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LOW-PRESSURE MEMBRANE FILTRATION FOR PATHOGEN REMOVAL: APPLICATION, IMPLEMENTATION, AND REGULATORY ISSUES

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LOW-PRESSURE MEMBRANE FILTRATION FOR PATHOGEN REMOVAL: APPLICATION, IMPLEMENTATION, AND REGULATORY ISSUES

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AFT   Alternate filtration technology

ASDWA Association of State Drinking Water Administrators

AWWA American Water Works Association

AWWARF American Water Works Association Research Foundation

CFE   Combined filter effluent

CIP   Clean-in-place

CPE   Comprehensive Performance Evaluation

CT   Disinfectant residual (mg/L) × contact time (minutes)

CWS   Community water system

DBP   Disinfection byproduct

DBPR   Disinfectant and Disinfection Byproducts Rule

DI   Deionized water

EPA   United States Environmental Protection Agency

ETV   Environmental Technology Verification

FACA   Federal Advisory Committee Act

FBR   Filter Backwash Rule

FR   Federal Register

FSR   Future state requirement

GAC   Granular activated carbon

gfd   Gallons per square foot per day

GWUDI Ground water under the direct influence (of surface water)

HAA   Haloacetic acid

HPC   Heterotrophic plate count

ICR	Information Collection Rule
IESWTR	Interim Enhanced Surface Water Treatment Rule
IO	Inside-out
LNTU	Laser turbidimetry
LRAA	Locational running annual average
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal
M-DBP	Microbial-Disinfection Byproducts
MF	Microfiltration
MGD	Million gallons per day
MIB	Methylisoborneol
MPA	Microscopic Particulate Analysis
MPN	Mean probable number
MRDL	Maximum Residual Disinfectant Level
MRDLG	Maximum Residual Disinfectant Level Goal
MWCO	Molecular weight cut-off
MWD	Metropolitan Water District (of Southern California)
NA	Not applicable
NF	Nanofiltration
NR	Not reported
NSF	National Sanitation Foundation
NTNCWS	Nontransient noncommunity water system
NTU	Nephelometric turbidity units

OI	Outside-in
PAC	Powdered activated carbon
PC	Particle counting
pfu	Plaque forming units
PM	Particle monitoring
psi	Pounds per square inch
PVDF	Polyvinyl difluoride
PWS	Public water systems
RO	Reverse osmosis
SDWA	Safe Drinking Water Act
SR	State requirement
SWTR	Surface Water Treatment Rule
TC	Total coliforms
TCU	True color units
THM	Trihalomethane
TMP	Transmembrane pressure
TOC	Total organic carbon
TSS	Total suspended solids
UF	Ultrafiltration
UV	Ultraviolet (light)
UV-254	Ultraviolet absorbance at 254 nm
WQ	Water quality
WWTP	Wastewater treatment plant

EXECUTIVE SUMMARY

Microfiltration (MF) and ultrafiltration (UF) are low-pressure membrane filtration processes that have gained considerable acceptance in the drinking water industry over the past ten years. MF and UF are primarily used for particle removal as stand-alone treatment, retrofit of existing conventional treatment plants (as a replacement for conventional particle removal processes), or as pretreatment to advanced processes such as nanofiltration (NF) and reverse osmosis (RO). MF and UF have been demonstrated to be capable of removing protozoa cysts to below detection, as well as meeting the turbidity requirements of surface water treatment regulations.

The primary objective of this report is to summarize the current use and status of membrane filtration technologies for drinking water applications as well as the regulatory requirements that govern this technology. Eight membrane equipment manufacturers, 29 State regulatory agencies, and 24 utilities were contacted to gather information regarding the growth of the membrane industry, permitting requirements, and operation of MF/UF facilities in the United States.

A utility may choose to install membranes for a number of reasons; however, the decision is usually influenced by existing, pending, and/or anticipated regulatory requirements. Concern over microbial contaminants, independent of the regulations, is another frequently cited reason for selecting membranes. Other drivers for membrane technology include ease of operation, minimal staffing requirements, ability to handle fluctuations in source water quality, and cost competitiveness of membrane technology with conventional processes.

The results from a number of challenge studies have demonstrated that integral membrane filtration systems can remove protozoan cysts to below detection limits. Removal of virus by these processes is more variable and depends on membrane properties, solution chemistry, and the formation of a dynamic cake layer on the membrane surface. In general, UF membranes have demonstrated greater virus removal than MF membranes. However, breaches in integrity can compromise the removal capability of membrane filtration processes. Thus, even though intact membranes represent an absolute barrier, it is necessary to verify the integrity of the membrane system through routine testing.

There are two general types of integrity test methods, direct and indirect. Direct methods are non-destructive techniques that are applied directly to the membrane system to identify or isolate breaches. The most commonly applied direct methods are the pressure hold test and the diffusive air flow test. Both methods are applied to an entire membrane rack and can detect a very small breach over several hundred thousand fibers. The primary disadvantage of current direct methods is that they cannot be performed continuously while the system is in operation. However, new innovations, such as continuous sonic testing, may eventually provide a reliable, on-line method for directly monitoring membrane integrity.

Indirect methods are not applied to the physical membrane system, but rather monitor some aspect of filtrate water quality as a surrogate measure of integrity. Particle counting, particle monitoring and turbidity monitoring are all used as forms of indirect integrity monitoring. These methods characterize potential integrity problems by a deviation in filtrate quality from an

established baseline. A primary advantage of indirect methods is that they can be applied in a continuous, on-line mode. In addition, the instruments used for indirect testing can be applied to any membrane system, independent of manufacturer, system configuration, or any other parameter intrinsic to a proprietary system. Moreover, indirect methods are likely to remain applicable to any new systems that are developed. The disadvantage of these monitoring techniques is that they currently lack the sensitivity to detect small breaches that are of concern.

The demonstrated ability of membrane filtration processes to remove pathogens, and the ability of integrity monitoring techniques to demonstrate that a membrane system is intact, are factors considered in the regulation of these technologies. Twenty-seven states with operational membrane facilities in the US have had to address these issues in order to develop a regulatory approach for this technology. States have had to develop these approaches somewhat independently due to the absence of federal guidance, and this has resulted in variable requirements for this technology.

State agencies have considered a variety of factors when determining removal credits, including demonstration of treatment efficiency, total removal/inactivation requirements, experience with the technology, and approach towards multiple barrier treatment. Although the results of microbial challenge studies demonstrate very high levels of removal, states rarely grant removal credits in excess of the federal requirements for removal/inactivation of pathogens. Most states contacted during this project grant between 2.5- and 3-log of *Giardia* removal credit for MF and UF membranes. Only seven states have awarded removal credit for *Cryptosporidium* ranging from 2- to 4-log. With only a few exceptions, states did not grant virus removal credits to MF processes, and in no case was the virus removal credit greater than 0.5-log. Seven states have awarded virus removal credit to membranes classified as UF processes, with credits up to the 4-logs required under the Surface Water Treatment Rule (SWTR).

Regardless of the removal credits granted to a membrane process, in almost all cases states required some level of chemical inactivation following membrane filtration. In cases where less than the level of treatment required by the SWTR was awarded, disinfection sufficient to make up the balance of these requirements is necessary. However, even in cases where complete removal credit was granted to a membrane filtration process, states still required a minimum level of chemical inactivation.

There were also significant differences in the monitoring required by different states. Fourteen of the 29 states did not require any integrity monitoring for MF/UF plants aside from turbidity, which typically lacks the sensitivity to detect small breaches in integrity that are of concern. Of the remaining 15 states, 12 require physical integrity testing with or without continuous monitoring and one state requires only continuous testing. All states that require periodic physical integrity testing stipulate use of the pressure hold test, while states that require continuous testing permit use of particle counting, particle monitoring, laser turbidimetry, or pressure drop.

Integrity testing is a key component in a membrane filtration application, both from a regulatory and a public health perspective. However, both direct and indirect methods have limitations as integrity testing tools. Pressure-driven tests are extremely sensitive and can verify integrity to

very high levels; however, these methods are not continuous, and provide no measure of filtrate water quality. Indirect methods are continuous and on-line, but cannot verify integrity to the levels necessary to ensure high removal efficiency. However, direct and indirect methods can complement each other in a comprehensive monitoring program. Seven of the states contacted during this project do require a dual approach to integrity monitoring: periodic direct testing to verify integrity to a very high level, and indirect monitoring to ensure that a minimum level of performance is achieved on a continuous basis.

The commonly used integrity tests provide information in the form of a response that is typically used in a relative manner to evaluate whether or not system performance is acceptable. However, the information that is of primary concern is the risk of microbial passage resulting from an integrity breach. It is possible to have an integrity breach that is sufficiently small such that the membrane process is still capable of achieving the required level of removal. Conversely, an insensitive monitoring technique may leave a critical integrity breach undetected.

In general, states have taken the approach that any integrity breach identified during monitoring must be immediately addressed, regardless of the impact of the breach on removal efficiency. Although this practice is certainly justified from the standpoint of maintaining the integrity of the treatment barrier and providing superior public health protection, it does not provide any indication regarding the severity of the breach as it relates to microbial passage. Integration of the relationship between membrane integrity and microbial risk into the regulatory framework would improve the constancy in which these tests are applied as well as the interpretation of test results. This approach would not eliminate the need to address minor integrity breaches that are identified during routine monitoring, but would provide an indication of the impact of any breach on microbial removal efficiency, and better demonstrate the manner in which integrity monitoring fits into the overall context of multiple barrier protection.

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1.0   INTRODUCTION

The Surface Water Treatment Rule (SWTR) was promulgated in 1989 to provide public health protection against pathogens in surface water supplies. This regulation includes combined filter effluent turbidity standards, requires minimum levels of removal and/or inactivation for viruses (4-log) and *Giardia* (3-log), and mandates filtration for all surface water systems unless strict source water controls are met. The Interim Enhanced Surface Water Treatment Rule (IESWTR), promulgated in December 1998, establishes more stringent filtered water quality standards for turbidity and sets a Maximum Contaminant Level Goal (MCLG) of zero for *Cryptosporidium* for large systems (i.e., those serving more than 10,000 persons) utilizing filtration. The Long Term 1 ESWTR (LT1ESWTR), scheduled for promulgation in 2001, will extend the requirements of the IESWTR to smaller systems (serving fewer than 10,000 persons).

In September 2000, the Long Term 2 ESWTR (LT2ESWTR) Agreement in Principle was signed by the United States Environmental Protection Agency (EPA) and members of the Microbial-Disinfection Byproducts (M-DBP) Rule Cluster Federal Advisory Committee Act (FACA) Committee (65 FR 83015). The LT2ESWTR agreement includes source water quality-based requirements for up to 2.5-log inactivation and/or removal of *Cryptosporidium* beyond conventional treatment.

Conventional treatment has been proven effective for surface water treatment, and relies on the combination of coagulation, sedimentation, and filtration processes to remove microbial contaminants through a variety of mechanisms (Patania, et al., 1995; Lipp and Baldauf, 2000). There are also "barrier" technologies that achieve very high levels of pathogen removal, primarily through a sieving or size exclusion mechanism.   Microfiltration (MF) and ultrafiltration (UF) are two technologies that have consistently proven effective for the removal of larger pathogens such as *Giardia* and *Cryptosporidium*.

The SWTR addresses conventional treatment plants, as well as other media filtration technologies, such as direct filtration, slow sand filtration, and diatomaceous earth filtration. All other filtration technologies are addressed under the alternate filtration technology (AFT) provision of the SWTR. Since the application of MF/UF to surface waters was still a novel concept at the time the SWTR was developed, these processes are not specifically addressed in the associated guidance (EPA, 1990).   Rather, these advanced filtration technologies are considered under the AFT provision of the SWTR, which does not adequately address the removal capabilities and specific requirements of MF and UF. As a result, state primacy agencies have had to develop an approach for permitting and regulating membrane filtration technologies. Some states have elected to treat MF/UF as AFT, while others have developed requirements specific to these technologies. This has resulted in a range of permitting practices for membrane filtration applications in the United States.

1.1   Purpose

The LT2ESWTR Agreement in Principle proposes greater than 2.5-log *Cryptosporidium* removal credit for membrane technologies provided that specific performance criteria are met, including demonstration of removal efficiency and adequate integrity testing. However, there is some disparity in the current paradigm for demonstrating removal efficiency and performing integrity testing, which has implications for the regulation of this technology. This report provides a summary of these issues and will be a useful resource for regulators and utilities considering membrane filtration for control of pathogens. Specifically, this report is intended to:

1) Document the ability of existing membrane filtration processes to remove microorganisms and surrogate parameters.

2) Summarize the advantages, disadvantages, and limitations associated with direct and indirect integrity test methods.

3) Identify the factors that affect integrity monitoring methods, and relate the impact of those factors to method sensitivity and microbial risk.

4) Summarize operational practices of existing membrane plants, including the drivers leading to the installation of membrane filtration, pretreatment processes employed, backwash and chemical cleaning practices, and integrity testing methods.

5) Describe the regulatory approaches used by state agencies to permit MF/UF for pathogen removal during drinking water treatment, including demonstration of process performance, determination of removal credits, and integrity monitoring requirements.

1.2   Methodology

To achieve the objectives outlined above, a number of sources were contacted and the resulting information summarized in this report. The data sources and information targeted during this project are described in the following sections and summarized in Table 1.

1.2.1   NSF International

The Environmental Technology Verification (ETV) program is a peer-reviewed certification program designed to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. One phase of this program involves testing of membrane filtration for the removal of microbiological and particulate contaminants. The ETV protocol for membrane filtration includes an evaluation of the removal of turbidity and particles, as well as optional microbial challenge studies. The ETV protocol also requires the evaluation of the integrity test used with a given membrane system. Reports and supporting data from six NSF ETV studies were used during this project.

Table 1. Project Data Elements

NSF International
- List of participating MF/UF systems
- Copies of ETV test reports, including all test and operating conditions, water quality test parameters, 90th percentile and maximum membrane pore size, testing protocols, results of membrane integrity tests and surrogate monitoring, and results of microbial challenge studies
MF/UF Equipment Suppliers
- Descriptions of MF/UF system configuration, membrane geometry, basic principles of operation, and backwashing and chemical cleaning methods employed
- Details of integrity test methods, including established criteria for determining pass/failure
- Results of manufacturer in-house tests (performance test data) and interpretation of test results
- Installation list and information specific to each installation that was required to obtain state approval
Utilities
- Description of treatment facilities, source waters, treatment objectives, disinfection strategies, and operational problems (i.e., system failures)
- Water quality data, including feed water temperature, pH, hardness, alkalinity, turbidity, and particle counts
- Membrane equipment supplier, design and typical operating ranges for membrane flux, transmembrane pressure, specific flux, feed water recovery, backwashing and chemical cleaning frequencies, and cleaning protocols and chemicals
- Results of bench- or pilot-scale tests, including seeding and challenge studies, as well as simulated system failures (i.e., cut fibers)
- Membrane integrity test methods, frequency, and test results
- Removal credits granted by state agencies
State Regulatory Agencies
- MF/UF pilot testing for state approval including any re-testing requirements for subsequent locations and reciprocity allowances for testing conducted in other states
- The approach used by states to grant removal credits for membrane filtration processes
- Current disinfection/removal credits granted to MF/UF systems, focusing on *Giardia*, but including data on other pathogens when available
- Any data or information a state has regarding removal of microbial contaminants with MF/UF systems
- Integrity testing and other monitoring requirements
- List of operating or planned MF/UF systems in the state
- Strategy for dealing with MF/UF processes installed at different locations within a plant

1.2.2 MF/UF Equipment Suppliers

Eight MF and UF equipment suppliers (Aquasource, F.B. Leopold, Hydranautics, Ionics, Koch, Pall, US Filter, and Zenon) were contacted to obtain descriptions of their membrane filtration equipment as well as their installation lists. These eight manufacturers were selected since they either have full-scale installations in the United States and/or have completed the ETV program. These suppliers were asked to provide information regarding basic principles of operation, including details of integrity test methods, results of in-house performance studies, drinking water plant installation lists, and information or test results specifically required by state regulatory agencies.

