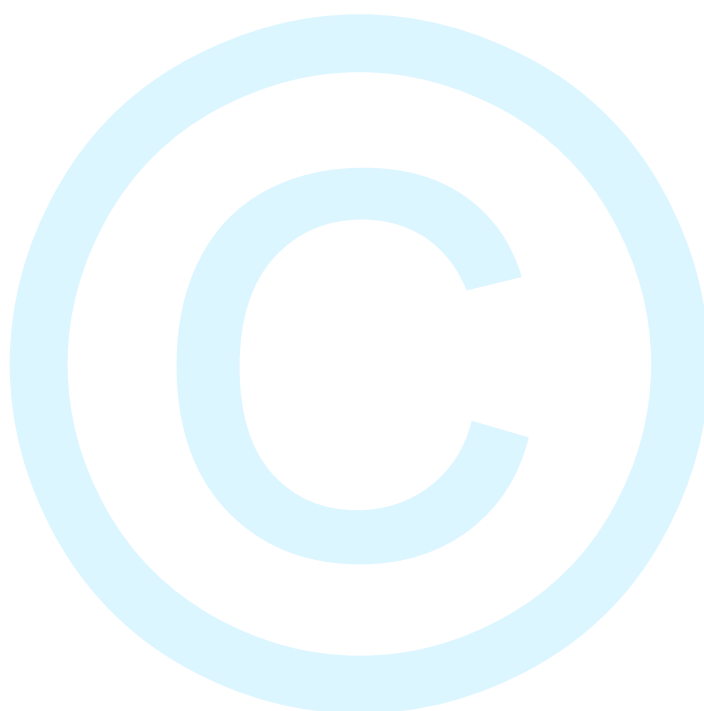
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Preface

Since the early 1990s, there has been rapid growth in the use of low-pressure hollow fiber microfiltration (MF) and ultrafiltration (UF) membrane processes for the production of drinking water. A number of factors have contributed to this growth, including promulgation of new regulations, a decline in costs of the technology, a wider range of MF and UF applications and improvements in system design and operation.

MF and UF initially gained rapid acceptance as processes that provide a high level of particle, turbidity and microorganism removal. They are now being employed in conjunction with various unit processes to provide removal of both organic and inorganic materials.

This manual was developed to describe MF and UF technology for operators, administrators, engineers, scientists, educators and anyone seeking an introduction to these processes. Chapters cover topics such as water quality, membrane science and theory, system concepts, MF and UF membrane manufacturers, applications, pilot testing, design concepts, operations, cost, residuals management and future trends.

For this second edition of the AWWA Manual M53, *Microfiltration and Ultrafiltration Membranes for Drinking Water*, the Membrane Processes Committee and the American Water Works Association welcome comments and suggestions for improving future editions. Please send an e-mail to the AWWA Engineering and Technical Services Department at etssup-port@awwa.org.

Chapter 1 provides an introduction to the manual of practice with an overview of low pressure membrane processes, the growth of the market and the past, present and future of the technology.

Chapter 2 covers myriad water quality issues and the challenges that each present to the membrane industry. Suggestions on possible solutions to mitigate these challenges are included.

Chapter 3 delves into the permeation and productivity of low pressure membranes and the theory by which predictions can be made on the response of a membrane in various scenarios.

Chapter 4 begins with a look at membrane materials and geometries and expands into detailed elements of process design and operating concepts, including the importance of pretreatment and post treatment.

Chapter 5 provides guidelines for piloting membrane systems with instruction on what should comprise the protocol, infrastructure needed, labor requirements, parameters to monitor and optimizing operation.

Chapter 6 addresses overall system design concepts for various and changing site specific issues, membrane specific issues and design issues with the objective of determining the most cost effective option and ease of operation of the equipment.

Chapter 7 details the operation and troubleshooting of low pressure membrane systems treating water having diverse quality and the modes of operation and the associated controls to maximize the productivity of the system.

Chapter 8 includes examples of membrane systems applications for suppliers that have installation(s) of 1 MGD or greater. These include turbidity and microbial removal, integrated systems, pretreatment approaches and concentrating the reject stream.

Chapter 9 evaluates the manner in which capital costs, installation costs and operating costs affect the life cycle costs of low pressure membrane systems. Taken into account is how effective project management can impact short and long term costs via piloting, equipment selection, installation and system operation.

Chapter 10 instructs on how to handle the waste streams that result from different low pressure membrane systems, associated cost of disposal and the regulatory guidelines that are relevant.

Chapter 11 presents information on membrane manufacturers having full-scale operating MF/UF membrane drinking water installations of 1 MGD or larger in North America. An overview of each company, their products and sample installations are presented for Dow, GE Water, Koch Membrane Systems Inc., Pentair X-Flow, Pall Corporation, Evoqua, Toray Industries Inc. and Wes Tech Engineering, Inc. There may be other membrane system suppliers in the marketplace at present time; however, these were the most prevalent system/membrane suppliers at the time of Manual development.

Chapter 12 covers the trends in the low pressure membrane market, based upon a survey of industry leaders. It presents their responses on the trends in system capacity, product standardization, material and module configuration, technical advances, regulatory changes, applications, cost reductions and solutions to industry challenges.

I am pleased to present this manual as it offers great value to anyone interested in gaining knowledge of low pressure membranes in their widely diverse applications, operations and system designs. It holds a wealth of information that answers many practical questions; guides engineers and end users and will likely increase the success of an installation.

Judith A. Herschell
Chair, AWWA Membrane Processes Committee

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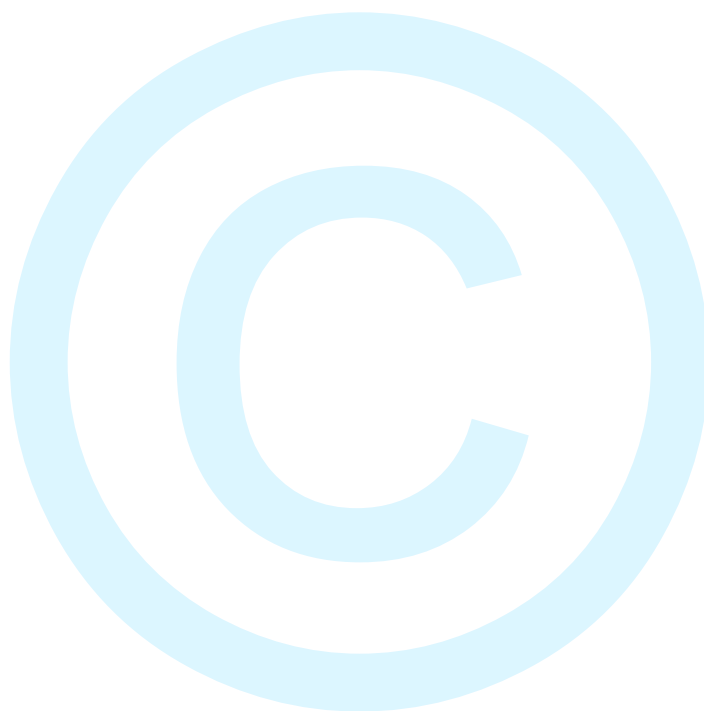
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Metric Conversions

Linear Measurement

inch (in.)	×	25.4	=	millimeters (mm)
inch (in.)	×	2.54	=	centimeters (cm)
foot (ft)	×	304.8	=	millimeters (mm)
foot (ft)	×	30.48	=	centimeters (cm)
foot (ft)	×	0.3048	=	meters (m)
yard (yd)	×	0.9144	=	meters (m)
mile (mi)	×	1,609.3	=	meters (m)
mile (mi)	×	1.6093	=	kilometers (km)
millimeter (mm)	×	0.03937	=	inches (in.)
centimeter (cm)	×	0.3937	=	inches (in.)
meter (m)	×	39.3701	=	inches (in.)
meter (m)	×	3.2808	=	feet (ft)
meter (m)	×	1.0936	=	yards (yd)
kilometer (km)	×	0.6214	=	miles (mi)

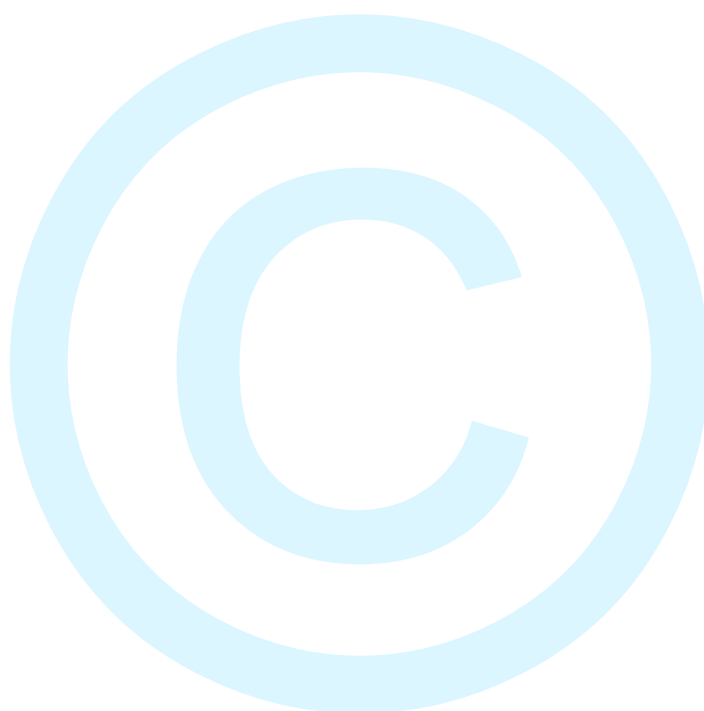
Area Measurement

square meter (m ²)	×	10,000	=	square centimeters (cm ²)
hectare (ha)	×	10,000	=	square meters (m ²)
square inch (in. ²)	×	6.4516	=	square centimeters (cm ²)
square foot (ft ²)	×	0.092903	=	square meters (m ²)
square yard (yd ²)	×	0.8361	=	square meters (m ²)
acre	×	0.004047	=	square kilometers (km ²)
acre	×	0.4047	=	hectares (ha)
square mile (mi ²)	×	2.59	=	square kilometers (km ²)
square centimeter (cm ²)	×	0.16	=	square inches (in. ²)
square meter (m ²)	×	10.7639	=	square feet (ft ²)
square meter (m ²)	×	1.1960	=	square yards (yd ²)
hectare (ha)	×	2.471	=	acres
square kilometer (km ²)	×	247.1054	=	acres
square kilometer (km ²)	×	0.3861	=	square miles (mi ²)