1.2.3 Utilities

Utilities that currently operate a MF/UF facility, have piloted the technology and are in the process of constructing a MF/UF plant, or have operated a MF/UF plant in the past were contacted and asked to provide information regarding their operational experiences. Each utility was asked to provide a description of the treatment facility, source water, treatment objectives, disinfection practices, integrity testing methods, and the results of special studies (either pilot- or full-scale) demonstrating microbial removal capabilities of the MF/UF membrane used. Due to the substantial number of membrane filtration facilities located in the United States, a limited number of membrane utilities were selected to represent a cross-section of states and manufacturers. When possible, the first MF/UF plant permitted in a state was contacted since it was expected that the first membrane plant would have been subjected to the most rigorous permitting requirements.

1.2.4 State Regulatory Agencies

Regulatory agencies in States in which one or more MF/UF facilities are installed, or which have established procedures for permitting membrane filtration processes, were contacted to obtain information regarding their permitting process. State agencies were asked to provide information regarding pilot testing requirements, removal credits, and integrity monitoring requirements for permitting and operating a membrane filtration facility.

1.3   Report Overview

This report is divided into the following Chapters:

Chapter 1. Introduction: Provides the basis for the information contained in this report, the purpose of the report, and the data collection methods used to achieve these objectives.

Chapter 2. Background: Presents a brief history of microbial and surface water treatment regulations, an overview of the application of MF/UF for compliance with these regulations, and a summary of recent regulatory developments that make MF/UF a viable compliance option for surface water systems facing *Cryptosporidium* removal requirements. Provides a brief overview of the basics of membrane filtration operation, as well as the use of MF and UF in the United States.

Chapter 3. Microbial Removal: Documents the removal efficiency of membrane filtration processes for microbial contaminants, including protozoa, bacteria, viruses, and surrogates.

Chapter 4. Integrity Testing: Describes the integrity monitoring techniques commonly used in membrane filtration applications, including the limitations, advantages, and disadvantages of each method.

Chapter 5. Membrane Integrity and Microbial Risk: Discusses factors that affect the performance, sensitivity, and detection limit of integrity monitoring methods. Relates the theory of these methods to the impact of a detectable breach on membrane performance and microbial passage.

Chapter 6. Regulatory Approaches to Microfiltration and Ultrafiltration: Discusses the approach to regulating MF/UF by various state agencies. Includes the initial evaluation of membrane products, pilot testing requirements, log removal credits granted, and integrity monitoring requirements.

Chapter 7. Utility Practices: Summarizes MF/UF operating practices reported by utilities located throughout the United States. Includes driving force for MF/UF installation, design and operational considerations, and chemical cleaning and backwash practices.

Chapter 8. Summary and Conclusions: Summarizes the findings of this project, including the ability of MF/UF to remove microbial contaminants, design and operational issues, permitting requirements, and integrity testing and monitoring considerations.

Section 9. References: Lists all literature used during the preparation of this report in a bibliographic format.

Appendices: Provides a comprehensive MF/UF installation list at the time of this report.

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2.0   BACKGROUND

2.1   Regulatory History

In 1990, the EPA Science Advisory Board concluded that exposure to microbial contaminants such as bacteria, viruses, and protozoa was likely the greatest remaining health risk management challenge for drinking water suppliers (EPA, 2000a). Acute health effects from exposure to microbial pathogens are well-documented, and associated illness can range from mild to moderate cases lasting only a few days to more severe infections that can last several weeks and may result in death for those with weakened immune systems.

Between 1972 and 1981, 50 waterborne outbreaks of *Giardia*sis occurred nationwide involving approximately 20,000 reported cases (EPA, 1999a). In 1993, an estimated 403,000 people became ill, and 4,400 were hospitalized during a *Crypto*sporidiosis outbreak in Milwaukee, Wisconsin. In 2000, an *E. coli* outbreak in Canada infected hundreds of people and may have been responsible for as many as seven deaths (AWWA, 2000). The Safe Drinking Water Act (SDWA) provided the mandate for the EPA to develop regulations to protect against such waterborne pathogenic health threats.

Under the SDWA, as amended in 1986, EPA can establish a treatment technique requirement in lieu of a Maximum Contaminant Level (MCL) for those contaminants for which the agency determines "it is not economically or technically feasible to ascertain the level of the contaminant." Pathogens are discrete microorganisms that typically occur at low levels in source waters, and large sample volumes are necessary to ensure analysis of a representative sample. The presence of pathogens is not easily translated to viability or infectivity, and therefore not necessarily an indicator of public health risks (Allen, et al., 2000). Microbial contamination is often associated with a specific event, such as high surface water runoff, and as a result, can be difficult to detect using routine periodic monitoring. Since measuring microbial contaminants in drinking water can be challenging and expensive, EPA has established treatment technique requirements for microbial contaminants.

Treatment requirements for microbial contaminants are generally expressed in terms of log removal or log inactivation. For example, the SWTR established treatment requirements of 3-log and 4-log removal/inactivation of *Giardia* and viruses, respectively. The efficacy of membrane treatment is typically expressed in terms of log removal, which is defined by the following equation:

$$\text{log removal} = \log_{10}\left[\frac{C_{in}}{C_{out}}\right]$$

Where: C_{in} = Feed concentration
C_{out} = Filtrate concentration

Since chemical (and ultraviolet light) disinfection methods kill or prevent reproduction of microbial contaminants rather than remove them from the finished water, control by these methods is expressed as log inactivation. Log inactivation is calculated in the same manner as log removal, only the finished water concentration is expressed in terms of the viability of the remaining pathogens.

The log removal/inactivation concept is also easily translated to percent removal/inactivation. For example, 1-log is equivalent to 90 percent, 2-log is equivalent to 99 percent, 3-log is equivalent to 99.9 percent, and so forth.

Public water systems (PWSs) that utilize surface water or ground water under the direct influence of surface water (GWUDI) are typically more vulnerable to microbial contamination. Since 1989, several regulations have been developed to address this potential vulnerability, including the Surface Water Treatment Rule, Interim Enhanced Surface Water Treatment Rule, and the Long Term 1 and Long Term 2 Enhanced Surface Water Treatment Rules.

MF and UF can be used to meet the turbidity and disinfection requirements of the surface water treatment rules. Both have demonstrated the ability to reduce turbidity to less than 0.1 NTU, and are considered effective for the removal of *Cryptosporidium* and *Giardia*; furthermore, UF can also be used for virus removal. Chapter 3 discusses the removal capabilities of MF/UF in greater detail. The following sections discuss the requirements of existing and proposed drinking water regulations affecting surface water systems.

2.1.1 Surface Water Treatment Rule

The SWTR was promulgated in June 1989 and applies to all PWSs that utilize surface water or GWUDI (54 FR 27486). The SWTR includes treatment technique requirements for filtered and unfiltered systems that are intended to protect against the adverse health effects associated with *Giardia*, viruses, and *Legionella*, as well as other pathogenic organisms. Specifically, the following requirements are included in the SWTR:

1) MCLGs of zero for *Giardia*, viruses and *Legionella*.

2) Requirements for maintenance of a disinfectant residual in the distribution system.

3) 3-log (99.9%) removal or inactivation of *Giardia*.

4) 4-log (99.99%) removal or inactivation of viruses.

5) Combined filter effluent turbidity performance standard of 5 NTU as a maximum and 0.5 NTU at the 95th percentile on a monthly basis, calculated using 4-hour monitoring data. Applicable to treatment plants using conventional treatment.

6) Watershed protection and other requirements for unfiltered systems.

2.1.2 Interim Enhanced Surface Water Treatment Rule

The Interim Enhanced Surface Water Treatment Rule, finalized in December 1998, applies to PWSs serving 10,000 or more people that use surface water or GWUDI. Affected systems must comply with the requirements of the IESWTR by January 2002. The objectives of the IESWTR are to improve control of microbial pathogens, specifically the protozoan *Cryptosporidium*, and address risk trade-offs between pathogens and disinfection byproducts (63 FR 69477). Key provisions established by the rule include:

1) MCLG of zero for *Cryptosporidium*.

2) 2-log (99%) *Cryptosporidium* removal requirements for systems that filter. Systems that utilize conventional or direct filtration are credited with 2-log removal if they comply with the more stringent turbidity standards of the rule.

3) Reducing the combined filter effluent turbidity standard to 1.0 NTU as a maximum and 0.3 NTU as the 95th percentile on a monthly basis, calculated using 4-hour monitoring data. Applicable to treatment plants using conventional treatment or direct filtration.

4) Requirements for individual filter turbidity monitoring. All systems using surface water or GWUDI must continuously monitor turbidity from each filter and must provide an exceptions report to the state agency on a monthly basis. Exceptions include: individual filter with a turbidity greater than 1.0 NTU based on two consecutive measurements 15 minutes apart; and individual filter with turbidity level greater than 0.5 NTU at the end of the first four hours of operation based upon two consecutive measurements 15 minutes apart. A self-assessment and filter profile must be produced within seven days of the exception if no obvious reason for the exception can be identified.

   If an individual filter has turbidity levels greater than 2.0 NTU based on two consecutive samples taken 15 minutes apart, the system must have a Comprehensive Performance Evaluation (CPE) conducted by the state or a third party.

5) Microbial benchmarking/profiling provisions to assess the level of microbial protection provided as PWSs take steps to comply with new disinfection byproduct standards. This is to prevent significant reductions in microbial protection as systems modify disinfection practices to meet MCLs for trihalomethanes (THMs) or haloacetic acids (HAAs).

6) Inclusion of *Cryptosporidium* in the definition of GWUDI and in the watershed control requirements for unfiltered systems. Any ground water determined to be susceptible to *Cryptosporidium* is considered GWUDI. Any PWS using a watershed control program to avoid filtration must expand the program to include *Cryptosporidium*.

7) Requirement for covers on new finished water reservoirs.

8) States must conduct sanitary surveys for all surface water systems regardless of size at least once every three years.

2.1.3 Long Term 1 Enhanced Surface Water Treatment Rule

The Long Term 1 ESWTR, proposed in April 2000, is designed to 1) improve control of microbial pathogens in drinking water, including *Cryptosporidium*, for PWS serving fewer than 10,000 persons; and 2) prevent increases in microbial risk while PWS serving fewer than 10,000 modify treatment to comply with the Stage 1 D/DBP Rule (65 FR 19046). The LT1ESWTR extends the requirements of the IESWTR to systems serving fewer than 10,000 persons.

2.1.4 Filter Backwash Rule

The purpose of the Filter Backwash Rule (FBR), also proposed in April 2000, is to require certain PWSs to institute changes to the return of recycle flows within the treatment process to reduce the potential effects of increased microbial concentrations in recycle residuals on treatment plant performance (65 FR 19046). The rule contains three basic provisions for conventional and direct filtration plants that recycle and use surface water or GWUDI:

1) Recycle flows must be introduced prior to the point of primary coagulant addition.

2) Systems employing 20 or fewer filters and recycling backwash to the treatment process must perform a one time self-assessment of their recycle practice and consult with their primacy agency to address and correct high-risk recycle operations.

3) Systems utilizing direct filtration must report to the State on whether flow equalization or treatment is provided for recycle flows.

2.1.5 Long Term 2 Enhanced Surface Water Treatment Rule

In September 2000, an Agreement in Principle was reached by EPA and members of the FACA Committee regarding the requirements of the proposed LT2ESWTR. The agreement contains the following provisions (65 FR 83015):

1) Systems serving more than 10,000 persons will be required to conduct *Cryptosporidium*, *E. coli*, and turbidity source water monitoring on a predetermined schedule for 24 months. Systems with historical data that is equivalent in sample number and frequency may use that data in lieu of new monitoring at the discretion of the primacy agency. Systems that provide an additional 2.5-log removal/inactivation of *Cryptosporidium* (i.e., 2.5-log treatment beyond conventional filtration) are exempt from monitoring. The log removal/inactivation determination will be based upon a framework of "microbial toolbox options" discussed below.

   EPA and a panel of stakeholders will evaluate alternative indicators, such as *E. coli*, for predicting *Cryptosporidium* occurrence in systems serving fewer than 10,000 persons. If an alternative surrogate cannot be identified, small systems will begin one year of *E. coli* monitoring two years after large systems initiate *Cryptosporidium* monitoring. Small systems will be required to conduct *Cryptosporidium* monitoring if annual average *E. coli* concentrations exceed 10/100 mL for lakes and reservoirs or 50/100 mL for streams.

2) Based upon monitoring results, systems will be classified in four "bins." The bin determination will specify what additional level of treatment for *Cryptosporidium* is required beyond conventional treatment. Table 2 summarizes the bin requirements outlined in the September 2000 agreement.

Table 2. LT2ESWTR Bin Requirements

Bin Number	Average *Cryptosporidium* Concentration	Additional Treatment Requirements for Systems with Conventional Treatment and in Full Compliance with IESWTR
1	< 0.075 cysts/L	No action.
2	≥ 0.075 to < 1.0 cysts/L	1-log treatment (systems may use any technology or combination of technologies from microbial toolbox provided total credit is at least 1-log)
3	≥ 1.0 to < 3.0 cysts/L	2-log treatment (systems must achieve at least 1-log of the required 2-log treatment using ozone, chlorine dioxide, UV, membranes, bag/cartridge filters, or in-bank filtration)
4	≥ 3.0	2.5-log treatment (systems must achieve at least 1-log of the required 2.5-log treatment using ozone, chlorine dioxide, UV, membranes, bag/cartridge filters, or in-bank filtration)

3) The requirements of an action bin may necessitate that a PWS take one or more actions to meet the additional treatment levels. EPA and the FACA Committee developed a "toolbox" approach that would allow a PWS to choose from a number of alternatives to meet the requirements of the rule. The microbial toolbox options and removal/inactivation credits outlined in the Agreement in Principle are shown in Table 3.

4) Unfiltered systems will be required to continue to meet the filtration avoidance criteria, and provide 4-log virus inactivation, 3-log *Giardia* inactivation, and 2-log *Cryptosporidium* inactivation. Disinfection requirements must be met using a minimum of two disinfectants.

5) Systems using uncovered finished water reservoirs will be required to install a cover, unless the system installs treatment to achieve a 4-log virus inactivation or the state agency determines existing risk mitigation is adequate.

Table 3. LT2ESWTR Microbial Toolbox Components*

	Potential Log Credit			
	0.5	1	2	>2.5
Watershed Control				
Watershed Control Program (1)	X			
Reduction in oocyst concentration (3)	As measured			
Reduction in viable oocyst concentration (3)	As measured			
Alternative Source				
Intake Relocation (3)	As measured			
Change to Alternative Source of Supply (3)	As measured			
Management of Intake to Reduce Capture of Oocysts in Source Water (3)	As measured			
Managing Timing of Withdrawal (3)	As measured			
Managing Level of Withdrawal in Water Column (3)	As measured			
Pretreatment				
Off-Stream Raw Water Storage w/ Detention ~ X days (1)	X			
Off-Stream Raw Water Storage w/ Detention ~ Y weeks (1)		X		
Pre-Settling Basin w/Coagulant	X	———→		
Lime Softening (1)	——————→			
In-Bank Filtration (1)		X ——————→		
Improved Treatment				
Lower Finished Water Turbidity (0.15 NTU 95% tile CFE)	X			
Slow Sand Filters (1)				X
Roughing Filter (1)	X ——————————→			
Membranes (MF, UF, NF, RO) (1)				X
Bag Filters (1)		X ——————→		
Cartridge Filters (1)			X	
Improved Disinfection				
Chlorine Dioxide (2)	X	X		
Ozone (2)	X	X	X	
UV (2)				X
Peer Review / Other Demonstration / Validation or System Performance				
Peer Review Program (*ex. Partnership Phase IV*)		X		
Performance studies demonstrating reliable specific log removals for technologies not listed above. This provision does not supercede other inactivation requirements.	As demonstrated			

* As outlined in the September 2000 Agreement in Principle (65 FR 83015). The removal credits identified in this table are based upon the September 2000 Agreement in Principle and are subject to change. The final LT2ESWTR (anticipated in May 2002) will include the final toolbox components and identify design and operational criteria necessary to receive log removal credit.