Volume Measurement

cubic inch (in. ³)	×	16.3871	=	cubic centimeters (cm ³)
cubic foot (ft ³)	×	28,317	=	cubic centimeters (cm ³)
cubic foot (ft ³)	×	0.028317	=	cubic meters (m ³)
cubic foot (ft ³)	×	28.317	=	liters (L)
cubic yard (yd ³)	×	0.7646	=	cubic meters (m ³)

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Chapter **1**

Introduction to Low-Pressure Membrane Processes

The past 20 years have seen phenomenal growth in the use of low-pressure hollow fiber microfiltration (MF) and ultrafiltration (UF) membrane processes for the production of drinking water. This growth has been propagated by the changes in the regulatory requirements of the Safe Drinking Water Act (SDWA), beginning with the Surface Water Treatment Rule (SWTR) that requires lower filtered water turbidity and removal of disinfectant-tolerant microorganisms such as *Giardia* and *Cryptosporidium*. Also, the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) has contributed to the growth of the use of low-pressure membranes. The intent of the LT2ESWTR is to reduce illness linked with the contaminant *Cryptosporidium* and other disease-causing microorganisms in drinking water.

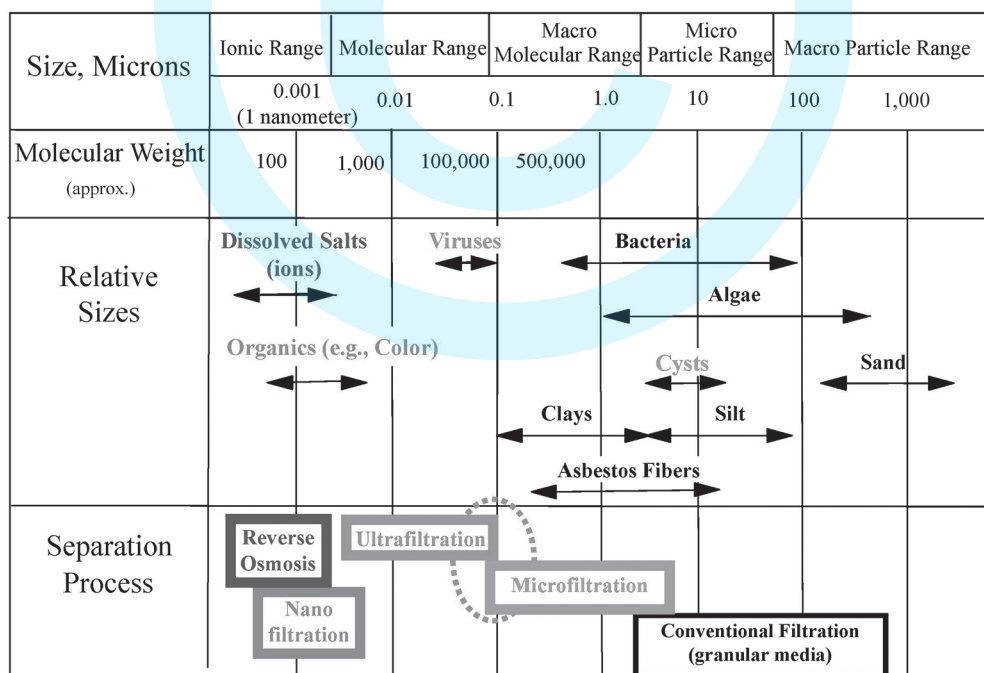
In wastewater reclamation, MF and UF have enjoyed a similar level of growth, where the processes have essentially replaced media filtration as the preferred method of pre-treatment prior to reverse osmosis for advanced reclamation projects.

The objective of this AWWA MF/UF manual is to describe MF and UF system technologies and provide information to the growing market of communities considering or utilizing this type of equipment. This manual serves as a bridge between theory and real-world applications. Microfiltration and ultrafiltration have gained rapid acceptance as processes that provide a reliable and very high level of particle, turbidity, and microorganism removal.

PROCESS OVERVIEW

Figure 1-1 illustrates the differences in removal among various filtration processes, both conventional and membrane based. The focus of this manual is MF and UF treatment processes. These filtration methods remove particles and microorganisms very effectively. When compared to their conventional counterparts, two distinctions become important. The first distinction is that MF and UF processes achieve separation through physical removal. Removal is essentially accomplished through size exclusion. Unlike conventional coagulation/sedimentation/filtration-based processes, they do not require physicochemical pretreatment to agglomerate particles or manipulate particle surface charge to achieve the desired level of particle removal. There are applications, however, in which particle conditioning enhances membrane system operation. The second aspect of membrane filtration is that the pore size is highly uniform and, therefore, capable of very high or *absolute* removal of a targeted particle size or microorganism.

The growth of MF and UF as a treatment process has followed a substantially different path from that of the established desalting membrane processes of reverse osmosis (RO) and nanofiltration (NF). The concepts and fundamentals of RO and NF technologies were established prior to the introduction of the technologies into the municipal water treatment industry. However, the proliferation of MF and UF system technology has been characterized by numerous manufacturers that offer proprietary membrane system technology. These membrane systems incorporate proprietary design features that vary considerably and largely are not interchangeable. In recent years, this has been changing with the evolution of the industry and with manufacturers that are making membranes that are interchangeable with leading module designs.



Source: Courtesy of Black & Veatch.

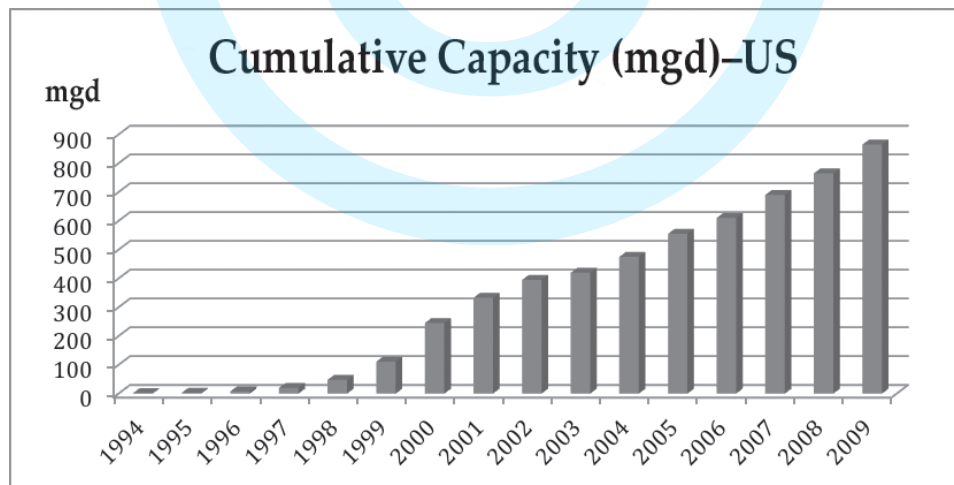
Figure 1-1 Membrane removal size ranges

A common feature of most of the currently available MF and UF membrane equipment is that hollow fibers are used to perform the separation. The hollow fiber is particularly suited for use as a separation medium because it has a high surface-to-volume ratio and the hollow fiber exhibits radial bidirectional strength. This property allows for backwashing with water, air, or a combination of both. Hollow fibers are flexible in their configuration and can be operated in the outside-in or inside-out manner of flow and may use either pressure or vacuum as the driving force across the membrane. The variations in membrane materials and the variety in the ways that the membrane can be configured and operated facilitate the use of proprietary designs.

Although the system concepts, membranes, and nomenclature vary considerably from manufacturer to manufacturer, a key aspect that has contributed to the success of this technology is the ability to test and verify the integrity of the membrane. Manufacturers have adapted integrity-testing concepts from cartridge-based filtration processes to their hollow fiber counterparts. Integrity testing provides the user with the ability to verify the particle removal performance of the membrane process and facilitates the diagnosis and repair of membranes in the event of an integrity failure. Although some have questioned the appropriateness of this aspect of LT2ESTWR, LT2ESTWR does recognize the importance of integrity testing and incorporates direct integrity testing as a component that will allow a membrane process to receive higher log removal credits.

GROWTH OF MEMBRANE TECHNOLOGY

At the end of 2009, installed capacity of drinking water microfiltration and ultrafiltration systems worldwide was estimated to exceed 1.5 bgd. Figure 1-2 illustrates the growth in the use of membrane technology. This upward trend should continue as numerous membrane facilities in the range of 25 to 100 mgd in capacity are either planned, in design, or in operation.



Source: Some data provided by Tom Pankratz, Global Water Intelligence.

Figure 1-2 Growth in use of membrane technology: 1994–2009

The fundamental reasons for this growth can be categorized as follows.

- *Regulatory:* As evidenced by the SWTR and the subsequent iterations that require a higher level of turbidity and particle removal, MF and UF treatment processes can be used to consistently achieve treatment objectives.
- *Public sensitivity:* In recent years, there has been an increasing level of public sensitivity to pathogen outbreaks.
- *Broader applicability:* MF and UF treatment processes are particulate filters and unlike RO or NF do not remove dissolved constituents. This aspect of treatment makes them more applicable for use as a replacement for conventional filters, and thus MF and UF have exhibited widespread geographical impact.
- *Cost:* Over the past 20 years, the capital cost of MF and UF treatment has decreased as economies of scale, innovation, and competitive market forces influenced projects. In addition, the implementation of innovative backwash or cleaning strategies has helped to reduce operational costs and water consumption by the processes. Many MF and UF membrane system operate at pressure differentials of less than 15 psi.
- *Operational flexibility:* MF and UF treatment processes are highly flexible and can be used in conjunction with other treatment processes to achieve additional removal. Thus, as further detailed in chapter 8, there has been a great deal of creativity in the application of the MF and UF membrane processes to achieve additional treatment objectives. In addition, membrane systems can be easier to operate as the filtrate quality is typically not affected by process chemistry or variations in flow. Operations activities are discussed in chapter 7.

To better understand some of the underlying considerations of this growth, the following section provides a historical overview of this technology.

HISTORICAL OVERVIEW OF MF AND UF

In the mid- to late 1980s, investigators began to consider the use of low-pressure membrane filtration as a method to produce high-quality drinking water. At that time, membrane filtration processes were limited to small-volume semibatch operations such as wine and juice filtration and industrial waste treatment. Membrane systems of this type generally relied upon inside-out flow patterns and high crossflow velocity to maximize membrane flux and minimize membrane fouling.

Initial efforts to commercialize MF and UF membranes for drinking water treatment were pioneered by Lyonnaise des Eaux (Aquasource) and Memtec (currently an Evoqua product). The Aquasource technology was developed in France, where the use of chlorine is disfavored, for treatment of groundwater and the removal of viruses. The Australian Memcor (currently an Evoqua product) technology was originally developed for industrial use in a crossflow configuration with an innovative gas backwash. Its applicability to water treatment was initially established by C. Hibler and later by V.P. Olivieri, who was funded by Memcor to determine if the membrane product could be applied to the treatment of drinking water and secondary effluent.

Memcor established that CMF, its abbreviation for *crossflow microfiltration* (now *continuous microfiltration*), could be operated as a dead-end filter, relying on the gas backwash alone to maintain productivity. Pilot systems were established at local drinking water and wastewater locations to demonstrate that the product would be operationally viable in a municipal environment. These findings were reported in the proceedings of the AWWA 1991 Membrane Technology Conference, which also described the initial efforts using

CMF to determine if coagulant-enhanced microfiltration could be used to improve filtrate quality and reduce disinfection by-product (DBP) formation potential. The second aspect of the Memcor technology that was of particular note was the incorporation of a membrane test that could be used to confirm hollow fiber integrity. Various versions of this test were adopted by the membrane suppliers.

Awareness of and interest in MF and UF technologies gained further momentum through projects funded by AwwaRF (now Water Research Foundation) with J.G. Jacangelo and research performed by M.M. Clark at the University of Illinois Champaign-Urbana and J.S. Taylor and C.R. Reiss at the University of Central Florida. M. Wiesner of Rice University established that MF and UF membrane systems could be considered cost-effective at capacities of 5 mgd. About this time, Olivieri joined Memcor on a full-time basis and began to develop pilot projects with consulting engineers and municipalities.

Memcor's piloting efforts culminated in the first significant microfiltration facility, the Saratoga, California, location of the San Jose Water Company, in early 1993. The facility, rated at 3.6 mgd, was roughly 4.5 times larger than any existing Memcor installation. The Saratoga water treatment plant (WTP) was typical of most early treatment facilities installed by Memcor. Most, if not all, were facilities required by the SWTR, which was passed in 1989 and became effective in 1993. These facilities could be characterized as generally having unfiltered water, with low total organic carbon (TOC) concentration and disinfection by-product formation potential and with periodic excursions of turbidity. This type of facility was ideal for MF and UF technologies, and Memcor's initial commercial success was with this type of application. Many facilities, including those located at Kenosha, Wisconsin, and Marquette, Michigan, fit this basic profile.

As membrane technology proliferated, the process intrigued consulting engineers and utilities. Although MF and UF produce low-turbidity filtered water, the limitations of the processes are readily apparent. The processes alone do not significantly reduce the concentration of dissolved contaminants, such as dissolved organic carbon (DOC), manganese, and many constituents causing taste-and-odor issues. One such example occurred at Newport News, Virginia, where it was demonstrated that the placement of the MF process downstream of a clarifier, in this case a dissolved air flotation (DAF) device, could be used to reduce DOC and DBP formation. The pretreatment also allowed the membrane to be operated at significantly higher membrane flux. In this case, the flux increase was greater than 50 percent.

The higher membrane flux fundamentally changed the economic balance and allowed the process to be considered cost-effective, even at a 50-mgd capacity. Although the facility at Newport News was not constructed using a membrane process because of the large number of treatment units that would have been required, the viability of this approach was soon demonstrated elsewhere. To cite a few examples, three facilities using pretreatment processes were soon constructed by various manufacturers in San Patricio County, Texas; Bexar Metropolitan, Texas (near San Antonio); and Appleton, Wisconsin.

The potential of large-scale membrane facilities for drinking water treatment and wastewater reclamation (which had similar parallel success) resulted in more membrane equipment manufacturers entering the MF and UF drinking water market. Companies such as Pall Corporation and Zenon Environmental Systems (now part of General Electric) began to develop drinking water systems and also attained measurable commercial success. The Zenon technology was particularly noteworthy as it was the first membrane process that used submerged membranes applying vacuum as the driving force. In addition, membrane module suppliers such as Dow and Norit X-Flow (now part of Pentair) gained ground in the market.

CURRENT STATUS

MF and UF membrane treatment processes are now accepted as being capable of meeting the filtration requirements for drinking water production. LT2ESTWR has identified membrane filtration (including MF, UF, NF, RO, and cartridge membrane filtration) as separate treatment techniques that can be used as part of a toolbox of treatment options to obtain higher levels of *Cryptosporidium* removal. This recognition has been an important element in the acceptance of the technology, as the previous rules categorized membrane filtration as an alternative filtration technology or as a process that was regulated by the local primacy agency. Thus, even though relatively few facilities are required to provide additional removal for compliance with LT2ESTWR, the greater impact upon the membrane industry is that membrane-related regulatory concepts and guidance developed for LT2ESTWR will be adapted for other membrane facilities. The *Membrane Filtration Guidance Manual* (USEPA 2005) contains general technical and conceptual information. Its primary focus is facilitating regulatory compliance. In contrast, AWWA Manual M53 is intended to be a detailed technical resource on MF and UF membranes and systems.

In terms of membrane system development, substantial diversification of the types of membrane processes that can be used has taken place. Some of these approaches are documented in chapter 8. In general, treatment objectives, economics, and operability drive the selection of membrane processes and system configuration. Many membrane systems incorporate more than a single treatment objective. For example, a coagulant or powdered active carbon (PAC) may be fed in front of the membrane to reduce DBP formation potential or pretreatment may be used to enhance membrane filterability, thereby producing more water per unit area of membrane. (Note: Use of any coagulant or PAC must be coordinated with the membrane supplier, as the improper application of either can void a membrane warranty and irreversibly damage the membrane itself.)

System size has increased dramatically over the years. In the early days, a 5-mgd facility was a large system. Now that size would be considered a rather small facility. One noteworthy installation is an Evoqua system installed at Orange County Water District (in California). The system is 86 mgd and is being expanded to 123 mgd. GE has two systems in Ontario at or near 100 mgd, and Pall has several systems greater than 20 mgd. A large drinking water system of note is the Minneapolis Water Works Columbia Heights facility—a 70-mgd system that was built by Ionics (now part of General Electric) with Norit X-Flow membranes. What was not feasible in the early years of the development of the market is now a reality.

FUTURE TRENDS

With the amount of change that has been observed over the past 20 years, it is anticipated that membrane technology will continue to evolve as new products and treatment concepts are developed. Chapter 11 of this manual explores some of the concepts that are currently envisioned.

It is anticipated that the trend to larger-capacity systems will continue. Systems in the planning stages are as large as 300 mgd. It is believed by those in the industry that the limitations on the capacity of the systems have been removed.

It is also anticipated that membrane materials will continue to become more robust with development advances. As the life cycle costs of ceramic membranes become more attractive, it is expected that companies offering this product will capture a reasonable market share. This will require a reduction in the capital costs of those systems. A systematic approach to realize the value of robust membrane materials/systems, including their

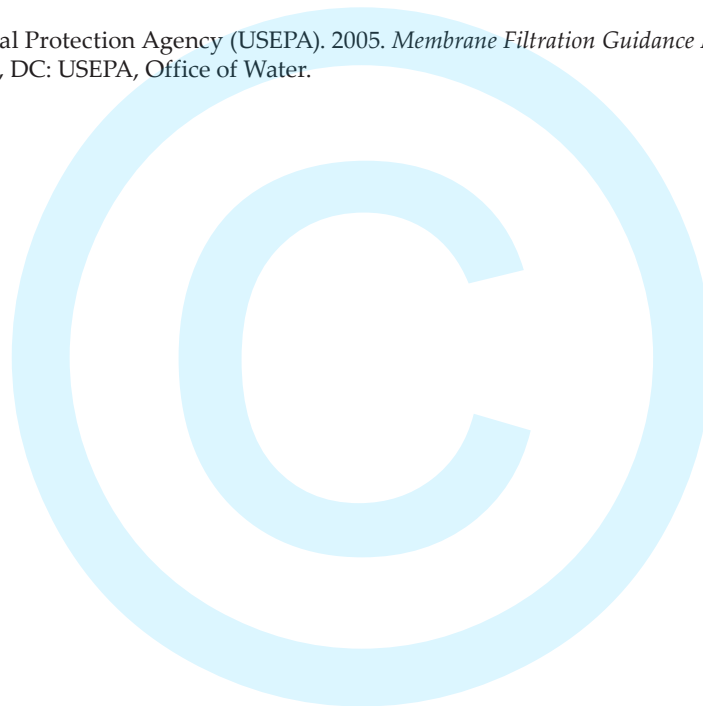
flexibility and durability in handling various types of changes in operating conditions, will also help to encourage the development of such products.

Technical advances are seen in the areas of membrane integrity testing, more effective cleaning regimes, and enhanced prevention of fouling. Membrane integrity designs are moving toward online testing with resolution that permits the estimation of virus removal. Fouling-resistant membranes and improved cleaning regimes will contribute to the control of fouling. A central technical consideration is proper pretreatment as this affects the operation of the downstream membrane system.