Key to table symbols: (X) indicates potential log credit based on proper design and implementation in accordance with EPA guidance. Arrow indicates estimation of potential log credit based on site specific or technology specific demonstration of performance.

Table footnotes: (1) Criteria to be specified in guidance to determine allowed credit, (2) Inactivation dependent on dose and source water characteristics, (3) Additional monitoring for *Cryptosporidium* after this action would determine new bin classification and whether additional treatment is required.

2.1.6 Stage 1 Disinfectants and Disinfection Byproducts Rule

Although MF and UF do not remove disinfection byproduct (DBP) precursors, they can reduce distribution system DBP formation by reducing the disinfectant dose required to meet the disinfection/removal requirements of the surface water treatment rules. The Disinfectants and Disinfection Byproducts Rule (DBPR) will be promulgated in two stages. Stage 1 of the DBPR applies to all PWSs that are community water systems (CWSs) or nontransient noncommunity water systems (NTNCWS) and which use a chemical disinfectant for either primary or residual disinfection. Surface water and GWUDI systems serving at least 10,000 people are required to comply with the DBPR by January 2002. All groundwater systems (regardless of size), and surface water and GWUDI systems serving fewer than 10,000 persons must comply with the Stage 1 DBPR by January 2004. The Stage 1 DBPR includes the following provisions (63 FR 69389):

1) Maximum Residual Disinfectant Level Goals (MRDLGs) for chlorine (4 mg/L), chloramines (4 mg/L) and chlorine dioxide (0.8 mg/L).

2) MCLGs for four THMs: chloroform (0 mg/L), bromodichloromethane (0 mg/L), dibromochloromethane (0.06 mg/L), and bromoform (0 mg/L).

   MCLGs for two HAAs: dichloroacetic acid (0 mg/L) and trichloroacetic acid (0.3 mg/L).

   MCLGs for bromate (0 mg/L) and chlorite (0.8 mg/L).

3) Maximum Residual Disinfectant Levels (MRDLs) for three disinfectants: chlorine (4 mg/L), chloramines (4 mg/L) and chlorine dioxide (0.8 mg/L).

4) MCLs for total trihalomethanes (TTHMs) (0.08 mg/L), the sum of five haloacetic acids (HAA5) (0.06 mg/L), bromate (0.01 mg/L) and chlorite (1.0 mg/L).

5) Systems utilizing surface water or GWUDI and using conventional filtration are required to remove specified percentages of organic material (measured as total organic carbon - TOC). TOC removal will be achieved primarily through enhanced coagulation or enhanced softening. Table 4 summarizes the TOC removal requirements.

Table 4. Required TOC Removal by Enhanced Coagulation and Enhanced Softening

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as $CaCO_3$)		
	0-60	>60-120	>120
>2.0-4.0	35.0%	25.0%	15.0%
>4.0-8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

Source: *National Primary Drinking Water Regulations: Disinfectants and Disinfection Byproducts; Final Rule* (63 FR 69389)

The rule also provides a number of alternatives to meet the enhanced coagulation requirement as described in the final rule (63 FR 69389).

2.1.7 Stage 2 Disinfectants and Disinfection Byproducts Rule

The Stage 2 DBPR, which will be proposed along with the LT2ESWTR in mid-2001, will apply to all CWSs and NTNCWSs that add a disinfectant other than UV or deliver disinfected water. Compliance will be based on a locational running annual average at monitoring locations throughout the distribution system. This compliance framework is intended to control spatial peaks in the distribution system. The Stage 2 M-DBP Agreement in Principle (65 FR 83015) outlines the following provisions:

Systems must comply with the Stage 2 DBPR in two phases. In Phase I, systems must comply with a locational running annual average (LRAA) of 120 and 100 µg/L for TTHM and HAA5, respectively, at each Stage 1 DBPR monitoring location. Additionally, systems must continue to meet the Stage 1 DBPR running annual averages for TTHM and HAA5 during Phase I. Systems must comply with Phase I within three years of rule promulgation, which is anticipated to be mid-2002.

During Phase II, which begins six years after rule promulgation, systems will need to comply with a LRAA of 80 and 60 µg/L for TTHM and HAA5, respectively, at new monitoring locations selected during an initial distribution system evaluation. These new monitoring points will include locations that are representative of long residence times and high DBP concentrations.

2.2 Membrane Filtration

2.2.1 Overview of Low-Pressure Membrane Filtration

Membranes act as selective barriers, allowing some constituents to pass through the membrane while blocking the passage of others. The movement of material across a membrane requires a driving force (i.e., a potential difference across the membrane), and the membrane processes commonly used in drinking water applications use pressure as the driving force. There are four categories of pressure-driven membrane processes: microfiltration, ultrafiltration, nanofiltration (NF), and reverse osmosis (RO). RO and NF processes are typically applied for the removal of dissolved constituents including both inorganic and organic compounds, and these processes operate at pressures significantly higher than MF and UF. Low-pressure membrane processes (i.e., MF and UF) are typically applied for the removal of particulate and microbial contaminants, and can be operated under positive pressure or negative pressure (i.e., vacuum pressure). Positive pressure systems typically operate between 3 and 40 psi, whereas, vacuum systems operate between –3 to –12 psi. There is no significant difference between the range of pressures at which MF and UF systems operate.

In the membrane process industry, the distinction between MF and UF is typically based upon the molecular weight cut-off (MWCO) or pore size. MWCO is a manufacturer specification that refers to the molecular mass of a macrosolute (e.g. glycol or protein) for which a membrane has a retention capability of greater than 90 percent (Anselme and Jacobs, 1996). The pore size refers the diameter of the micropores in a membrane surface. It is difficult to measure the true pore size, and as a result membrane manufacturers typically use some measure of performance to categorize the pore size of a membrane. The nominal pore size is typically based upon a given percent removal of a marker (e.g., microspheres) of a known diameter. The absolute pore size is often (though not always) characterized as the largest pore size in a membrane surface. That is, the absolute pore size is the minimum diameter above which 100 percent of a marker of a specific size is removed by a membrane. Figure 1 presents the MWCO/pore size ranges for membrane process, as well as the relative size of some common drinking water contaminants.

Although pore size is an important consideration in determining which contaminants a membrane process can remove, it is not the only factor that impacts removal. The relevancy of pore size to membrane performance is limited by the lack of a standard methodology for characterizing and reporting the pore size of different membrane products. Furthermore, factors other than pore size can impact performance, such as the build up of a cake layer on a membrane surface over the course of a filtration cycle. For this reason, membrane rejection characteristics are often assessed through challenge studies in which the ability of a membrane to reject a specific contaminant is demonstrated. In this manner, the actual exclusion characteristic of the membrane is empirically determined and accounts for all of the factors that impact performance. The exclusion characteristic is a direct measure of performance and thus can be used to compare two different membranes, whereas the pore size is an indirect measure of rejection capability and may not be an appropriate metric for comparison.
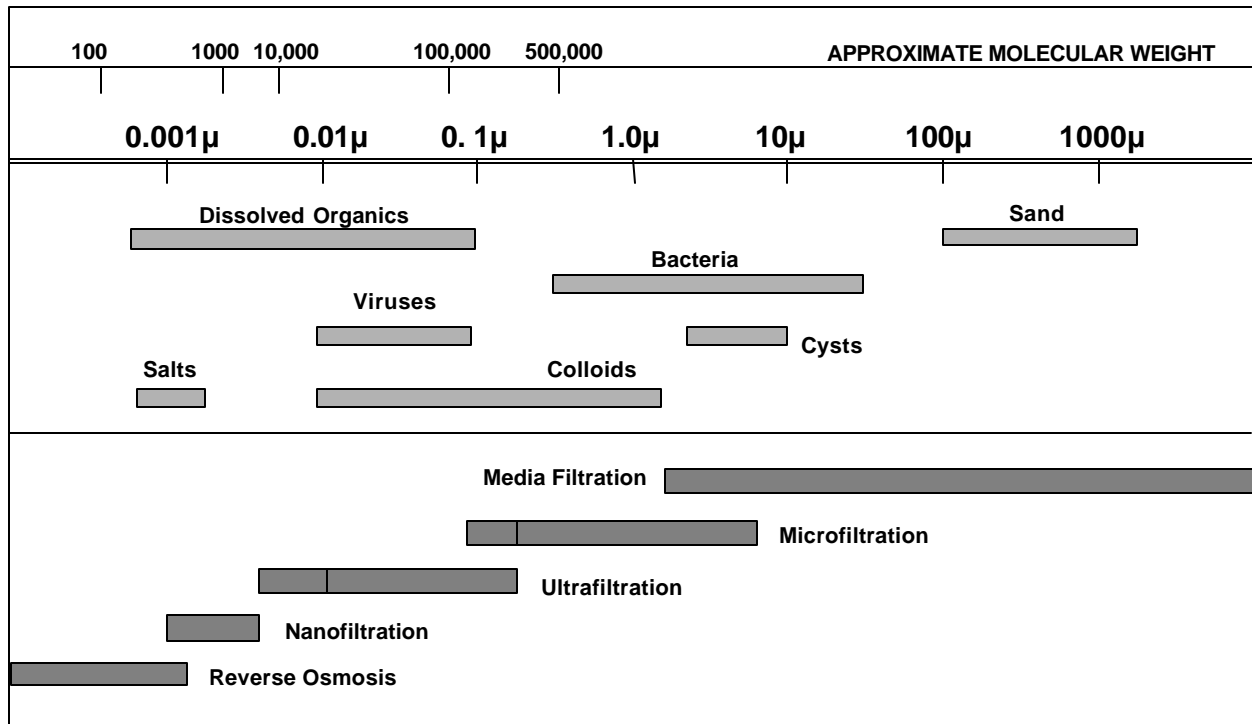
Figure 1. Membrane Process Classification

MF and UF membranes are made from a wide variety of materials, including: polypropylene, polyvinyl difluoride (PVDF), polysulfone, polyethersulfone and cellulose acetate. The various membrane materials have different properties, including pH and oxidant sensitivity, surface charge, and hydrophobicity. These material characteristics can affect the exclusion characteristic of a membrane as well as operating constraints such as the potential use of pre-chlorination to control biological fouling.

All commercially available MF and UF membranes currently used for drinking water treatment are constructed in a hollow fiber configuration. Hollow fiber membranes are operated in either an inside-out or outside-in mode. During inside-out operation, the feed enters the fiber lumen and passes through the fiber wall to generate filtrate. During outside-in operation, the filtrate is collected in the fiber lumen after the feed is passed through the membrane. A cross section of a fiber is shown below in Figure 2.
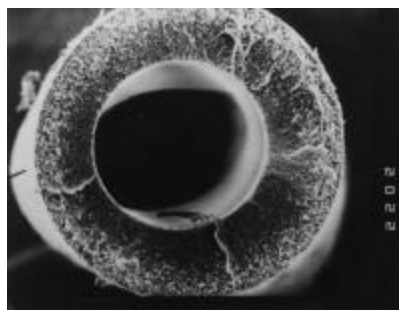
Figure 2. Photomicrograph of a Hollow Fiber

Another characteristic that can affect the performance of hollow fiber membranes is the trans-wall symmetry. Two constructions are commonly used in MF/UF membrane: asymmetric and composite. In asymmetric construction, the membrane material is homogeneous throughout the membrane cross-section; however, the density of the membrane decreases from the feed to the filtrate side of the membrane. Composite membranes are constructed by casting a thin, dense membrane skin onto the surface of a porous substructure. The thin film is always cast onto the feed side of the membrane, but in some cases, is cast onto both sides to provide additional mechanical strength and to allow bi-directional filtration. Figure 3 presents schematics of both symmetric and composite membranes.
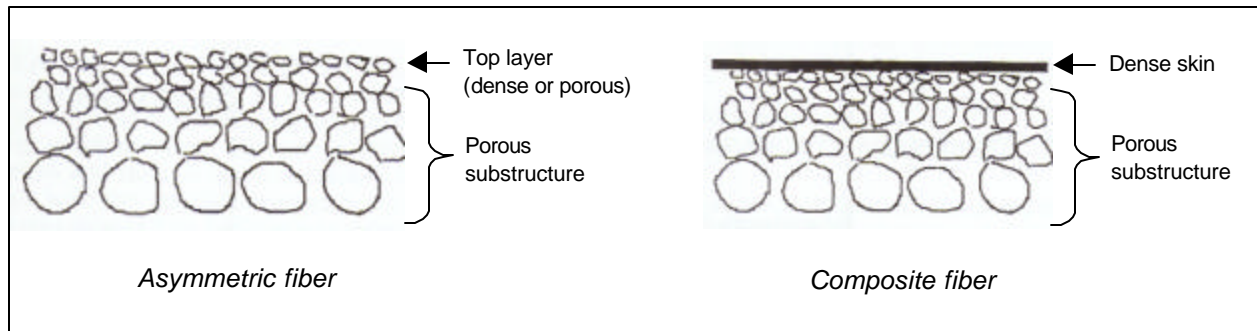
Figure 3. Schematic of Asymmetric and Composite Membranes

Typically, membrane fibers are bundled in groups of several thousand, potted in a resin on both ends, and housed in a pressure vessel, or module. When operated in an inside-out mode, the feed water enters the lumen at one or both of the potted ends of the vessel. In the outside-in mode, the feed water typically enters the center of the pressure vessel and is forced into the lumen. There are also submersible membrane systems in which the fibers are immersed in a tank containing the feed water, open to the atmosphere, and vacuum pressure is applied to filtrate side of the membrane. Figure 4 shows a typical hollow-fiber membrane module configuration.
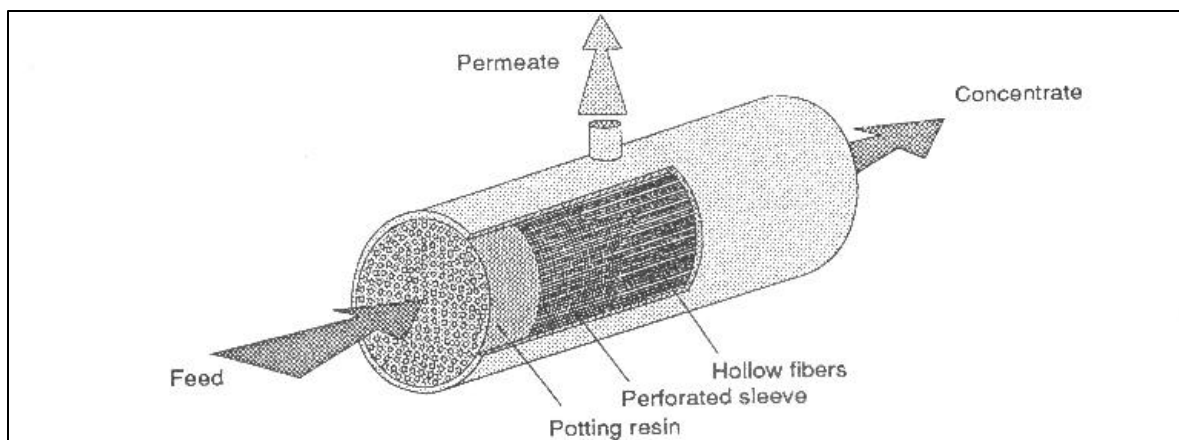
Figure 4. Typical Hollow Fiber Module Configuration (Aptel and Buckley, 1996)

Membrane processes are designed using one or more water production units, typically referred to as racks or skids. A rack consists of a number of modules, or cartridges, which share common

feed and filtrate valving. Typically, individual membrane racks can be isolated from the rest of the system for testing, cleaning or repair.