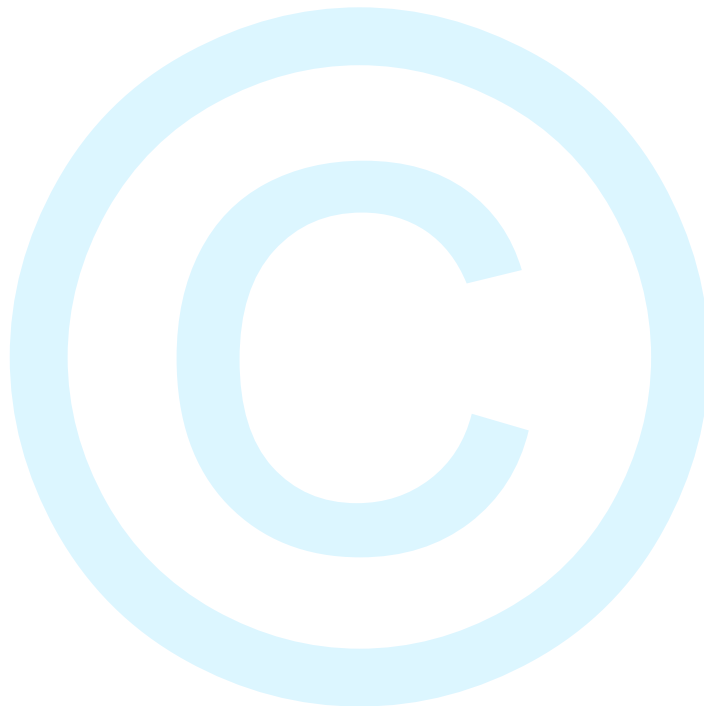
The projected reduction of costs has been tapering off in recent years, as compared to the more dramatic cost reductions experienced earlier in the market development. A portion of the cost reduction will be attributable to increased production and the inherent savings of having a fully utilized manufacturing facility.

REFERENCES

- US Environmental Protection Agency (USEPA). 2005. *Membrane Filtration Guidance Manual*. EPA 815-R-06-009. Washington, DC: USEPA, Office of Water.



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Chapter 2

Water Quality

As with any drinking water treatment process, the quality of the water to be treated using MF and UF is the single most critical factor in terms of predicting the effectiveness of the process. Microfiltration (MF) and ultrafiltration (UF) membranes are designed to remove particulates from water via a sieving mechanism. Each membrane has a distribution of pore sizes that defines what type of barrier is expected under normal operation. However, dissolved organic and inorganic species are not removed by MF or UF membranes without proper pretreatment. Therefore, for an MF or UF membrane to remove a dissolved species, the dissolved species must be transformed into particulate form, which is then rejected by the membrane. Caution is recommended when using any coagulant, powdered activated carbon, or oxidants prior to a membrane system as there is always the possibility for adverse effects, most notably increased fouling potential.

This chapter presents a variety of water-quality factors common to drinking water treatment and describes how MF and UF membranes can be utilized for their removal. Included in the chapter are references to many studies that evaluated the removal of microbial contaminants, microbial surrogates, and organic or inorganic contaminants by MF and UF membrane processes. The intent of this chapter is to demonstrate through numerous examples that MF and UF membranes are able to remove most drinking water contaminants of concern either alone or with compatible and effective cotreatment processes. The studies referenced in this chapter are intended to give the reader confidence in this technology, to demonstrate the immense amount of work with MF and UF membranes that has occurred, and to compare the myriad of operational issues such as membrane type, contaminant type, water source, coagulant usage, adsorbent usage, and oxidant usage as related to water quality.

WATER-QUALITY FACTORS

The most common water-quality and treatment challenge for most MF and UF systems that treat surface waters is the presence of natural organic matter (NOM). NOM is a

heterogeneous mixture with wide ranges in molecular weight (size) and functional groups. The mixture of NOM is formed by terrestrial vegetative debris, algae, and associated cellular products. NOM has been shown to be aesthetically undesirable and to adversely impact public health through the formation of disinfection by-products (DBPs) during chlorination. Hence NOM is considered a DBP precursor. NOM is difficult to quantify because of its complexity. For practical purposes, organic matter is quantified by measuring organic carbon concentrations such as total organic carbon (TOC), particulate organic carbon (POC), and dissolved organic carbon (DOC). There are many processes to reduce DBP precursors, i.e., to reduce organics. Some of them are listed here: (1) coagulation, (2) powdered activated carbon (PAC), (3) ozonation followed by biological active filtration (BAF), (4) granular activated carbon (GAC), and (5) magnetic ion exchange process (MIEX). The selected process should consider any limitations of the membrane material and be coordinated closely with the selected membrane system supplier. For example, abrasion may be a concern with some membranes and system designs with the use of PAC and, depending on the type and dosage of PAC utilized, could void a warranty.

As an introduction to the rest of the chapter, Table 2-1 presents an overview of potential pretreatment approaches for removing specific contaminants in combination with MF/UF, including NOM.

Table 2-1 Potential MF and UF pretreatment to achieve substantial removal for specified contaminants

Parameter		Pretreatments Needed for Substantial Removal	
		MF	UF
Particulate/microbial	Turbidity	None	None
	Protozoa	None	None
	Bacteria	None	None
	Viruses*	Coagulation	None
Organic	TOC	Pretreatment [†]	Pretreatment [†]
		Coagulation	Coagulation
		PAC/GAC	PAC/GAC
		Ozone-BAF	Ozone-BAF
	DBP precursor	Pretreatment [†]	Pretreatment [†]
		Coagulation	Coagulation
		PAC/GAC	PAC/GAC
		Ozone-BAF	Ozone-BAF
	Color	Pretreatment [†]	Pretreatment [†]
		Coagulation	Coagulation
		PAC/GAC	PAC/GAC
		Ozone-BAF	Ozone-BAF
Inorganic	Taste and odor (T&O)	Oxidation [‡]	Oxidation [‡]
		Coagulation	Coagulation
		PAC/GAC	PAC/GAC
	Pesticides	Oxidation [‡]	Oxidation [‡]
		PAC/GAC	PAC/GAC
	Iron and manganese	Oxidation [‡]	Oxidation [‡]
	Arsenic	Coagulation	Coagulation
	Hydrogen sulfide	Oxidation [‡]	Oxidation [‡]

* The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) does not award any credits for virus removal to low-pressure membranes (MF or UF) but delegates that decision making to states. Most states are consistent in allowing very little virus removal credit for membrane filtration.

[†] Pretreatment could include ozone or magnetic ion exchange resin treatment.

[‡] Oxidation could include chlorine, aeration, chlorine dioxide, and/or ozonation.

PARTICLE REMOVAL

Turbidity

MF and UF membranes are very successful in removing turbidity with typical filtrate values of less than 0.1 ntu. The positive barrier provided by an MF or UF system results in a consistent filtrate that is independent of feedwater quality. This has made MF and UF systems highly applicable for compliance with the Surface Water Treatment Rule (SWTR) and its derivatives, such as the Interim Enhanced Surface Water Treatment Rule (IESWTR), that require finished-water turbidity levels of 0.3 ntu or less for 95 percent of the samples within a month.

Figure 2-1 shows the turbidity results for numerous studies that were conducted between 1989 and 2001. Figure 2-1 plots the filtrate turbidities, both mean and maximum reported values, versus the average influent turbidity as determined from the reported mean, from the reported median, or by averaging the minimum and maximum reported influent turbidity readings. The results show that MF and UF membranes produce high-quality water regardless of influent turbidity and that there is no apparent difference in turbidity removal between membrane type, manufacturer, or whether a coagulant was used. The reported filtrate turbidities had a mean value of 0.097 ntu and a median value of 0.06 ntu ($n = 72$). The reported maximum filtrate turbidities had a mean value of 0.13 ntu and a median value of 0.08 ntu ($n = 68$).

Of the 122 sets of filtrate turbidity readings shown in Figure 2-1, only 6 show maximum or mean filtrate turbidities above the IESWTR limit of 0.3 ntu. The majority of the filtrate turbidities were below 0.3 ntu, with a smaller number of outlying samples indicated in the high end of the range or dominating the calculated arithmetic mean. Each study contains numerous individual turbidity readings. High filtrate turbidities for membrane systems are often artifacts caused by air bubbles from air-scour cleaning. Although turbidity measurements are not sensitive enough to determine membrane integrity, they are useful for showing that MF and UF membranes produce high-quality filtrate waters that are comparable to, or better than, waters of a well-operated conventional clarification and filtration facility.

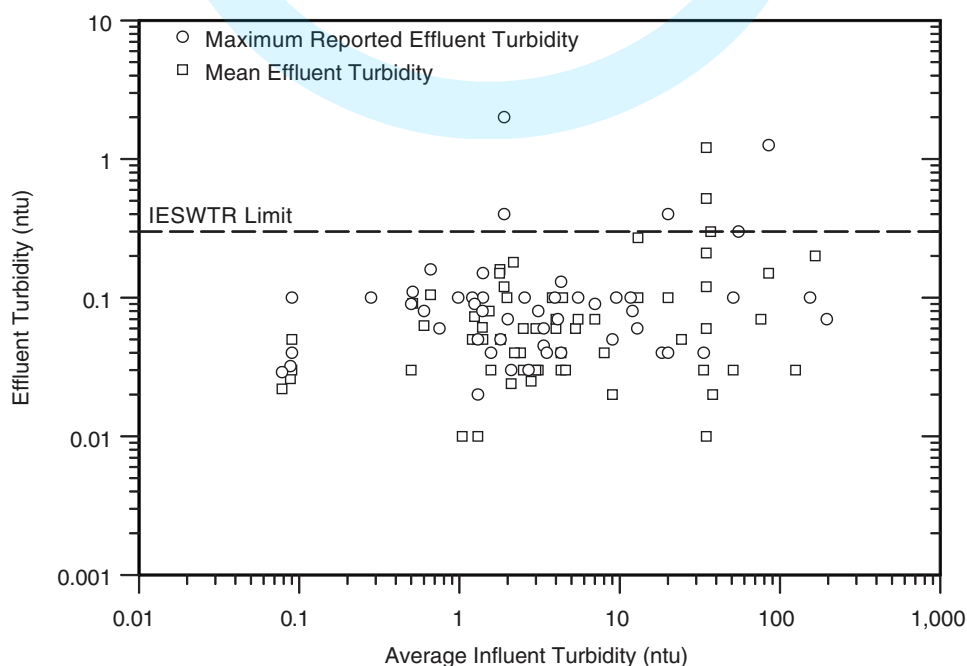


Figure 2-1 Summarized influent and effluent turbidity results from the literature review

Particles

Particle counting has greater sensitivity than turbidity for measuring the effectiveness of particle removal by MF/UF membranes. Figure 2-2 shows numerous particle-counting results under various conditions. Figure 2-2 plots minimum, mean, and maximum particle-count log removals versus the average influent particle count as determined from the reported mean or by averaging the minimum and maximum reported influent particle-count readings. In general, log removals for both MF and UF membranes, with and without coagulants, varied between 2 and 5. This is demonstrated in the studies with high influent particle counts (#/mL) greater than 5,000. The reason for the wide range of log removals at lower influent concentrations was related to how accurately the particle counters measured low concentrations of particles in the filtrate. As with turbidity, air bubbles introduced during backwashing and other artifacts in the filtrate artificially lower the reported log removals. This indicates that the removal of pathogenic microbes should be evaluated directly or conservative surrogates should be developed.

MICROBIAL CONTROL

MF and UF membranes sieve particles from water based on the pore size associated with the specific membrane material. For commercially available membrane systems, pore sizes are generally less than 0.3 micron. Therefore, turbidity and microbial removal can be essentially complete. One complicating factor for predicting microbial removal is that a natural or induced fouling cake layer can improve rejection characteristics (Jacangelo, Adham, and Laine 1995; DeCarolis et al. 2001). The fouling cake layer behaves as a second barrier to microbiological and particulate transport. Jacangelo, Laine et al. (1995) studied both natural fouling and induced fouling with kaolinite and found that fouling improved rejection characteristics.

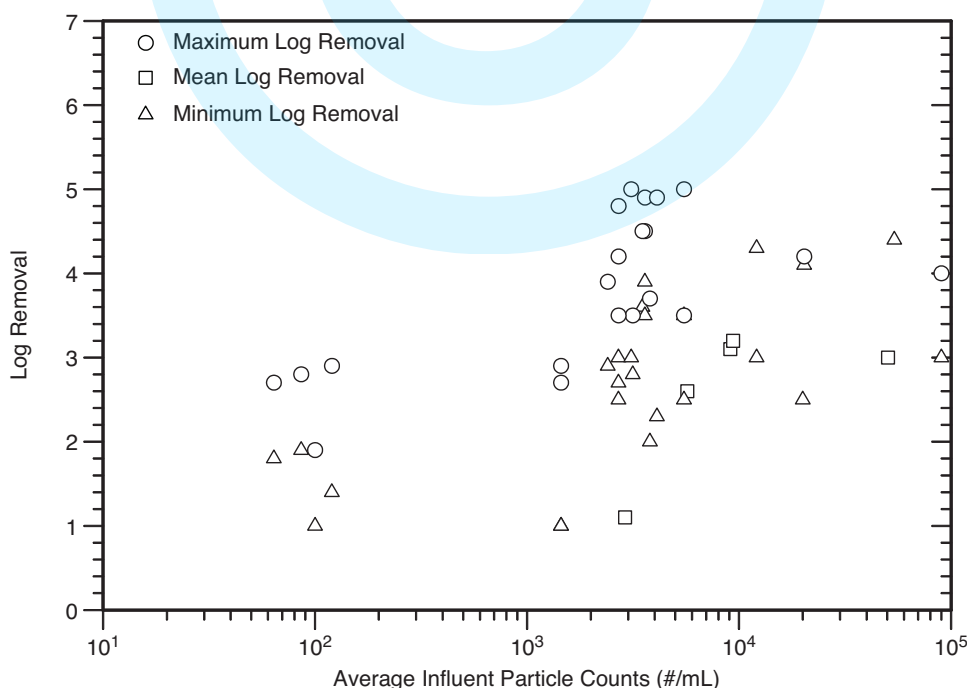


Figure 2-2 Summarized MF/UF particle count log removals from the literature review

NOTE: Percent reduction: 1 log = 90 percent, 2 log = 99 percent, 3 log = 99.9 percent, and 4 log = 99.99 percent.

Giardia* and *Cryptosporidium

Table 2-2 lists numerous studies that have evaluated *Giardia* cyst and *Cryptosporidium* oocyst removal. Because *Giardia* and *Cryptosporidium* are rarely seen in natural waters at concentrations high enough to accurately determine log removals, the studies shown in Table 2-2 used feedwater spiked with pathogens. This is not easily done because it is often difficult to obtain enough *Giardia* cysts and *Cryptosporidium* oocysts for a long-term study at pilot-scale flow rates. Therefore, some studies spiked a known number into a batch feed tank and monitored the membrane effluent while feeding from that tank. The log removal was calculated by the total number recovered in the effluent compared to the total number spiked into the feed tank. Even with this technique, it is difficult to quantify log removals because of the effectiveness of MF/UF processes in rejecting microbial agents. Often, the log removal is represented as greater than a certain number, which indicates that the filtrate numbers were below the quantification limit. For *Giardia* and *Cryptosporidium*, the log removals found (Table 2-2) were generally greater than 4.5 for both MF and UF membranes.

Jacangelo et al. (1991) and Coffey et al. (1993) studied the removal of *Giardia* by MF and UF. Both studies demonstrated removals greater than 4 log, with no cysts measured in the filtrate. In these cases, the level of removal was limited by the concentration of the organism in the feedwater. At bench scale, all the tested membranes (three MF and three UF) except one (MF, which contained a defective O-ring seal) removed the *Cryptosporidium* and *Giardia* to below the detection limit (1 cyst/L) (Jacangelo, Laine et al. 1995). These results were confirmed at pilot scale. Removals ranged from 6 to 7 log and were limited only by the influent concentration of the *Cryptosporidium* and *Giardia*. More recent studies (NSF 2009a and NSF 2011) reported 5.5-log to 6.3-log removal of *Cryptosporidium* with laboratory clean water. Therefore, it appeared that both polymeric MF and UF membranes were absolute barriers to protozoan cysts as long as the membrane was intact for the microbial challenge concentrations studied.

Other Microbial Agents

Table 2-3 shows the removals of various other microorganisms by MF and UF membranes. The studies primarily evaluated *Bacillus* spores, total coliform, fecal coliform, and *Pseudomonas* agents. The log removals varied from greater than 0.7 to greater than 9.8; however, the low removals were hampered by low influent/effluent values and the same minimum detection limitations as those seen for the *Cryptosporidium* and *Giardia* studies. When the studies conducted with low influent values (below 100,000 #/100 mL) are excluded, the log removals were above 5.5 for both membrane types. Recent studies have focused on surrogates such as *B. atrophaeus* (NSF 2009a, 2009b, 2009c; NSF 2011) and *B. subtilis* (Sethi et al. 2004), and respective log removals of 6–7.7 and 4.5–6.4 were reported.

Aerobic Spores

As a surrogate measure for *Giardia* and *Cryptosporidium*, *Bacillus* spores have shown great promise based on the number of studies conducted (Table 2-4). The log removals for the several studies varied between 1.7 and greater than 7.0, with no distinguishable difference between MF and UF membranes, and no distinguishable difference whether or not a coagulant was used. The 1.7-log removal result was likely influenced by low influent values that resulted in low effluent values. Excluding that reference, the log removals are above 3.5 log. Using ceramic membranes, 1.8-log to 4.5-log removals of *Bacillus* spores were observed by Muhammad et al. (2009).

Table 2-2 *Giardia* cyst and *Cryptosporidium* oocyst removal results for MF and UF membrane systems

Reference	Water	Reported Membrane Type	<i>Giardia</i> Cysts		<i>Cryptosporidium</i> Oocysts	
			Influent Mean (#/100 mL)	Log Removal	Influent Mean (#/100 mL)	Log Removal
NSF 2011	Laboratory clean	Dow SFD-2880 UF	—	—	9.4×10^5 – 2.4×10^6	6.0–6.3
NSF 2009a	Laboratory clean	Siemens L10V	—	—	3.2×10^5 – 7.5×10^5	5.5–5.7
NSF 2000a	Highland reservoir	Microza MF	11.8×10^6 TN	>5.8	1.01×10^8 TN	>6.8
NSF 2000b	Highland reservoir	Aquasource UF	8.4×10^6 TN	>5.5	8.2×10^7 TN	>6.5
NSF 2000c	Highland reservoir	Ultrabar UF	13.8×10^6 TN	>4.9	9.9×10^7 TN	>5.8
NSF 2000d	Highland reservoir	ZeeWeed 500 UF	8.6×10^6 TN	>5.3	1.1×10^7 TN	6.4
Dwyer et al. 1995	Laboratory clean	Koch PMPW UF	NR	5.7	NR	5.7
Jacangelo, Adham, and Laîné 1995	Laboratory clean	Three MF	5.4×10^4 – 1.5×10^5	4.6–>5.2	2.6×10^4 – 8.2×10^4	4.2–>4.9
		Three UF	5.4×10^4 – 1.5×10^5	>4.7–>5.2		>4.4–>4.9
	Bull Run Reservoir	Three MF	2.8×10^4 – 1.3×10^5	>6.4–>7.0	1.1×10^4 – 7.4×10^4	>6.0–>6.9
	Lake Elsman	Three UF	2.6×10^4 – 1.0×10^5	>6.4–>7.0	2.4×10^4 – 9.1×10^4	>6.3–>7.0
Kachalsky and Masterson 1995	New York conventionally treated sewage	Moustic MF	NR	5.0	NR	4.9
		Moustic UF		7.3		6.9
		Ceramem MF		5.8		5.7
		Ceramem UF		7.4		7.0
		Membralox MF		7.3		>7.3
		Membralox UF		>7.3		>7.1
		Memcor CMF		>6.6		>6.4
Movahed et al. 1995	Guyardotte River	Memcor CMF	1.0×10^7 TN	>7.0	NR	NR
Coffey et al. 1993	Colorado River	Memcor CMF	2.8×10^4 TN 2.8×10^4 TN 2.6×10^4 TN	>4.4 >4.4 >4.4	NR	NR
Pearce and Hanks 1993	England surface water	Fibrotex MF	NR	NR	1,000	2–3
Olivieri et al. 1991	Fishing Creek	Memcor CMF	1.0×10^4	>5.6	42.5	>4.8