The major components of a typical MF or UF membrane system include cartridge filters or strainers for removal of large debris, low pressure feed pumps, membrane modules, high-pressure backwash pumps, a chemical cleaning system, a chlorine feed system, and a concentrate handling and disposal system.

Membrane modules may also be operated using either a cross-flow or dead-end flow pattern. With a dead end flow pattern, all of the feed water passes through the membrane, trapping particles on the membrane surface until backwashing or chemical cleaning removes them. In a cross-flow mode, the feed water flows tangential to the membrane surface, which is intended to enhance productivity by limiting the extent of particle deposition and cake layer formation on the membrane surface. In order to achieve a significant scour velocity at an acceptable product water recovery during cross-flow operation, it is necessary to recirculate a portion of the concentrate, which requires additional pumping and thus can substantially increase operating costs. Figure 5 presents a graphical representation of the differences in the two operational configurations.
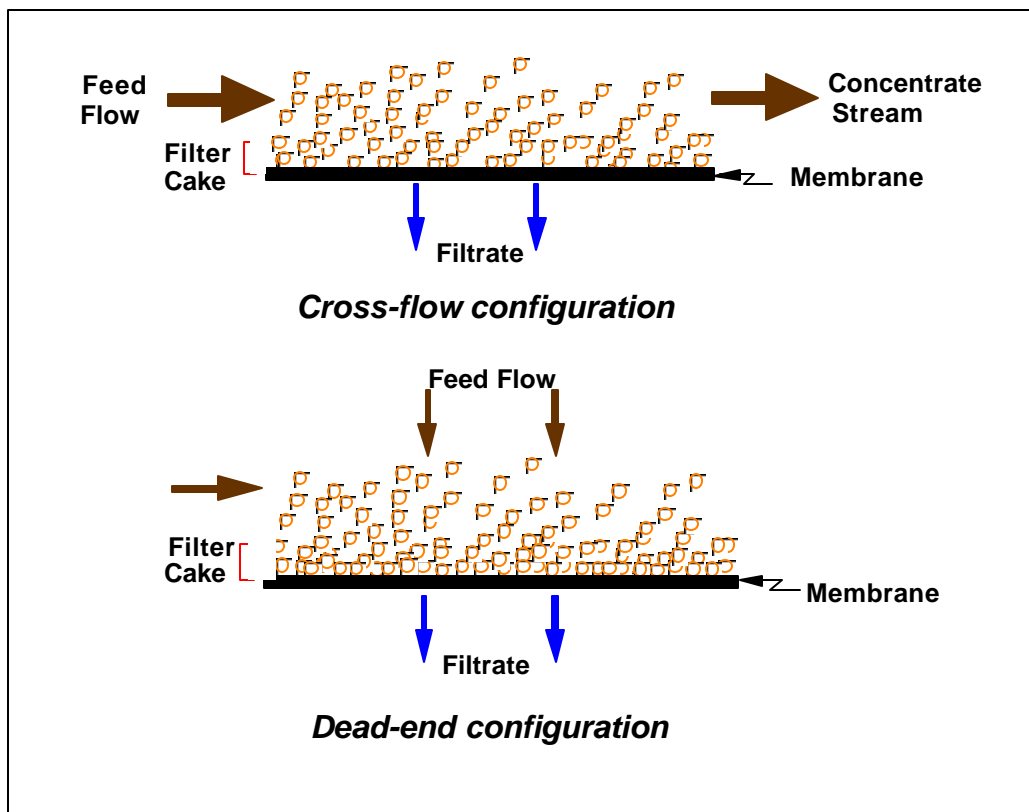
Figure 5. Schematic of Membrane Flow Configurations

Typical process monitoring in a membrane treatment process includes flow, pressure, temperature, and turbidity, all of which can be monitored continuously. The data collected can be used to monitor system performance and generate production reports. In addition, membrane

filtration systems rely on periodic integrity testing to check for breaches. The types of integrity testing most commonly used are discussed in greater detail in Chapter 4.

The membrane filtration process may be designed to operate using positive pressure or negative pressure (i.e., vacuum pressure) as the driving force. The pressure that is used to drive water through the membrane is termed transmembrane pressure (TMP). In a positive pressure process the feed water is pressurized and fed to membranes typically housed in pressure vessels. Immersed membrane systems are not housed in a pressure vessel, and thus cannot be pressurized. Instead, the membranes are placed in a basin containing the feed water and the filtrate is collected in the fiber lumens by applying a partial vacuum on the filtrate side.

One of the critical design parameters for a membrane process is flux, which is typically expressed in gallons of filtrate per day per square foot of membrane area (gfd). The preferred method for determining design flux is through pilot testing, but in the absence of pilot data, other water quality data and manufacturer information may be used to estimate this parameter. The design flux determines the membrane area required for a specific plant capacity. Thus, flux has a significant impact on capital cost, and results in a competitive motivation for design engineers to use a higher membrane flux, thereby reducing the area requirements. Although, increasing the membrane flux can reduce the capital cost, it will increase operational costs due to higher operating pressure, more frequent chemical cleaning, and a potential increase membrane replacement costs. Many equipment manufacturers and design engineers target a cleaning interval of 30 days or greater to minimize the amount of operator involvement and system downtime to maintain acceptable productivity, as well as minimize the costs associated with chemical cleaning and cleaning residuals disposal. However, an analysis of total system costs must be conducted to understand the cost implications of various cleaning intervals.

Another important design parameter is recovery, the ratio of feed water to filtrate. Recovery for MF/UF systems is typically 85 to 97 percent. High-pressure membrane systems typically operate at significantly lower recoveries (70 to 90 percent). In a membrane filtration system, recovery is typically a function of the frequency of the backwash and the method of backwash disposal. That is, more frequent backwashing will typically result in lower recoveries. Some states may allow recycling of backwash water to the treatment process, which can improve recovery rates.

Backwashing of membranes is accomplished using air, water, or a combination of both. Some membrane processes also use chlorinated water to enhance the effectiveness of the backwash process. MF and UF processes are backwashed more frequently than conventional filters. A typical range of backwash frequencies for MF/UF systems is between 15 and 60 minutes, and the backwash duration ranges from 30 seconds to 3 minutes. Ideally, the backwash process restores the TMP to the same value following each backwash. However, most systems experience a gradual increase in post-backwash TMP that must be addressed by chemical cleaning.

Chemical cleaning is used to restore the post-backwash TMP to its initial level, i.e., the TMP of a new, clean membrane. In the chemical cleaning process, acid, caustic, chlorine, and/or surfactants are circulated through the membrane system to dissolve or dislodge contaminants that have not been removed by backwashing. The spent cleaning solution is then flushed from the

system and neutralized prior to disposal. Requirements for membrane system cleaning vary with the type of membrane. Some systems use a chemically enhanced backwash instead of a dedicated chemical cleaning approach; however, most systems, are chemically cleaned once every one to six months, depending on system design and operation. Irreversible membrane fouling is a loss of productivity that cannot be restored through chemical cleaning. Irreversible fouling occurs in all membrane systems, and eventually requires the membranes to be replaced.

Suspended solids and other contaminants can result in more rapid fouling of the membrane, decreases in flux, and increases in TMP. As a result, most membrane filtration systems include some level of pretreatment to reduce the concentration of these foulants, with the level of pretreatment dependent upon raw water quality.

Water temperature can also impact the membrane flux due to the increase in water viscosity with decreasing temperature. The viscosity of water affects the rate at which water travels through the membrane pore structure. As the viscocity increases at lower temperatures, a greater TMP is required to maintain the target flux, resulting in increased operating costs. Table 5 presents an approximation of the effect of water temperature on water viscosity, as well as a correction factor for membrane flux (Karimi, et al., 1999). This effect can vary from membrane to membrane, and many manufacturers have developed membrane-specific correction factors.

Table 5. Effect of Water Temperature on Flux

Temperature ^{o}C (^{o}F)	Viscosity (cp)	Viscosity Correction Factor
25 (77)	0.891	0.89
20 (68)	1.00	1.00
15 (59)	1.15	1.13
10 (50)	1.30	1.27
5 (41)	1.55	1.43
0.1 (32)	1.79	1.61

Thus, in the design of a membrane treatment facility, a design water temperature range is normally established. The effect of viscosity on water production is generally considered to be complementary, as most facilities have lower production demands when the water is cold, i.e., during the winter. However, if the facility is required to meet full design capacity under cold water conditions, additional membrane surface area will be required.

MF and UF membrane treatment processes are effective for the removal of particles and microorganisms, as discussed in Chapter 3. However, these treatment processes are generally not effective for removing dissolved materials present in water sources, including TOC, arsenic, color, or undesirable taste and odor compounds, such as methylisoborneol (MIB) and geosmin. Removal of these contaminants will typically require a chemical or physical treatment process in addition to membrane filtration. Removal of TOC, DBP precursors and color causing

compounds may be achieved through coagulation prior to membrane filtration. Coagulation with ferric salts followed by MF/UF has been shown to be a viable method to remove arsenic (Chwirka, et al., 2000). Some UF membrane processes may be used with powdered activated carbon to absorb taste and odor compounds (Jack and Clark, 1999).

2.2.2   The Use of Microfiltration and Ultrafiltration in the United States

Stricter regulations and concerns over waterborne disease outbreaks resulting from inadequate treatment have lead water utilities to seek alternative technologies, such as membrane treatment, to ensure safe drinking water. In some situations, membrane processes have the potential to provide increased assurance of safe drinking water since microbial contaminants are completely removed via a physical barrier.

MF and UF are low-pressure filtration processes, which have gained considerable acceptance in the drinking water industry over the past ten years, and have demonstrated excellent capabilities for removal of pathogens (see Chapter 3). MF and UF are primarily installed either as a replacement for clarification/filtration or filtration in a conventional treatment process, or as pretreatment for processes such as NF and RO. Typically, MF and UF systems do not require any pretreatment beyond straining, although this may not be the case in all instances. In some cases, particularly with inside-out configurations, MF/UF must be preceded by clarification to operate effectively.

A list of 120 drinking water treatment facilities in the United States that utilize MF/UF was developed from installation lists provided by the following manufacturers: US Filter, Zenon, Aquasource, Pall, and Koch. These manufacturers accounted for all of the MF/UF installations in the United States at the time of this report. However, a number of other manufacturers, including Ionics, Hydranautics, Leopold, and Smith & Loveless produce MF/UF membranes and/or process equipment.

The comprehensive installation list is based on current full-scale facilities, pilot- and demonstration-scale plants, and planned future facilities. Only one facility, a pilot plant in New Rochelle, New York, is no longer in operation. Of the remaining 119 installations, there are currently 108 full-scale facilities on-line. The remainder of the facilities are planned for installation in 2001, most of which conducted pilot studies or constructed demonstration plants. Eighty-seven (73 percent) of the facilities utilize MF technology.

The subsequent analysis of the utility information includes only the current full-scale facilities unless otherwise noted. The information includes the type of membrane process, manufacturer, treatment capacity, source water type, geographic distribution, and year of installation.

2.2.2.1 Treatment Capacity

The treatment capacities of the membrane plants in operation at the time of this report are organized into five categories in Figure 6. The mean capacity for all installations is 1.71 MGD, and the median is 0.36 MGD. The median is significantly less then the mean due to the predominance of small facilities. More than half of the MF/UF installations provide a treatment

capacity less than 0.5 MGD. Some of the reasons that MF/UF is an attractive small system technology include: ease of operation, excellent finished water quality, high degree of automation that reduces the need for continual staffing, and modular design that does not require custom engineering. The largest operating facility is located in the City of Kenosha, Wisconsin. The 14 MGD MF plant began operation in October 1998.
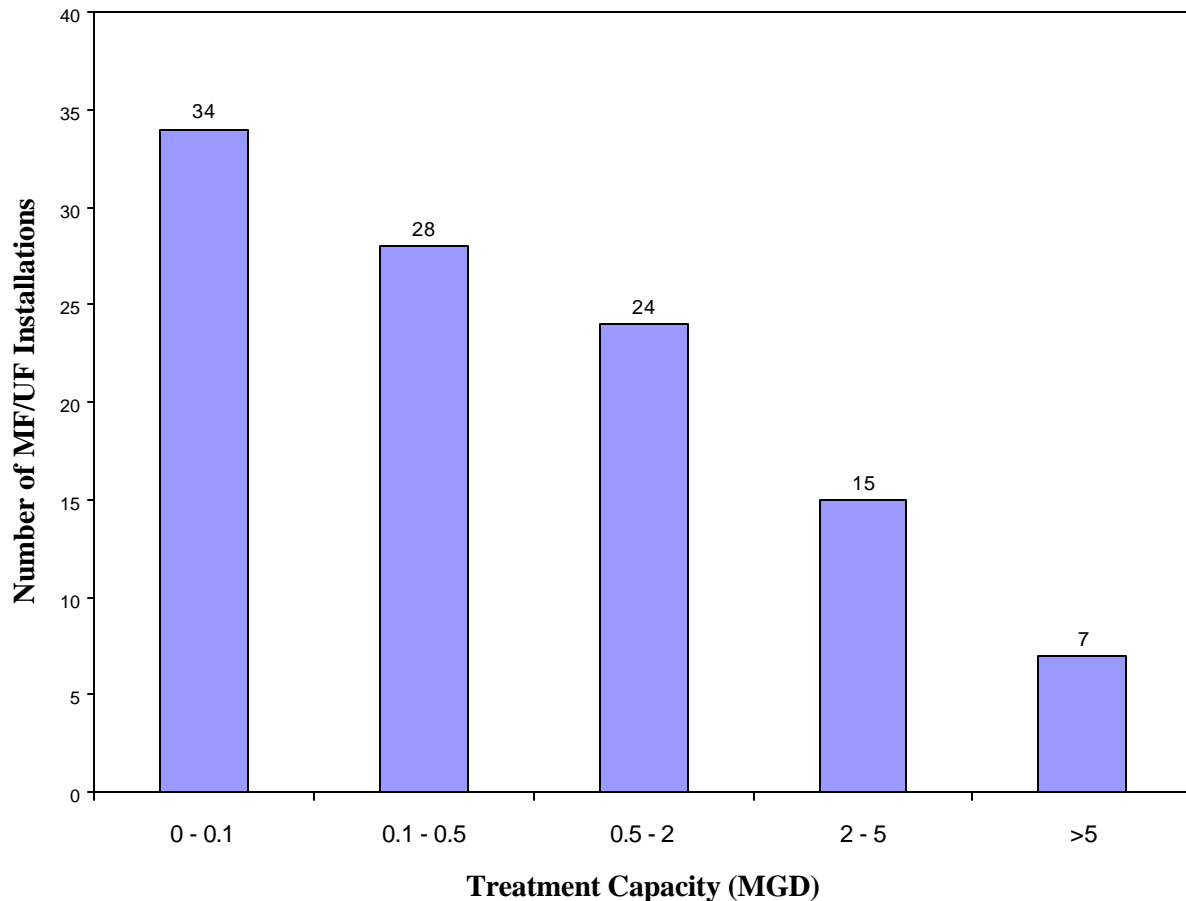
Figure 6. Distribution of Installed Membrane Treatment Capacity as of April 2000

There are also several large installations that are planned in the near future. The Olivenhain Municipal Water District in California has a 25 MGD UF facility under construction that is planned for start-up in 2001. The City of Westminster, Colorado has a 15 MGD MF facility planned for start-up in June 2001. A 20 MGD MF facility is under construction for the Pittsburgh Water and Sewer Authority and is scheduled to be on-line in 2001. Construction is near completion in the City of Appleton, Wisconsin on a 24 MGD UF facility scheduled for start-up in the spring of 2001. Minneapolis, Minnesota is planning a 70 MGD facility for start-up in 2004, and Carmicheal, California is planning a 15 MGD facility. Bakersfield, California and the Otay Water Treatment Plant in San Diego, California are planning 20 and 40 MGD facilities, respectively. Finally, Del Rio, Texas is currently planning a 16 MGD facility.

2.2.2.2 Source Water

MF/UF processes can be used to remove particles and pathogens from surface waters and GWUDI. The types of sources used by membrane filtration plants identified during this project include: reservoirs, lakes, rivers, surface water impoundments, and aquifers under the influence of surface water.

2.2.2.3 Manufacturer

Figure 7 presents the distribution of membrane installations among the major manufacturers. The manufacturer with the largest number of membrane installations for drinking water treatment is US Filter with nearly a 70 percent share of the market. Koch has the largest number of new facilities, increasing its current number of installations by more than 50%, from 9 to 14 between 2000 and 2001. Two large Pall facilities are scheduled for installation in 2001: a 30 MGD facility in Westminster, Colorado facility and a 20 MGD facility in Pittsburgh, Pennsylvania.
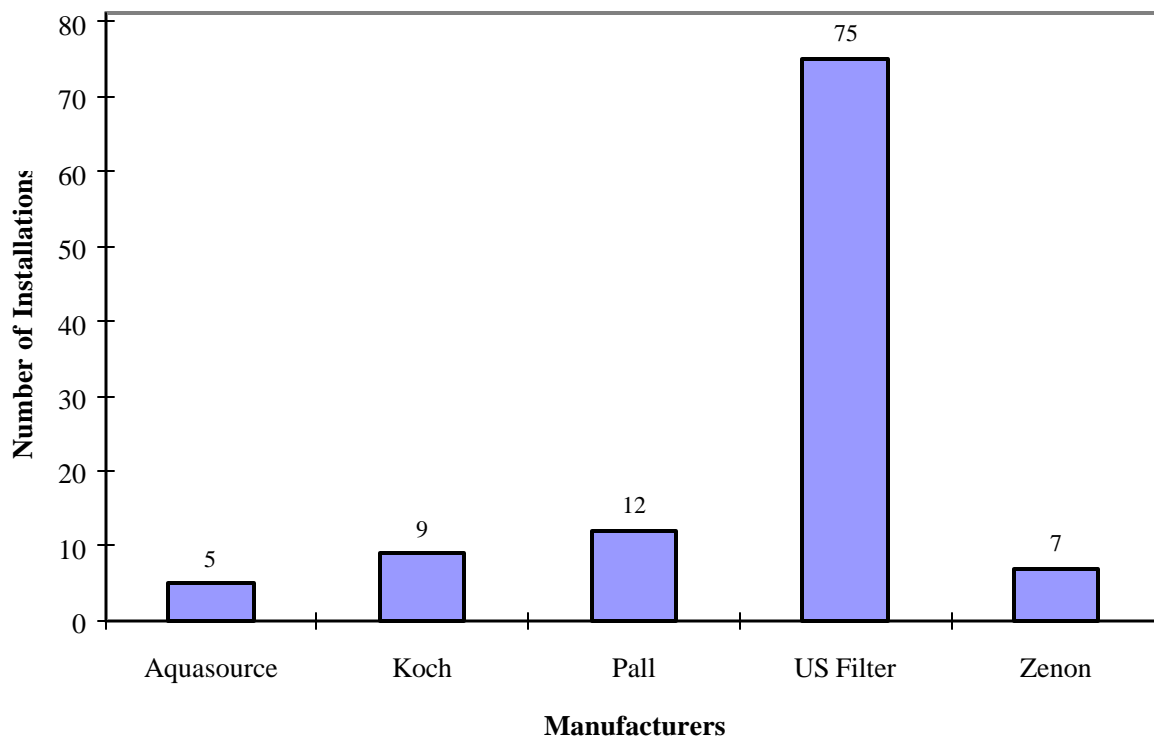
Figure 7. Distribution of Membrane Installations by Manufacturer as of April 2000

Figure 8 presents the distribution of installed capacity by manufacturer. Again, US Filter has the largest percentage of installed capacity in the United States at 48 percent. However, installed capacity is more evenly distributed among the five leading manufacturers than is the number of installations. Pall currently has 19 percent of the market, followed by Zenon at 16 percent, Koch at 10 percent, and Aquasource at 6 percent. The difference in percent of market share by number

of installations compared to installed capacity is largely the result of increased use of MF/UF technology in the United States, as well as the increased capacity of new installations. US Filter (Memcor) dominated the early market and installed a number of small facilities. As the use of membranes has increased, the number of large installations has also increased which has allowed the share of installed capacity to grow disproportionate to the number of installations.
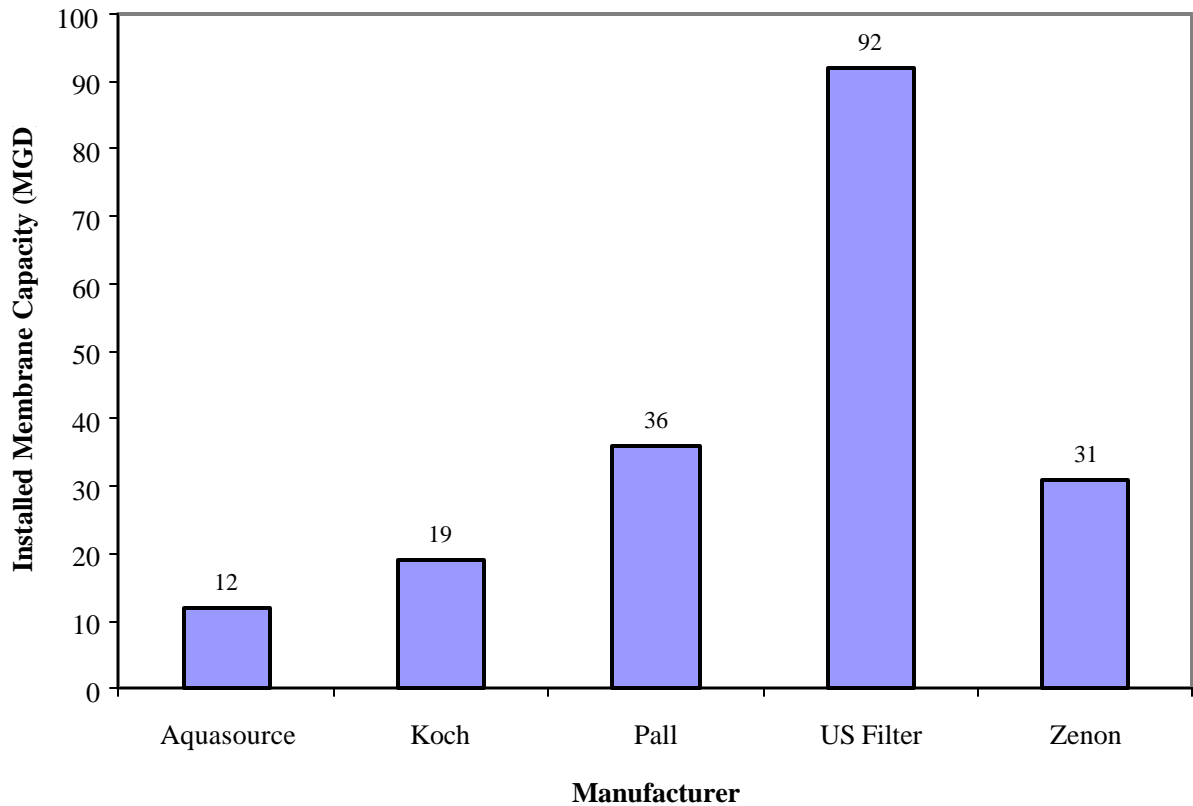
Figure 8. Distribution of Installed Membrane Capacity by Manufacturer as of April 2000

2.2.2.4 Geographic Location

The geographic distribution of existing membrane installations is shown by region in Figure 9 and by state in Figure 10. The figures do not include future installations, as reported by the manufacturers. The states with existing or planned membrane facilities were grouped into five regions for the purpose of this summary:

- West region – Alaska, Hawaii, California, Oregon, and Washington

- Mountain region – Arizona, Colorado, Idaho, Nevada, Utah, and Wyoming

- Midwest region – Michigan, Kansas, Missouri, Oklahoma, South Dakota and Wisconsin

- South region – Florida, North Carolina, Tennessee, and Texas

- Northeast region – Connecticut, Massachusetts, New York, New Jersey, Pennsylvania, and Virginia.

The West region has the largest number of MF/UF facilities in the United States with 40 percent of the total number of installations. Two new installations are planned for the coming year in the Western region. The Northeast region is second with 20 percent of the existing installations. Growth in the Midwest region is highest with four new facilities planned. The Mountain and Southern regions each have two new facilities planned.

The reasons for the dominance of the West and Northeast regions are the disproportionately high number of installations in California and Virginia, respectively. California alone has approximately 25 percent of the total installations in the United States, and Virginia accounts for more than 10 percent of the installations.

As experience grows, more states are expected to accept membranes and award appropriate removal credits. Consequently, the use of MF/UF technology is expected to continue to grow in the United States. Existing and future regulations make membranes an attractive treatment option, for reasons discussed throughout this report.
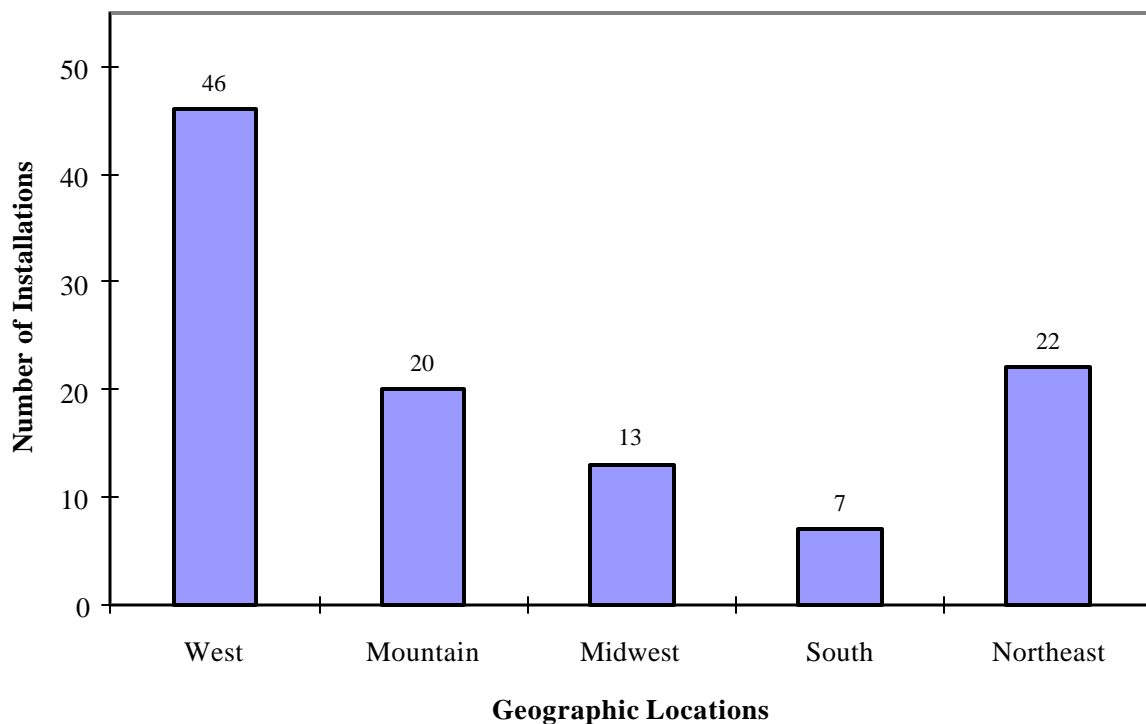
Figure 9. Geographic Distribution of Membrane Installations in the United States
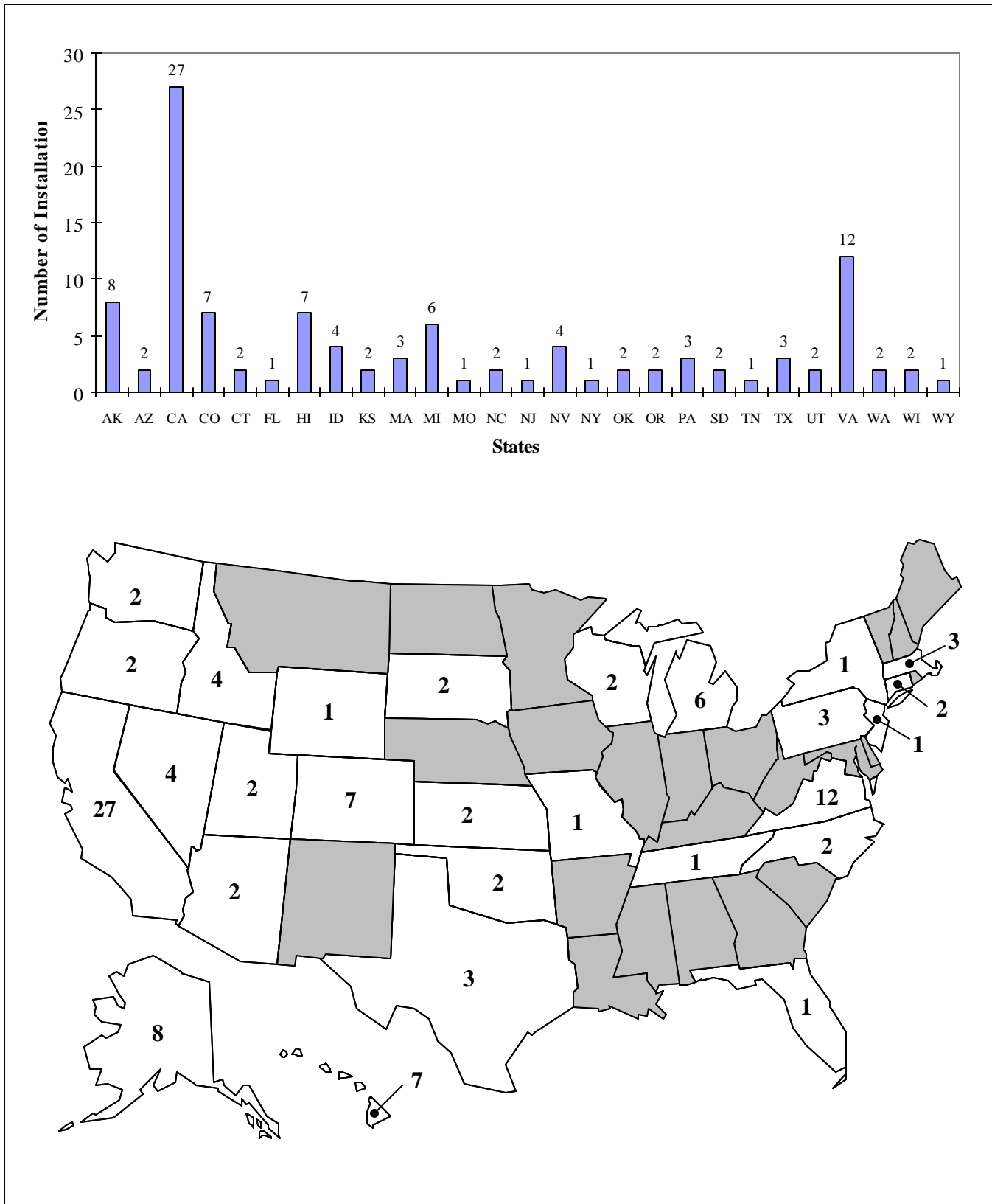
Figure 10. Distribution of Membrane Installations by State

2.2.2.5 Installation Trends and Treatment Capacity

Membrane filtration first entered the drinking water treatment market in 1987 with the installation of a 0.06 MGD system at Keystone Resorts in Keystone, Colorado. Since then, the number of installations has steadily risen. Figure 11 shows the cumulative number of membrane installations corresponding to installation year. In the first six years of MF/UF installations, 30 membrane facilities, about one-quarter of the current facilities, were installed, while 83 facilities were installed in the past five years.