NR = not reported

TN = total number of cysts added to system

Table 2-3 Other microbial removal results for MF and UF membrane systems

Parameter	Reference	Water	Reported Membrane Type	Influent Mean* (#/100 mL)	Log Removal
<i>Bacillus atrophaeus</i>	NSF 2011	Laboratory clean	Dow SFD-2880 UF	7.3×10^6 – 1.63×10^7	6.7–7.2
<i>B. atrophaeus</i>	NSF 2009a	Laboratory clean	Siemens L10V	6×10^6 – 1.1×10^7	6.0–7.0
<i>B. atrophaeus</i>	NSF 2009b	Laboratory clean	Siemens L20V	6.5×10^6 – 1.7×10^7	6.8–7.1
<i>B. atrophaeus</i>	NSF 2009c	Laboratory clean	Siemens S10V	3.6×10^7 – 6.1×10^7	6.6–7.7
<i>Bacillus subtilis</i>	Sethi et al. 2004	Settled surface water	MF PVDF	2.3×10^6 – 3.1×10^6	4.5–6.4
<i>B. subtilis</i>	Sethi et al. 2004	UF permeate	UF polysulfone	5.6×10^5 – 8.3×10^5	4.5–5.4
Total coliform	Adham et al. 2001	Primary-treated wastewater	ZeeWeed 500 UF Sterapore UF	$(2.2 \times 10^6$ – $9 \times 10^7)$ 1.7×10^7 & $(2.3 \times 10^6$ – $5 \times 10^7)$ 9.5×10^6	>6.9 & >6.7 5.6 & >6.7
Fecal coliform			ZeeWeed 500 UF Sterapore UF	$(2.8 \times 10^5$ – $1.7 \times 10^8)$ 5×10^6 & $(7.0 \times 10^5$ – $1.1 \times 10^7)$ 2.3×10^6	>6.4 & >6.1 >6.4 & >6.1
Total coliform	DeCarolus et al. 2001	Tertiary-treated wastewater	HYDRAcap UF w/ FeCl ₃	479,000	1.2–>7.0
Total coliform	Glucina and Laïné 2001	Seine River	Aquasource UF	$(800$ – $1 \times 10^5)$ 2.0×10^4	>4.3
<i>Escherichia coli</i>	Jacangelo et al. 1997	Laboratory clean	Three MF Three UF	6.6×10^7 6.6×10^7 – 9.6×10^8	>7.8 5.6–>9.0
<i>Pseudomonas aeruginosa</i>		Laboratory clean	Three MF Three UF	1.5×10^8 1.5×10^8 – 5.3×10^8	>8.2 >8.2–>8.7
Total coliform		Lake Elsmar Bull Run Reservoir	Two MF Two UF	11–972 6–160	>0.7–>3.0 >0.7–>2.2
Fecal coliform	Kachalsky and Masterson, 1995	New York conventionally treated sewage	Moustic MF Moustic UF Ceramem MF Ceramem UF Membralox MF Z8 UF	NR	1.4 1.8 2.8 2.2 4.9 4.0
Total coliform	Movahed et al. 1995	Guyardotte River	Memcor CMF	2.8×10^6	>6.1
Total coliform <i>E. coli</i>	Coffey et al. 1993	Colorado River	Memcor CMF	$(14$ – $240)$ 90 $(9.8 \times 10^7$ – $2.7 \times 10^8)$	>1.7 >6.0–>6.4
Fecal coliform and <i>Enterococci</i>	Willinghan et al. 1993	Secondary-effluent wastewater	Memcor CMF	NR	2–6
<i>Pseudomonas diminuta</i>	Olivieri et al. 1991	Fishing Creek	Memcor CMF	7.0×10^9	>9.8
<i>E. coli</i>				2.0×10^7 3.0×10^7 2.9×10^7	>7.3 >7.4 >7.4

* Influent range shown in parentheses.

NR = not reported

Table 2-4 *Bacillus* spore removal results for MF and UF membrane systems

Reference	Water	Reported Membrane Type	Influent Mean* (cfu/L)	Log Removal
Bartley et al. 2010	Deionized	Siemens L10V (0.04 micron)	Not listed	>5.7
		Siemens L20V (0.04 micron)	Not listed	6.5
		Siemens S10V (0.04µm)	Not listed	>5.5
		Dow Filmtec SFP-2880 (0.03 micron)	Not listed	>5.8
		Hyflux Kristal 600ET PES (mPS 120KD)	Not listed	>5.2
Muhammad et al. 2009	Dechlorinated potable water	M&PT MP-UF-2A ceramic (0.01 micron)	7.5×10^5 – 2.2×10^6	3.4–4.5
		M&PT MP-UF-2A ceramic (0.05 micron)	1.6×10^5 – 4.5×10^5	1.8–2.3
Farahbakhsh et al. 2004	Membrane permeate	ZeeWeed 500d	Not listed	>7
		ZeeWeed 1000a	Not listed	>7
Côté et al. 2003	Membrane permeate	ZeeWeed 500d	10^6	7
Robert et al. 1999	Bowling Green Reservoir	MF	NR	3.5
		UF with ferric		3.6
Trimboli et al. 1999	Tau Tau Stream, New Zealand	Memcor CMF	$(5.0 \times 10^3$ – $1.1 \times 10^6)$	>3.7–>6.0
Freeman et al. 1997	Finished water	Memcor CMF	1,890	1.7
Owens et al. 1999	Hillsborough River	ZeeWeed 500 MF	1.0×10^8	5.0
				5.4
		ZeeWeed 500 MF w/alum		4.2
				4.9
		Memcor CMF		6.3
		Memcor CMF w/alum		6.3
				6.9
				5.6

* Influent range shown in parentheses.

NR = not reported

Viruses

The general distinction between MF and UF membranes is that UF membranes can reject viruses whereas MF membranes cannot. Table 2-5 displays studies that have been conducted with viruses. The predominant virus of choice was MS-2 bacteriophage because of the ability to obtain large amounts for spiking purposes and because of its acceptance as a good surrogate for enteric viruses. UF membranes with a relative pore size of 0.01 to 0.035 µm typically removed greater than 3.0 log of viruses, while MF membranes typically removed less than 2.5 log. Given the size of MS-2 phage (0.024 micron) relative to the pore size of the MF membranes tested (0.1 to 0.2 µm), the relatively high level of virus removal by MF membranes is explained by either attachment of the viruses to larger-sized particulates naturally occurring in the feedwater or by the retention of viruses by the fouling (cake) layer at the membrane surface. Using UF ceramic membranes with 0.01-µm pore size, Muhammad et al. (2009) reported log removals of 0.14–3.0 for virus.

In general, application of the LT2ESWTR regulatory framework for the removal of viruses necessitates that the membrane filtration process comply with appropriate pathogen-specific criteria for the three primary regulatory elements: challenge testing, direct integrity testing, and continuous indirect integrity monitoring. LT2ESWTR does not award any credits for virus removal to low-pressure membranes (MF or UF) but delegates that decision making to states. It is possible that a multibarrier treatment process scheme, including low-pressure membranes, could be awarded equivalent or greater virus removal credit than conventional treatment. The appropriate regulatory agency should be contacted for requirements within its jurisdiction. Because viruses are easily inactivated by low chlorine doses and contact times that are unlikely to yield significant disinfection by-products (DBPs), there is less of a necessity for states to award high virus removal credits to any alternative treatment process if some level of primary disinfection is required. By contrast, states generally award removal credit on par with that for conventional treatment for both MF and UF for larger pathogens such as *Giardia* and *Cryptosporidium*, which have more stringent chlorine inactivation requirements.

ORGANIC CONTROL

MF and UF membranes are designed to remove particulates and not dissolved organic species, although some reduction has been noted in pilot-scale and full-scale installations. To remove dissolved organics with MF and UF membranes, other processes, such as those using coagulants and adsorbents, have to be integrated into the treatment scheme. The organic contaminants can then be coagulated or adsorbed, hence associating themselves with particulates that can be rejected by the MF or UF membrane.

Coagulation

Historical data show that without coagulants DOC, trihalomethane (THM) precursor, haloacetic acid (HAA) precursor, and total organic halide (TOX) precursor, removals via MF and/or UF membranes alone were generally below 20 percent. With alum or ferric coagulants fed upstream of an MF and/or UF membrane, the percent removals ranged between 12 and 83 percent for DOC, 30 and 88 percent for THM precursors, 39 and 92 percent for HAA precursors, and 20 and 85 percent for TOX precursors. The amount of removal was a function of coagulant dose, coagulant type, pH, temperature, mixing time, and mixing velocity.

Adsorbents

Adsorbents, such as PAC and iron oxides, can remove DOC/DBP precursors. The removal is dependent on the DOC concentration, adsorbent dose, DOC adsorbability, pH, temperature, and contact time. In conventional treatment plants, PAC is usually not chosen for DOC or DBP precursor removal because the heterogeneous precursor material is not adsorbed well enough and the contact time is too short to allow PAC to be more cost-effective than granular activated carbon. Less is known about using iron oxide adsorbents, but similar conclusions are likely.

In previous studies with integrated adsorbent membrane systems, without adsorbent or coagulant, the removal of DOC, THM precursors, HAA precursors, and TOX precursors was generally below 20 percent. With PAC addition, the percent removals ranged between 10 and 80 percent for DOC, 0 and 90 for THM precursors, 30 and 80 for HAA precursors, and 20 and 85 percent for TOX precursors. For iron oxide addition, the percent removals ranged between 20 and 75 percent for DOC and between 30 and 90 percent for THM precursors. As such, an integrated adsorbent membrane system can be effective in removing precursors, but it is a site-, adsorbent-, and dose-specific phenomenon that must be evaluated for each utility contemplating such a system.