The cumulative treatment capacities of the on-line facilities as of April 2000 are shown in Figure 12. In the first six years, the cumulative treatment capacities were very low, less than 3 MGD. Since 1996, the cumulative treatment capacity has risen from approximately 7 MGD for 28 facilities to nearly 190 MGD for 110 facilities (an increase in the average plant capacity from 0.25 MGD to 1.7 MGD). Additionally, there is 54 MGD of future treatment capacity planned with the addition of 10 new facilities, and these numbers do not include potential facilities in Minneapolis (70 MGD), San Diego (40 MGD), and Carmichael (15 MGD), which were not included in the future installations list provided by the manufacturers.

* Projected based upon manufacturer provided information.
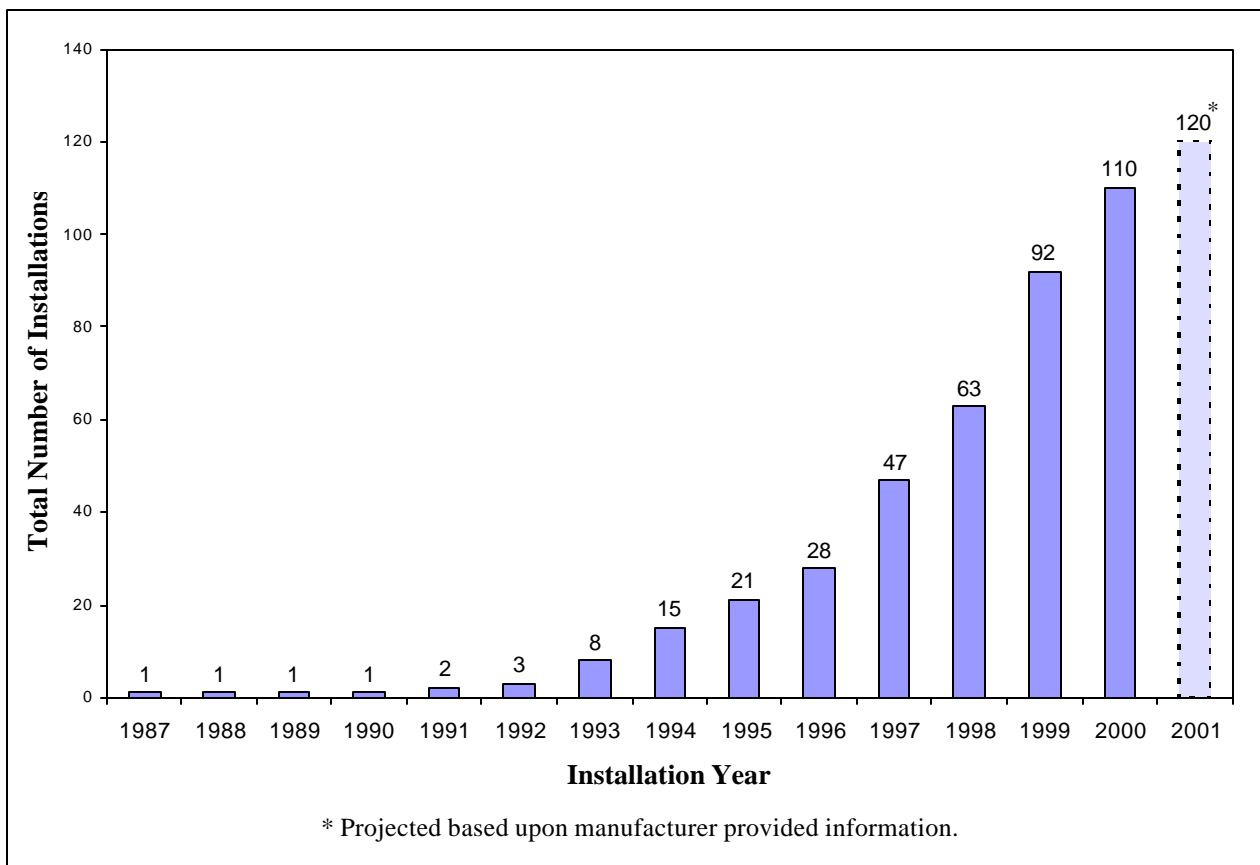
Figure 11. Cumulative Number of Membrane Installations
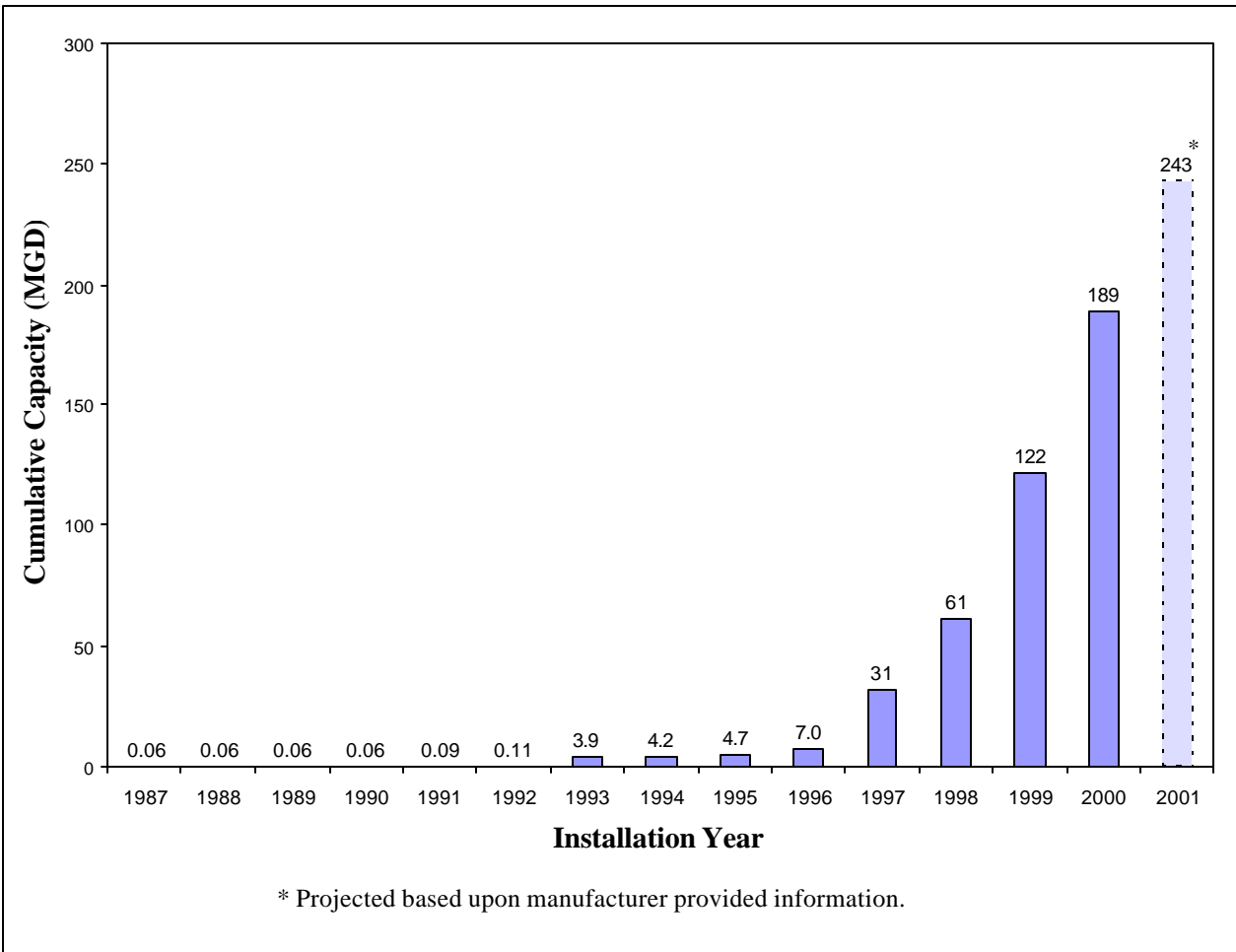
Figure 12. Cumulative Membrane Capacity

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3.0   MICROBIAL REMOVAL

3.1   Introduction

This section summarizes the results of a number of microbial and particle challenge studies that demonstrate the ability of MF/UF membranes to achieve up to 7-log removal of pathogens and particles. However, these results must be evaluated in the context of the study design. MF and UF are barrier technologies, and an integral membrane system will remove any particle (or pathogen) that is larger than the exclusion characteristic of the membrane system. Since log removal is a function of the influent contaminant concentration, the removal efficiencies reported for challenge studies are a function of the initial concentration as well as membrane performance. When organisms or particles are removed to below the detection limit, the reported log removal is limited by the influent concentration.

Seeded challenge studies are often performed to assess microbial removal. Typically, organism stock solutions are batched by adding live organisms to a small tank of dechlorinated water. This organism stock solution is continuously pumped to the membrane feed water. Samples are collected from the membrane feed water (post-organism addition) and from the filtrate to measure removal through the membrane system. Recycle streams and waste streams are also frequently sampled to perform a mass balance on the organisms. Samples are collected in sterile bottles, stored at the required temperature, and tested within the maximum holding time. These samples can be taken at various times during a filtration cycle to demonstrate either 'best-case' or 'worst-case' membrane removal conditions. For example, a membrane might best be able to remove particles and/or pathogens smaller than its pore size towards the end of a filtration cycle after a cake layer on the membrane surface has formed and matured. Conversely, a membrane might be least able to remove such particles and/or pathogens immediately after a chemical cleaning event due to the lack of a cake layer on the membrane surface.

Seeded challenge studies must often be performed to adequately assess membrane removal efficiencies for specific organisms since concentrations of certain organisms (e.g., *Giardia* and *Cryptosporidium*) in many natural waters are frequently too low to be accurately measured. That is, naturally occurring concentrations of these organisms are generally not sufficient for challenge studies that attempt to test the limits of treatment capabilities. As evidence of this, a statistical summary of the *Giardia* and *Cryptosporidium* monitoring results of the Information Collection Rule (ICR) are presented in Table 6.

The need for seeded challenge studies is compounded by the efficacy of the analytical methods used (Allen, et al., 2000). EPA conducted spiking studies to determine the recovery of the ICR *Giardia* and *Cryptosporidium* analytical methods (EPA, 1995). Results of those studies indicated the average recoveries were 12 percent for *Cryptosporidium* and 26 percent for *Giardia* (EPA, 2001). Recoveries of *Giardia* and *Cryptosporidium* are typically much higher in seeded challenge studies. It is worth noting that EPA has since issued improved analytical methods for the detection of *Cryptosporidium* and *Giardia* (EPA, 1999b and 1999c).

Table 6. ICR Monitoring - *Giardia* and *Cryptosporidium* Occurrence Summary

Parameter	*Cryptosporidium*	*Giardia*
Minimum (per 100 mL)	1	1
Maximum (per 100 mL)	1923	2521
Average (per 100 mL)	97	141
50th percentile (per 100 mL)	34	54
75th percentile (per 100 mL)	82	156
95th percentile (per 100 mL)	413	568
Number of samples with detectable protozoa[1]	401	1107
Number of non-detect samples[1]	5438	4732

1 – Minimum, maximum, average, and percentiles do not include samples in which protozoa were not detected. Statistics are based solely on those samples in which *Cryptosporidium* or *Giardia* were detected.

The removal of microorganisms by a membrane is dependent on a number of factors, one of which is the formation of a dynamic cake layer on the membrane surface. This cake layer will typically improve removal efficiencies for some pathogens over the filter cycle (Jacangelo, et al., 1995). Particles can be physically removed (sieving) by the cake layer, or may be adsorbed to particles in the cake layer. This phenomenon makes it difficult to compare results from different challenge studies, because the researchers do not generally account for the cake layer in the results presented, and it is often unclear whether the results were obtained using a clean membrane (early in the filtration cycle) or a fouled membrane (near the end of the filtration cycle).

This section presents the results of various studies evaluating the efficacy of membrane technology for the removal of microbial and surrogate parameters. Specifically, it evaluates MF/UF for the removal of protozoa, bacteria, viruses, turbidity and particles, and other organisms.

3.2 Protozoan Cysts

Protozoan cysts, which include the regulated pathogens *Giardia* and *Cryptosporidium*, are some of the larger microbial contaminants of concern. *Giardia* and *Cryptosporidium* cysts have diameters approximately one to two orders of magnitude greater than typical MF nominal pore diameters (0.1 to 0.5 µm) and two to three-and-a-half orders of magnitude greater than typical UF nominal pore diameters (0.005 to 0.05 µm). The primary removal mechanism for cysts is sieving which typically results in removal to detection limits when the membrane system is not compromised.

Results of *Giardia* and *Cryptosporidium* challenge testing are summarized in Tables 7 and 8, respectively. All studies were performed through seeding of the feed water. As seen in both Tables 7 and 8, for most studies cysts were removed to below the detection limit, thus the calculated log removal by MF and UF processes for *Giardia* and *Cryptosporidium* cysts was a function of influent organism concentration. This is expected since these cysts are larger than the absolute pore size of the MF and UF membranes tested. However, a breach in integrity, such as a broken fiber or a ruptured seal, can result in passage of cysts to the filtrate. As an example, during one study cysts were found in the treated water at levels above the detection limit

(Jacangelo, et al., 1997). In this case, the researchers identified a defective seal on the membrane module of the pilot unit as the breach in integrity.

Tables 7 and 8 also demonstrate that *Giardia* and *Cryptosporidium* removal efficiency is not a function of membrane configuration, pore size or membrane material, for the studies considered in this report. In addition, a variety of source water types, including wastewater treatment plant (WWTP) effluent, seeded deionized (DI) water, and surface waters, were used in the studies without influencing cyst removal efficiency. Several researchers reported pore size in units of MWCO. An approximate conversion scale for MWCO to µm is presented in Section 2.2, Figure 1.