Table 2-5 MS-2 bacteriophage removal results for MF and UF membrane systems

Reference	Water	Reported Membrane Type	Influent Mean (#/L)	Log Removal
Garcia-Aleman and Suydam 2011	CRW/SPW, San Diego County	PVDF (0.02 micron)	1.00×10^6	2.83
Bartley et al. 2010	Deionized	Siemens L10V (0.04 micron)	Not listed	>1.9
	Deionized	Siemens L20V (0.04 micron)	Not listed	>2.2
	Deionized	Siemens S10V (0.04 micron)	Not listed	>2.6
	Deionized	Dow Filmtec SFP-2880 (0.03 micron)	Not listed	>3.0
	Deionized	Hyflux Kristal 600ET (mPS 120 KD)	Not listed	>2.4
Muhammad et al. 2009	Dechlorinated potable water	M&PT MP-UF-2A ceramic (0.01 micron)	1.8×10^5 to 1.0×10^6	1.4 to 3.0
	Dechlorinated potable water	M&PT MP-UF-2A ceramic (0.01 micron)	1.8×10^5 to 3.8×10^5	0.14 to 0.22
Arkhangelsky and Gitis 2009	Not listed	PES mPS 20 KD	1.00×10^7	>2.8
Jacangelo et al. 2006	Clean water	mPS 10 KD	1.0×10^8	3.8
	Clean water	mPS 100 KD	1.0×10^8	>5.7
	Clean water	mPS 300 KD	1.0×10^8	>5.5
	Clean water	PVDF (0.035 micron)	1.0×10^8	3.8
	Clean water	PVDF (0.1 micron)	1.0×10^8	0.34
	Clean water	mPS (0.2 micron)	1.0×10^8	0.45
	Chattahoochee River, Atlanta	PVDF (0.1 micron)	1.0×10^8	0.2–5.0
	Thames River, London	PVDF (0.035 micron)	1.0×10^8	0.0–3.7
	Secondary effluent, Scottsdale	PVDF (0.1 micron)	1.0×10^8	0–4.4
Kramer et al. 2003	Mississippi River	Norit UF	1.0×10^6	>6.3
Curl and Mariñas 2003	Lake Decatur	PVDF mPS 90 KD	1.0×10^5	>2
	Clean water	PVDF mPS 90 KD	1.0×10^5	2
Adham et al. 2001	Primary-treated wastewater	Zenon UF	$(1.7 \times 10^4 - 2.5 \times 10^6)$	>4.1 & >3.7
		Mitsubishi UF	10^5 & $(4E3 - 8 \times 10^5)$	>4.1 & >3.7
Gramith et al. 2001	San Diego Aqueduct	UF #1 with alum	$(8 \times 10^7 - 6 \times 10^9)$	5.4–5.6
		UF #3		4.0–4.7
		UF #4		4.0–5.6
NSF 2000f	San Diego Aqueduct	Hydranautics (HYDRACap UF)	$(2.8 \times 10^9 - 1.7 \times 10^{10})$	3.9–4.7
			$(4.5 \times 10^9 - 1.1 \times 10^{10})$	3.4–4.3
NSF 2000g	San Diego Aqueduct	Ionics UF (UF-1-7T)	$(7.4 \times 10^8 - 2.8 \times 10^9)$	4.0–5.7
			$(3.5 \times 10^9 - 6.0 \times 10^9)$	2.9–4.3
NSF 2000h	San Diego Aqueduct	Zenon UF (ZW-500) with alum	$(3.5 \times 10^{10} - 5.9 \times 10^{10})$	>5.5–>5.8
			$(2.4 \times 10^{10} - 4.6 \times 10^{10})$	1.7–2.1
Kruithof et al. 1999	Yssel Lake	X-Flow UF	18,000	4.9

KD = kilodalton/s

NR = not reported

(continued)

Table 2-5 MS-2 bacteriophage removal results for MF and UF membrane systems (continued)

Reference	Water	Reported Membrane Type	Influent Mean (#/L)	Log Removal
Jacangelo et al. 1997	Laboratory clean	Three MF Three UF	(140–745) NR	>1.5 1.5–>7.0
Kruithof et al. 1997	Ijssel Lake	MF UF	$(1.0 \times 10^5 - 1.1 \times 10^5)$ $(2.2 \times 10^4 - 2.5 \times 10^4)$	0.7–2.3 >5.4
Dwyer et al. 1995	Laboratory clean	Koch Lab 5UF (PMPW) (PM10) (PM500)	$(2.4 \times 10^3 - 1.4 \times 10^4)$ NR NR	2.0–6.3 >6.2–>6.8 1.5–4.0
Jacangelo, Adham, and Laine 1995	Bull Run Reservoir Lake Elstman Seine River	Three MF Three UF	$10 \times 10^5 - 10 \times 10^{12}$	<0.5–2 3–>7
Coffey et al. 1993	Colorado River	Memcor MF (4M1)	1.3×10^9 3.0×10^{10} 1.6×10^{10}	1.7 2.0 2.9
Olivieri et al. 1991	Australian Wastewater	Memcor MF (CMF)	$(2 - 2.0 \times 10^4)$	>2–>6

KD = kilodalton/s

NR = not reported

Color and Taste and Odor

The issues involving the removal of color-causing compounds are similar to those issues for removing DOC, although color-causing compounds tend to be somewhat easier to remove than DOC. Available data indicate color removal is highly variable, ranging between 0 and 100 percent as shown in Table 2-6. Coagulants will greatly assist in the removal of color-causing compounds, as demonstrated by Adham et al. (2006), Lozier et al. (2008), Thompson and Galloway (2001), and Reiss et al. (1999). Clair et al. (1997) found that PAC can assist in the removal of color, although as with DOC removal, it is expected that high PAC doses would be required for substantive removal. Karnik (2008) demonstrated that with ceramic membranes and without any coagulant, 99.7 percent color removal is possible.

Additionally, integrated adsorbent membrane systems can be very effective for taste-and-odor (T&O) control as shown in Table 2-7. The removals without a coagulant or adsorbent were between 21 and 49 percent. With coagulation or PAC, most of the removals ranged from 30 to 100 percent for T&O, geosmin, and 2-methylisoborneol. The issues/limitations for T&O removal are similar to those for the removal of DOC and color. However, if the T&O issues are a result of algae compounds, care needs to be taken for effective pretreatment of the algae, as algae can foul a membrane significantly and reduce the membrane's overall effectiveness and throughput.

Table 2-6 Color removal results for MF and UF membrane systems

Reference	Water	Reported Membrane Type	Coagulant	Influent Color* (Pt-Co)	Color Removal (%)
Karnik 2008	Oyster Creek	Ceramic	None	370	99.7
Lozier et al. 2008	White River, Indiana	CMF (0.1 micron)	Alum	22.5	55
Lozier et al. 2008	Tampa Bay WTP, raw water, Florida	UF (0.02 micron)	Ferric sulfate	30	67
Adham et al. 2006	Raw water, Ashland WTP, Wisconsin	MF (0.1 micron)	ACH	25	80
Adham et al. 2006	Medina River, Texas	UF (0.02 micron)	Ferric sulfate	6	83
Adham et al. 2006	Raw water, Mered-ity, Australia	MF (0.1 micron)	ACH	55	90
Best et al. 2001	Red Deer River	ZeeWeed 500 UF	25 mg/L alum	5–85	73
			25–35 mg/L alum	5–85	64
			50 mg/L alum	35	83
Bourke et al. 2001	River Murray	MIEX + Memcor CMF-S	MIEX resin	15	80
Côté et al. 2001	California surface water	ZeeWeed 1,000 UF	None	23	78
Crawford and Bach 2001	Jackson, Mississippi	ZeeWeed 500 UF	KMnO ₄	26–32	86
Glucina and Laine 2001	Seine River	Aquasource UF	None	(6.5)	0
Gluzman et al. 2001	Pelican Lake	ZeeWeed 500UF	FeCl ₃ , CaCl ₂ , or alum	(48)	>90
Gramith et al. 2001	San Diego Aqueduct	UF	30 mg/L alum	NR	76
Mueller and Sloan 2001	Salmon River	ZeeWeed 500 UF	10–15 mg/L ACH	14	66
	Jesse Creek	Microza MF	10–15 mg/L alum		67
Sorgini and Ashe 2001	Lincoln pond	Memcor CMF	None	17.4	100
Thompson and Gal-loway 2001	Stonington pond	Ozone + UF	None	140	17–54
			10 mg/L FeCl ₃		50–75
			22 mg/L FeCl ₃		82–90
NSF 2000h	San Diego Aqueduct	ZeeWeed 500 UF	30 mg/L Alum	8.5	76
Maurato et al. 1999	Lake Ontario	ZeeWeed 500 UF	40 mg/L FeCl ₃	21	95
	Huntsville			33	100
	Croton Lake			10	100
Reiss et al. 1999	Hillsborough River	ZeeWeed 500 UF	None	195	22
			Fe ₂ (SO ₄) ₃	101	90
		Memcor CMF	None	48	23
Clair et al. 1997	Kansas River	Memcor CMF	None	8–15	10
			5 mg/L FeCl ₃		7
			5 mg/L PAC		27
			20 mg/L PAC		37
Lozier and Jones 1997	Isatkoak Reservoir	Memcor CMF	None	60	25–66

* Influent range shown in parentheses.