Table 7. MF and UF Studies Documenting *Giardia* Removal Efficiency

Researcher	Year	Process	Test Scale	Pore Size	Water Source	Log Removal
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	surface water	>6.4*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	surface water	>6.9*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	surface water	>6.9*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	surface water	>7.0*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	surface water	>6.7*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	seeded DI water	>4.7* to >5.2*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	seeded DI water	>4.7* to >5.2*
Jacangelo, et al.	1997	MF	Pilot	0.1 µm	seeded DI water	>4.6^{+} to >5.0*
Kachalsky, et al.	1993	MF	Pilot	0.2 µm	WWTP effluent	4.99
Kachalsky, et al.	1993	MF	Pilot	0.2 µm	WWTP effluent	5.76
Kachalsky, et al.	1993	MF	Pilot	0.2 µm	WWTP effluent	7.33
Kachalsky, et al.	1993	MF	Pilot	0.2 µm	WWTP effluent	6.6*
MWD report, Coffey	1992	MF	Pilot	0.2 µm	surface water	>4.4*
NSF	2000b	MF	Pilot	0.1 µm	treated surface water	>5.8*

Table 7. MF and UF Studies Documenting *Giardia* Removal Efficiency (continued)

Researcher	Year	Process	Test Scale	Pore Size	Water Source	Log Removal
Olivieri, et al.	1987	MF	Pilot	0.2 µm	NR	5.6
Schneider, et al.	1999	MF	Pilot	0.2 µm	filter backwash	>4.8
Schneider, et al.	1999	MF	Pilot	0.1 µm	filter backwash	>4.8
Schneider, et al.	1999	MF	Pilot	0.1 µm	filter backwash	>4.8
Trussel, et al.	1998	MF	Pilot	0.2 µm	tertiary wastewater effluent	>5.1*
Vickers, et al.	1993	MF	Pilot	0.2 µm	surface and groundwaters	4 to >6.4*
Jacangelo, et al.	1997	UF	Pilot	300,000 MWCO	seeded DI water	>5.0*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	seeded DI water	>5.0* to >5.2*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	seeded DI water	>4.7* to >5.2*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	surface water	>6.4*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	surface water	>7.0*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	surface water	>6.7*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	surface water	>6.7*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	surface water	>6.9*
Dwyer et al.	1995	UF	NR	100,000 MWCO	seeded DI	>5*

Table 7. MF and UF Studies Documenting *Giardia* Removal Efficiency (continued)

Researcher	Year	Process	Test Scale	Pore Size	Water Source	Log Removal
Hagen	1998	UF	Pilot	100,000 MWCO	surface water	>1.1*
Jacangelo, et al.	1989	UF	Pilot	100,000 MWCO	surface water	>5*
Jacangelo, et al.	1991	UF	Pilot	100,000 MWCO	surface water	>4
Kachalsky, et al.	1993	UF	Pilot	0.05 µm	WWTP effluent	7.31
Kachalsky, et al.	1993	UF	Pilot	0.01 µm	WWTP effluent	7.39
Kachalsky, et al.	1993	UF	Pilot	0.02 µm	WWTP effluent	7.26*
NSF	2000e	UF	Pilot	100,000 MWCO	treated surface water	>6.6* to >6.8*
NSF	2000a	UF	Pilot	100,000 MWCO	treated surface water	>5.5*
NSF	2000c	UF	Pilot	0.01 µm	treated surface water	>4.9*
NSF	2000d	UF	Pilot	0.03 µm	treated surface water	>5.3*
Trussel, et al.	1998	UF	Pilot	100,000 MWCO	tertiary wastewater effluent	>5.1*

* indicates removed below detection limit.

+ indicates a broken seal.

++ indicates a potentially contaminated filtrate tank or line.

NR – Not reported.

Table 8. MF and UF Studies Documenting *Cryptosporidium* Removal Efficiency

Researcher	Year	Process	Test Scale	Pore Size	Water Source	Log Removal
Jacangelo, et al.	1997	MF	Pilot	0.1 μm	seeded DI water	4.2[+] to >4.8*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	surface water	>6.9*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	surface water	>6.8*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	surface water	>6.1*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	surface water	>6.3*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	surface water	>6.0*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	seeded DI water	>4.4* to >4.9*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	seeded DI water	>4.4* to >4.9*
Kachalsky, et al.	1993	MF	Pilot	0.2 μm	WWTP effluent	4.86
Kachalsky, et al.	1993	MF	Pilot	0.2 μm	WWTP effluent	5.74
Kachalsky, et al.	1993	MF	Pilot	0.2 μm	WWTP effluent	>7.29*
Kachalsky, et al.	1993	MF	Pilot	0.2 μm	WWTP effluent	>6.4*
NSF	2000b	MF	Pilot	0.1 μm	treated surface water	>6.8*
Olivieri, et al.	1989	MF	Pilot	0.2 μm	NR???	4.8
Schneider, et al.	1999	MF	Pilot	0.2 μm	filter backwash	4.2
Schneider, et al.	1999	MF	Pilot	0.1 μm	filter backwash	>4.2
Schneider, et al.	1999	MF	Pilot	0.1 μm	filter backwash	>4.2
Trussel, et al.	1998	MF	Pilot	0.2 μm	tertiary wastewater effluent	>4.7*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	seeded DI water	>4.8* to >4.9*

Table 8. MF and UF Studies Documenting *Cryptosporidium* Removal Efficiency (continued)

Researcher	Year	Process	Test Scale	Pore Size	Water Source	Log Removal
Jacangelo, et al.	1997	UF	Pilot	300,000 MWCO	seeded DI water	>4.8*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	seeded DI water	>4.4* to >4.9*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	surface water	>6.9*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	surface water	>6.7*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	surface water	>7.0*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	surface water	>6.4*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	surface water	>6.3*
Dwyer, et al.	1995	UF	NR	100,000 MWCO	seeded DI	>5*
Hagen	1998	UF	Pilot	100,000 MWCO	surface water	>8*
Jacangelo, et al.	1989	UF	Pilot	100,000 MWCO	surface water	>5*
Kachalsky, et al.	1993	UF	Pilot	0.05 µm	WWTP effluent	6.89
Kachalsky, et al.	1993	UF	Pilot	0.01 µm	WWTP effluent	6.99
Kachalsky, et al.	1993	UF	Pilot	0.02 µm	WWTP effluent	>7.07*
NSF	2000e	UF	Pilot	100,000 MWCO	treated surface water	>5.4* to >6.3*
NSF	2000a	UF	Pilot	100,000 MWCO	treated surface water	>6.5*
NSF	2000c	UF	Pilot	0.01 µm	treated surface water	>5.8*
NSF	2000d	UF	Pilot	0.03 µm	treated surface water	>6.4*
Trussel, et al.	1998	UF	Pilot	100,000 MWCO	tertiary wastewater effluent	>5.1*

+ Indicates a broken seal.
++ Indicates a potentially contaminated filtrate tank or line.
NR – Not reported.

3.3 Bacteria

The biological category of bacteria encompasses many different microbial species. As a result, there exists a large range of shapes and sizes within this category; species range from spherical to almost thread-like in shape and 0.1 µm to 100 µm in size (AWWA, 1999). However, in general most species of bacteria are larger than the exclusion characteristics of common MF and UF membranes. As with protozoan cysts, bacteria are primarily removed by MF/UF membranes through sieving. However, filtration through the membrane cake layer and adsorption onto the cake layer may also play a role in the removal of bacteria. The combination of these mechanisms results in significant removal of bacteria by MF and UF systems.

Results of bacterial challenge testing are summarized in Table 9. Although many different types of specific bacteria exist, general indicators of bacterial contamination, such as total coliforms (TC) or Heterotrophic Plate Count (HPC), were used in most of the studies listed in this table.

The results in Table 9 show that for many of the studies, bacteria were removed to below the detection limit. Thus, the calculated log removal by MF and UF processes was a function of the influent organism concentration. In many cases this is expected since the bacteria are larger than the absolute pore size of the MF and UF membranes tested. However, a breach in integrity, such as a broken fiber or a ruptured seal, can result in passage of bacteria to the filtrate. Note that the reported log removals were lower and varied more widely for the bacterial tests than for the protozoan studies. This is because many of the bacterial tests were conducted using naturally occurring bacterial concentrations, as opposed to the seeded challenge studies conducted for protozoa. Ambient concentrations are much lower and more varied (e.g., 10^2 to 10^3 organisms per L) than seeded study influent concentrations which can be on the order of 10^5 or 10^6 organisms per L.

Unless aseptic practices are implemented, it is impossible in a plant environment to maintain sterile conditions for "filtrate-side" components of a MF or UF system (e.g., filtrate piping or storage tanks). As a result, the potential for bacterial regrowth and contamination of the product water downstream of the membrane barrier exists even though the membrane process may have removed all bacteria from the source water. Bacteria, unlike protozoan cysts and viruses, can propagate without a host organism. Contamination can occur through a number of routes, including the presence of airborne organisms and human contact with the treated water components. The potential for bacterial regrowth can be minimized through the use of a disinfectant, such as chlorine, or by chemically cleaning the filtrate side of the membrane.

Table 9. MF and UF Studies Documenting Bacteria Removal Efficiency

Researcher	Year	Process	Test Scale	Pore Size	Bacteria Type	Water Source	Log Removal**
Parker, et al.	1999	MF	Pilot	0.2 μm	HPC bacteria	Filter backwash	3.3
Parker, et al.	1999	MF	Pilot	O.2 μm	Total coliform	Filter backwash	> 4.3
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	*E. Coli*	surface water	>7.8*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	*E. Coli*	seeded DI water	>7.8*
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	*E. Coli*	seeded DI water	>7.8*
Jacangelo, et al.	1997	MF	Pilot	0.1 μm	*E. Coli*	seeded DI water	>7.8*
MWD report, Coffey	1992	MF	Pilot	0.2 μm	*E. coli*	surface water	>6.0* to >6.4*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	*E. Coli*	surface water	>7.8*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	*E. Coli*	seeded DI water	>9.0*
Jacangelo, et al.	1997	UF	Pilot	300,000 MWCO	*E. Coli*	seeded DI water	5.6 to 6.9
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	*E. Coli*	seeded DI water	>7.8*
Olivieri, et al.	1991	MF	Pilot	0.2 μm	*Enterococci*	WWTP effluent	>2.5*
Wilinghan, et al.	1992	MF	Pilot	0.2 μm	*Enterococci*	WWTP effluent	2 to 4
Kachalsky, et al.	1993	MF	Pilot	0.2 μm	Fecal coliform	WWTP effluent	1.39
Kachalsky, et al.	1993	MF	Pilot	0.2 μm	Fecal coliform	WWTP effluent	2.83
Kachalsky, et al.	1993	MF	Pilot	0.2 μm	Fecal coliform	WWTP effluent	2.83
Kachalsky, et al.	1993	MF	Pilot	0.05 μm	Fecal coliform	WWTP effluent	4.02
Olivieri, et al.	1991	MF	Pilot	0.2 μm	Fecal coliform	WWTP effluent	>4.5*
Olivieri, et al.	1991	MF	Pilot	0.2 μm	Fecal coliform	WWTP effluent	>7*
Kachalsky, et al.	1993	UF	Pilot	0.05 μm	Fecal coliform	WWTP effluent	1.80

Table 9. MF and UF Studies Documenting Bacteria Removal Efficiency (continued)

Researcher	Year	Process	Test Scale	Pore Size	Bacteria Type	Water Source	Log Removal**
Kachalsky, et al.	1993	UF	Pilot	0.02 µm	Fecal coliform	WWTP effluent	2.18
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	HPC	surface water	>1.7
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	HPC	surface water	>2.6
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	HPC	surface water	>2.1
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	HPC	NR	>1.8*
Clair, et al.	1996	MF	Pilot	0.2 µm	HPC	surface water	0.5 to 2.4
Clair, et al.	1997	MF	Pilot	0.2 µm	HPC	NR	2.4
Luitweiler	1991	MF		--	HPC	NR	1.7
MWD report, Coffey	1992	MF	Pilot	0.2 µm	HPC	surface water	0.4 to 2.2
NSF	2000b	MF	Pilot	0.1 µm	HPC	treated surface water	0.2 to 0.4++
Vickers, et al.	1993	MF	Pilot	0.2 µm	HPC	surface and groundwaters	1.2 to 2.2
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	HPC	surface water	>1.7
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	HPC	surface water	>1.8
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	HPC	surface water	>2.1
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	HPC	surface water	>2.5
Henegan, et al.	1991	UF	Pilot	100,000 MWCO	HPC	surface water	3.6 to 4
Henegan, et al.	1991	UF	Pilot	100,000 MWCO	HPC	surface water	>3.4
Jacangelo, et al.	1989	UF	Pilot	100,000 MWCO	HPC	surface water	2.8
NSF	2000g	UF	Pilot	150,000 – 180,000 MWCO	HPC	treated surface water	1.9 to 2.3

Table 9. MF and UF Studies Documenting Bacteria Removal Efficiency (continued)

Researcher	Year	Process	Test Scale	Pore Size	Bacteria Type	Water Source	Log Removal**
NSF	2000a	UF	Pilot	100,000 MWCO	HPC	treated surface water	1.2 to 1.8
NSF	2000e	UF	Pilot	100,000 MWCO	HPC	surface water	0 to 0.2++
NSF	2000c	UF	Pilot	0.01 µm	HPC	treated surface water	0.5
NSF	2000d	UF	Pilot	0.03 µm	HPC	treated surface water	1.2 to 1.7
NSF	2000f	UF	Pilot	0.03 µm	HPC	surface water	2.1 to 2.2
Glucina, et al.	1997	MF	Pilot	0.2 µm	HPC and total coliforms	NR	>3
Hofman, et al.	1998	MF	Pilot	150,000 to 200,000 MWCO	HPC, coliforms, thermo-tolerant coliforms, SSRC	surface water	2.5 to 3.5
Jacangelo, et al.	1997	MF	Pilot	100,000 MWCO	*P. Aeruginosa*	seeded DI water	>8.7*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	*P. Aeruginosa*	seeded DI water	>8.2*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	*P. aeruginosa*	seeded DI water	>8.2*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	*P. aeruginosa*	seeded DI water	>8.2*
Jacangelo, et al.	1997	MF	Pilot	0.1 µm	*P. aeruginosa*	seeded DI water	>8.2*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	*P. aeruginosa*	seeded DI water	>8.2*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	*P. aeruginosa*	seeded DI water	>8.7*
Olivieri, et al.	1991	MF	Pilot	0.2 µm	Total coliform	WWTP effluent	>5.5*
Olivieri, et al.	1991	MF	Pilot	0.2 µm	Total coliform	Surface water	Below detection limit
Vickers, et al.	1993	MF	Pilot	0.2 µm	Total coliform	surface and groundwaters	1* - >2.5*
Wilinghan, et al.	1992	MF	Pilot	0.2 µm	Total coliform	WWTP effluent	2 to 6

Table 9. MF and UF Studies Documenting Bacteria Removal Efficiency (continued)

Researcher	Year	Process	Test Scale	Pore Size	Bacteria Type	Water Source	Log Removal**
Henegan, et al.	1991	UF	Pilot	100,000 MWCO	Total coliform	Surface water	2* to 3*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	Total coliforms	NR	>1.8*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	Total coliforms	surface water	>1.7*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	Total coliforms	surface water	>3.0*
Jacangelo, et al.	1997	MF	Pilot	0.2 µm	Total coliforms	surface water	>1.9*
Clair, et al.	1997	MF	Pilot	0.2 µm	Total coliforms	NR	>3
Clair, et al.	1996	MF	Pilot	0.2 µm	Total coliforms	surface water	Below detection limit
Kothari, et al.	1997	MF	Pilot	0.2 µm	Total coliforms	surface water	Below detection limit
MWD report, Coffey	1992	MF	Pilot	0.2 µm	Total coliforms	surface water	>0.8* to 2.0*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	Total coliforms	NR	>2.1*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	Total coliforms	surface water	>0.8*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	Total coliforms	surface water	>2.1*
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	Total coliforms	surface water	>1.7*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	Total coliforms	surface water	>2.2*
Glucina, et al.	1997	UF	Pilot	100,000 MWCO	Total coliforms	NR	>3
Jacangelo, et al.	1991	UF	Pilot	NR	Total coliforms	NR	>3
NSF	2000a	UF	Pilot	100,000 MWCO	Total coliforms	treated surface water	>1.2* to >1.8*
NSF	2000g	UF	Pilot	150,000 – 180,000 MWCO	Total coliforms	treated surface water	>0.8*
NSF	2000e	UF	Pilot	100,000 MWCO	Total coliforms	surface water	>0.9* to >1.4*
NSF	2000f	UF	Pilot	0.03 µm	Total coliforms	surface water	>0.7* to 1.2*

* Indicates removal below detection limit.