ACH = aluminum chlorohydrate

NR = not reported

Table 2-7 Taste-and-odor removal results for MF and UF membrane systems

Reference	Water	Reported Membrane Type	Coagulant	Influent (ng/L or TON)	T&O Removal (%)
Trueger et al. 2008	Eagle Creek	MF PES	PAC	20–70 M	30–50
Trueger et al. 2008	Eagle Creek	MF PES	PAC	20–100 G	50–90
Walker et al. 2011	Lake Conroe	MF, Ceramic	ACH	4 TON	50
Braghetta et al. 2001	Medina River	Aquasource UF	10 mg/L PAC	NR	73 M / 88 G
		Koch UF			69 M / 89 G
		HYDRAcap UF			69 M / 92 G
		Aquasource UF	20 mg/L PAC		92 M / 93 G
		Koch UF			88 M / 93 G
		HYDRAcap UF			93 M / 93 G
Ford et al. 2001	Saltonstall Lake	ZeeWeed 500 UF	20 mg/L alum	37 M	74 M / 83 G
			10 mg/L PAC	30 G	90 M / 94 G
			20 mg/L alum		
			20 mg/L PAC		
Schideman et al. 2001	Lake Michigan	ZeeWeed 1,000 UF	10 mg/L PAC	30–150	49 M
			20 mg/L PAC		87 M
			30 mg/L PAC		90 M
Sorgini and Ashe 2001	Lincoln Pond	Memcor CMF	None	3.2 TON	49
Lainé et al. 1999	Delta River	UF	None	9 TON	44
	Apie Reservoir		8 mg/L PAC	5 TON	100
	Delta River		40 mg/L PAC	9 TON	78
Reiss et al. 1999	Hillsborough River	ZeeWeed 500 UF	None	<1 M	—
				9 G	44 G
			Fe ₂ (SO ₄) ₃	7.9 M	4 M
		Memcor CMF		2.5 G	24 G
			None	18 M	21 M
				2.7 G	>63 G

G = geosmin

M = methylisoborneol

NR = not reported

TON = threshold odor number

Pesticides

Integrated PAC/membrane systems can be effective for removing pesticides. Anselme et al. (1991) found that a PAC/UF system was effective for removing pesticides and synthetic organics. Jack and Clark (1998) found that a PAC/UF system was able to remove 61 percent of the influent atrazine, and 70 percent of the influent cyanazine, at 10 mg/L PAC. Clair et al. (1997) reported atrazine removals of 57 percent at 5 mg/L PAC and 89 percent at 20 mg/L PAC. These results are likely similar to those obtained with PAC addition in conventional plants, although as previously discussed, the adsorbent retention time can be increased in integrated membrane systems, which can lead to greater adsorption. The final degree of adsorption is dependent on other factors as well, such as PAC type, competitive adsorption from natural organic matter or other contaminants, contact time, PAC dose, temperature, and pH (if the pesticide is ionic in nature).

INORGANIC CONTROL

Like the removal of organics by MF and UF membranes, removal of inorganics is related to what percentage of the species is in particulate state. This can be enhanced by using a coagulant, oxidant, or ion-exchange resin. Some studies have shown that inorganic species can be removed by charged-repulsion phenomena if the membrane is highly charged. However, these phenomena occur to the greatest extent in laboratory-clean waters, which do not have naturally occurring ions that can neutralize the membrane surface. Therefore, for MF and UF membranes, removal of inorganic species is limited to the integrated use of a coagulant, oxidant, or ion-exchange resin.

Iron and Manganese

The removal of iron and manganese is dependent on the oxidation of these species so that they precipitate. The precipitate can be rejected by MF or UF membranes. As in conventional treatment plants, iron and manganese can be oxidized by either aeration or by chemical oxidants such as permanganate, chlorine, or ozone. Aeration is usually more effective for iron control than for manganese control.

The number of studies evaluating iron and manganese removal with MF/UF is limited, and results were varied in many cases (summaries of some representative study results are presented in Table 2-8), especially for manganese, which is typically more challenging to oxidize. Fourteen studies with iron showed greater than 70 percent removal with MF/UF following oxidation. For manganese control, Schneider et al. (2001) evaluated the effectiveness of various oxidants with MF and found that chlorine dioxide was the most effective. Suozzo (2011) found that 98 percent removal of manganese is possible with UF membranes and ozone as an oxidant. Crawford and Bach (2001) found that manganese removal was highly variable depending on coagulant and pH. Neemann et al. (2001) found that manganese removal was highly variable depending on the potassium permanganate dosage used. Generally, integrated membranes can remove iron reliably because of the ease of oxidation, whereas manganese removal is more difficult, being more dependent on the oxidant and the oxidant dose.

Other Inorganics

Arsenic can be removed with MF or UF membranes but only if an adsorbent or ferric coagulant is used. Jeffcoat et al. (2001) showed good arsenic removal using an integrated UF system with activated alumina. The removal of the strongly adsorbing As(V) was much greater than the poorly adsorbing As(III). As shown in Table 2-8, Chang et al. (2001) found good arsenic removals using ferric chloride, while Shorney et al. (2001) found good removals using ferric sulfate.

In some instances, such as the case of arsenic, transforming the species to a higher oxidation state allows for charge repulsion by a tight and charged UF membrane. Amy et al. (1995) found that a 10,000-dalton membrane was able to achieve 63 percent rejection of As(V), whereas it was not able to reject As(III). However, Yoon et al. (2001) and Liang et al. (2001) demonstrated that a charged UF membrane was not able to reject perchlorate in natural water because of the neutralization of the membrane surface by the natural mixture of ionic species in the water (Table 2-8). It should be noted that for arsenic and perchlorate removal, a coagulant or an ion-exchange resin must be incorporated into the membrane system.

Hydrogen sulfide is not generally removed with MF and UF membranes because of the relative costs when compared to removal via aeration. However, in specific applications, such as those requiring high removals, MF and UF can be effectively utilized. Studies by Talton et al. (2000) and Owen et al. (2007) showed essentially complete removal of

dissolved hydrogen sulfide gas using a chlorine-oxidation/membrane filtration process. Carriere et al. (2010) showed that 69–100 percent of the influent ammonia can be removed using ozone/PAC as pretreatment.

Table 2-8 Inorganic removal results for MF and UF membrane systems

Parameter	Reference	Water	Reported Membrane Type	Oxidant/Coagulant	Influent ($\mu\text{g/L}$ or mg/L)	Removal (%)
Hydrogen sulfide	Owen et al. 2007	Groundwater	Zenon	Chlorine	1.2 as S	>96
Hydrogen sulfide	Owen et al. 2007	Groundwater	Zenon	Bio-oxidation	1.2 as S	>96
Iron	Wetterau et al. 2009	Groundwater	Siemens CMF L10V, PVDF (0.04 μm)	Aeration	0.16	50–90
Ortho phosphate	Schimmoller et al. 2009	Reclaimed water	MF	Ferric chloride	10–20	90–99
Total phosphorous	Cisterna 2009	Reclaimed water	UF	Alum	2	up to 95
Ammonia	Carriere et al. 2010	Mille Iles River	UF 0.05 micron PES	Ozone/PAC	0.09	69–100
Iron	Suozzo 2011	3 studies in Massachusetts	UF	Ozone	0–5.4	>94
Manganese	Suozzo 2011	3 studies in Massachusetts	UF	Ozone	0.04–2.4	>98
Iron	Islam and Reed 2011	RO reject	UF–PVDF MWCO-200 kilodaltons	Ferric chloride	44	99.98
Iron	Lozier et al. 2008	Twente Canal, Netherlands	PES, UF, 200 kilodaltons	AC	0.61	95
Iron	Lozier et al. 2008	White River, Indiana	CMF, 0.1 microns	Alum	0.25	92
Manganese	Lozier et al. 2008	White River, Indiana	CMF, 0.1 microns	Alum	0.03	23
Iron	Lozier et al. 2008	Tampa Bay WTP, raw water, Florida	UF, 0.02 microns	Ferric sulfate	3,300	99
Manganese	Lozier et al. 2008	Twente Canal, Netherlands	UF, 0.02 microns	Ferric sulfate	0.017	35
Iron	Adham et al. 2006	Raw water, Meredity WTP, Australia	MF, 0.1 microns	ACH	2.5	88
Manganese	Adham et al. 2006	Raw water, Meredity WTP, Australia	MF, 0.1 microns	ACH	1	90
Arsenic	Chang et al. 2001	Yellowstone River	Two MF units	None 5 mg/L FeCl_3	14.1–17.1 1.3–6.7	8 77–85
Arsenic	Shorney et al. 2001	Salt River Project Canal (Arizona)	Microza MF Memcor CMF-s MF ZeeWeed 500 UF UF	None	5	4 As(V) 8 As(V) 8 As(V) 4 As(V)

AC = polyaluminum chloride

ACH = aluminum chlorohydrate

NR = not reported

(continued)

Table 2-8 Inorganic removal results for MF and UF membrane systems (continued)

Parameter	Reference	Water	Reported Membrane Type	Oxidant/ Coagulant	Influent (µg/L or mg/L)	Removal (%)
			Microza MF	5–15	16–18	4– >96
			Memcor CMF-s MF	mg/L		As(V)
			ZeeWeed 500 UF	Fe ₂ (SO ₄) ₃		41– >96
			UF			As(V)
						36– >96
						As(V)
						23– >96
						As(V)
			Microza MF	10–15	4	—
			Memcor CMF-s MF	mg/L		56–83
			ZeeWeed 500 UF	Fe ₂ (SO ₄) ₃		As(III)
			UF			60–82
						As(III)
						90 As(III)
Iron	Clark and Griffin 2001	Lower Sunshine Reservoir	Memcor CMF	None	320	91
Iron	Paxman et al. 2001	Rockport Reservoir	Memcor CMF	10 mg/L	45–101	70
			Aquasource UF	FeCl ₃		70
			Koch UF			70
			ZeeWeed 500 UF			70
Iron	Chan et al. 1997	West River	MF	15 mg/L	190	90
			Aquasource UF	AC	242	>96
Iron/manganese	Lynk et al. 2001	Edwards Aquifer	Aquasource UF	None	1,390 Fe 50 Mn	>96 Fe >40 Mn
Iron/manganese	Schneider et al. 2001	Alcovy River	MF	None Chlorine ClO ₂ KMnO ₄	NR	100 Fe / 22 Mn 98 Fe / 29 Mn 100 Fe / 99 Mn 98 Fe / 70 Mn
Iron/manganese	Sorgini and Ashe 2001	Lincoln pond	Memcor CMF	None	140 Fe 120 Mn	100 Fe 91 Mn
Iron/manganese	O'Connell and Danos 1997	Spectacle pond	UF	Ozone	20–300 Fe 300–490 Mn	97 Fe 91 Mn
Manganese	Crawford and Bach 2001	Jackson, Miss.	ZeeWeed 500 UF	10–15 mg/L ACH 10 mg/L alum	180	50–100
Perchlorate	Liang et al. 2001	Colorado River	Osmonics GM UF	None	85 & 1,760	0–10
Perchlorate	Yoon et al. 2001	Laboratory Colorado River	Osmonics GM UF	None	NR	75–80 < 5

AC = polyaluminum chloride

ACH = aluminum chlorohydrate

NR = not reported

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