** If value does not indicate removal below detection limit, the reference which the value was taken from did not state removal below detection limit. However, this does not necessarily indicate that there were organisms detected in the filtrate.

+ Indicates a broken seal.

++ Indicates a potentially contaminated filtrate tank or line.

NR – Not reported.

3.4 Viruses

The category of viruses also comprises a large group of organisms. Viruses are much smaller than protozoan cysts and bacteria. Generally, virus sizes (i.e., 0.005 to 0.1 µm) compare to the entire range of UF and the lower end of MF pore sizes. There are a number of mechanisms by which viruses are removed by membranes, including physical sieving, adsorption onto the membrane, filtration through and adsorption onto particles in the cake layer, and sieving as a result of constriction of the membrane pores due to irreversible fouling (Jacangelo, et al., 1995). Reported virus removal by MF and UF membranes has varied widely, which is expected since many viruses are smaller than the pore sizes of MF membranes and comparable to the pore sizes of UF membranes. UF membranes have exhibited virus removal to detection limits, while MF membranes often exhibit lower removal, and, in some cases, do not remove viruses to any appreciable extent. This distinction between MF and UF performance is a function of the membrane exclusion characteristic, and not the MF or UF classification used by the membrane supplier. In practical terms, the difference between MF and UF can be characterized by their ability to remove viruses; UF acts as a physical barrier to viruses, MF does not.

Results of virus testing are summarized in Table 10. Removals vary from marginal (i.e., less than 0.5-log) to below detection limits (i.e., > 6.5-log), demonstrating the wide range in removal efficiencies for virus by MF and UF systems. For membranes with pore sizes of 100,000 MWCO (or ~0.01 µm) or tighter, Table 10 shows that viruses were frequently reduced to detection limits. However, for membranes with pore sizes greater than approximately 100,000 MWCO, viruses were less often removed to detection limits. Figure 13 presents virus removal capabilities, as reported in the studies cited in Table 10, by MF or UF classification.
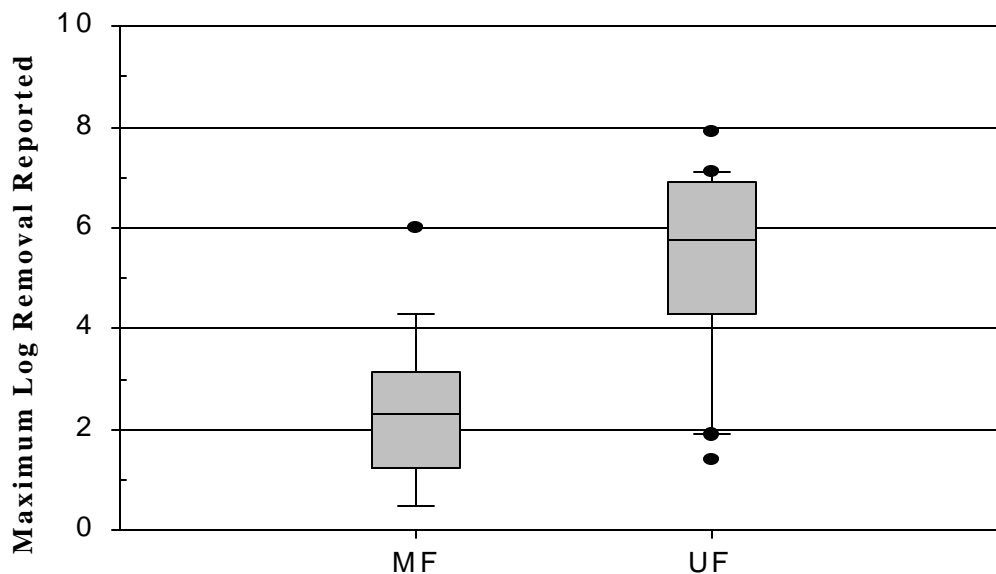
Figure 13. Summary of Virus Removal by MF/UF Processes Classification

Some studies demonstrate that the elapsed operating time after a backwash or chemical cleaning event may significantly impact virus removal (Jacangelo, et al., 1995). This is likely due to the formation of a cake layer on the membrane surface. As the cake layer thickens and compresses over the course of a filtration cycle, the ability of the membranes to remove viruses is improved.

The age of a membrane can also impact virus removal. Pore constriction may occur as a result of irreversible fouling of a membrane, reducing the pore size and improving virus removal. The extent of pore constriction is a function of feed water quality (i.e., concentration of the foulant) and membrane age.

Viruses may adsorb onto the membrane surface or larger particles in the feed water, which are more effectively removed by the membrane. Thus, water quality parameters such as turbidity or particle counts, may have an impact on virus removal. As evidence, the studies cited in Table 10 that were conducted with seeded DI water generally show less efficient virus removal than those studies conducted using natural waters containing significant levels of particles.

The majority of the results presented in Table 10 are based upon MS2 bacteriophage removal. MS2 is commonly used as an indicator for virus removal because it is similar in size (0.025 μm), shape, and nucleic acid makeup to poliovirus and hepatitis virus (Valegard, et al., 1990).

Table 10. MF and UF Studies Documenting Virus Removal Efficiency

Researcher	Year	Process	Test Scale	Pore Size	Virus Type	Feed Concentration	Water Source	Log Removal
Parker, et al.	1999	MF	Pilot	0.2 μm	Male specific coliphage	35200 per 100 mL	Filter backwash	3.7
Parker, et al.	1999	MF	Pilot	0.2 μm	Total culturable virus	83,405 per 100 L	Filter backwash	2.8
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	MS2 bacteriophage	NR	surface and ground waters	0 to 1.7
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	MS2 bacteriophage	NR	surface and ground waters	0 to 2.4
Jacangelo, et al.	1997	MF	Pilot	0.1 μm	MS2 bacteriophage	NR	surface and ground waters	0 to 2.2
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	MS2 bacteriophage	NR	seeded DI water	0.2 ± 0.3
Jacangelo, et al.	1997	MF	Pilot	0.2 μm	MS2 bacteriophage	NR	seeded DI water	1.2 ± 0.7
Jacangelo, et al.	1997	MF	Pilot	0.1 μm	MS2 bacteriophage	NR	seeded DI water	0.3 ± 0.4
Kruithof, et al.	1997	MF	Demonstration	NR	MS2 bacteriophage	1.0×10^5 to 3.5×10^5 pfu/ml	surface water	0.7 to 2.3
MWD report, Coffey	1992	MF	Pilot	0.2 μm	MS2 bacteriophage	1.3×10^6 to 3.0×10^7 pfu/ml	surface water	1.65 – 2.87
Olivieri, et al.	1991	MF	Pilot	0.2 μm	Human enterovirus		WWTP effluent	2 - 6
Olivieri, et al.	1991	MF	Pilot	0.2 μm	Male specific virus	1.6×10^1 to 1.6×10^4 #/ml	WWTP effluent	1.3* to 4.3*
Schneider, et al.	1999	MF	Pilot	0.2 μm	MS2 bacteriophage	NR	filter backwash	0.5
Schneider, et al.	1999	MF	Pilot	0.1 μm	MS2 bacteriophage	NR	filter backwash	1.1
Schneider, et al.	1999	MF	Pilot	0.1 μm	MS2 bacteriophage	NR	filter backwash	2.3
Trussel,et al.	1998	MF	Pilot	0.2 μm	MS2 bacteriophage	2.1×10^7 to 2.6×10^8 pfu/ml	tertiary wastewater effluent	0.4 to 3.2
Wilinghan, et al.	1992	MF	Pilot	0.2 μm	Male specific	3.0×10^1 to 3.0×10^4 #/ml	WWTP effluent	0.3 to 4*
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	MS2 bacteriophage	NR	surface and ground waters	>6.0 to >7.9

Table 10. MF and UF Studies Documenting Virus Removal Efficiency (continued)

Researcher	Year	Process	Test Scale	Pore Size	Virus Type	Feed Concentration	Water Source	Log Removal
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	MS2 bacteriophage	NR	surface and ground waters	0 to 1.4
Jacangelo, et al.	1997	UF	Pilot	500,000 MWCO	MS2 bacteriophage	NR	seeded DI water	1.5 ± 0.4
Jacangelo, et al.	1997	UF	Pilot	100,000 MWCO	MS2 bacteriophage	NR	seeded DI water	>6.8* ± 0.3
Dwyer, et al.	1994	UF	NR	100,000 MWCO	MS2 bacteriophage	2.43×10^7 to 3.12×10^8 pfu/ml	seeded DI	1.0 to 6.5
Dwyer, et al.	1994	UF	NR	10,000 MWCO	MS2 bacteriophage	2.43×10^7 pfu/ml	seeded DI	6.2 to 6.8*
Dwyer, et al.	1994	UF	NR	500,000 MWCO	MS2 bacteriophage	6.55×10^8 pfu/ml	seeded DI	1.5 to 6
Jacangelo, et al.	1991	UF	Pilot	100,000 MWCO	MS2 bacteriophage	1.0×10^7 to 1.0×10^8 pfu/ml	surface water	>6.5 to > 7.0
Kruithof, et al.	1997	UF	Demonstration	NR	MS2 bacteriophage	2.2×10^4 to 2.5×10^4 pfu/ml	surface water	>5.4
NSF	2000e	UF	Pilot	100,000 MWCO	MS2 bacteriophage	7.4×10^6 to 2.8×10^7 pfu/ml	surface water	4.0 to 5.7
NSF	2000e	UF	Pilot	100,000 MWCO	MS2 bacteriophage	3.5×10^7 to 6.0×10^7 pfu/ml	surface water	2.9 to 4.3
NSF	2000f	UF	Pilot	0.03 µm	MS2 bacteriophage	3.5×10^8 to 5.9×10^8 pfu/ml	surface water	>5.5* to 5.8
NSF	2000f	UF	Pilot	0.03 µm	MS2 bacteriophage	2.4×10^8 to 4.8×10^8 pfu/ml	surface water	1.7 to 2.1
NSF	2000g	UF	Pilot	150,000 – 180,000 MWCO	MS2 bacteriophage	2.8×10^7 to 1.7×10^8 pfu/ml	surface water	3.9 to 4.7
NSF	2000g	UF	Pilot	150,000 – 180,000 MWCO	MS2 bacteriophage	4.5×10^7 to 1.1×10^8 pfu/ml	surface water	3.4 to 4.3
Trussel, et al.	1998	UF	Pilot	100,000 MWCO	MS2 bacteriophage	2.2×10^5 to 1.1×10^5 pfu/ml	tertiary wastewater effluent	>6.9*

* indicates removed below detection limit.
+ indicates a broken seal.
++ indicates a potentially contaminated filtrate tank or line.
NR – Not reported.

3.5 Algae

Protozoan cysts, bacteria, and viruses represent the three groups of pathogens currently of concern to the water treatment industry for the protection of public health. Algae are also of concern to many water treatment facilities since the chemical byproducts they produce can impart an unpleasant taste and odor to water (AWWA, 1999). Algae are larger than the typical pore size of MF and UF systems, and Table 11 presents several ETV studies that have documented the removal of algae through MF and UF processes. In nearly all cases, algae counts were reduced to below the detection limit of 8 cells/ml. Although MF and UF membranes have been demonstrate capable of removing algae to detection limits, these processes may not remove their byproducts.

3.6 Surrogate Challenge Parameters

Using *Cryptosporidium* or *Giardia* for the purpose of conducting challenge studies can be cost prohibitive. However, there are a number of potentially suitable biotic and abiotic surrogates that could be used to assess the ability of a membrane to remove *Cryptosporidium*. Some of these surrogates include *Pseudomonas*, *Serratia*, *Bacillus*, polystyrene microspheres, and endospores. At the time of this report, little information was available regarding the performance of MF and UF with respect to these surrogates. As such, it is difficult to draw a conclusion regarding the appropriateness of these parameters as an indicator of membrane performance and *Cryptosporidium* removal. However, they have been identified as surrogates for other technologies (AWWA, 1999).

Another biological surrogate parameter that may be used to assess membrane performance is a Microscopic Particulate Analysis (MPA). A MPA is primarily used to assess the removal of larger microorganisms, including bacteria and protozoa, and is only applicable to relatively clean drinking water sources. In a MPA test, the filtered water is analyzed using polarized light microscopy. The analyst then looks for particles that may be microorganisms. If organisms are found, further testing may be performed to determine specific organism type. The MPA is seldom used due to the time and complexity of the procedure, and at the time of this report there was no data to demonstrate that MPA had been used as an indicator of membrane performance. It has, however, been used as an indicator for other technologies (Schulmeyer, 1995).

Although biological surrogates can provide a less costly alternative to the use of certain microorganisms for challenge studies, their measurement still requires substantial technical expertise. Consequently, the removal capability of a membrane system is frequently monitored through the use of non-biological surrogate parameters. These parameters primarily include polystyrene microspheres and particle count measurements. Microspheres have not been used extensively to evaluate membrane performance; however, they have been used to assess the performance of other technologies (Goodrich, et al., 1995; Li, et al., 1997).

Particle counting is often used to assess removal of bacteria and protozoan cyst sized particles. *Giardia* cysts are approximately 7μm to 14 μm in size, while *Cryptosporidium* cysts are approximately 4 μm to 7 μm in size. Bacteria can range in size from 0.1 μm to 100 μm. Particle counting is frequently conducted in discrete size ranges varying from 2 μm to 100 μm, and

counts in the 2 μm to 15 μm range typically used to assess the ability of a process to remove *Giardia* and *Cryptosporidium*.

Table 12 summarizes the results of several MF and UF studies that document the log reduction of particle counts in various size ranges. These results show significant reductions in particle counts for sizes ranging from 2 μm to 100 μm, which encompasses the size range of many bacteria and protozoan cysts. Log removals ranged from 2.9- to 4.7-log for particles in the 3 μm to 5 μm range, which is similar to *Cryptosporidium*, and from 1.4- to 4.6-log for particles in the 5 μm to 15 μm range, which is comparable to *Giardia*. Overall, particle counts were reduced from 1.4- to 4.7-log over the entire range of 2 μm to 100 μm. It should be noted, however, that these studies have been conducted on natural waters and influent seeding was not performed as it was in many of the previously cited studies that used organisms. Also, it is common to have some detectable level of particles in filtrate, even when the membrane system is integral. These factors result in relatively low log-removals compared to those observed in seeded microbiological studies.

Table 11. MF and UF Studies Documenting Algae Removal Efficiency

Researcher	Year	Process	Test Scale	Pore Size	Water Source	Log Removal
NSF	2000f	UF	Pilot	0.03 µm	surface water	0.5 to >0.9*
NSF	2000c	UF	Pilot	0.01 µm	treated surface water	>0.6* to >0.9*
NSF	2000b	MF	Pilot	0.1 µm	treated surface water	>0.6* to >0.9*
NSF	2000a	UF	Pilot	100,000 MWCO	treated surface water	>0.7* to 1.2

* indicates removed below detection limit.

Table 12. MF and UF Studies Documenting Particle Count Removal Efficiency

Researcher	Year	Process	Test Scale	Pore Size	Water Source	Log Removal
NSF	2000a	UF	Pilot	100,000 MWCO	treated surface water	2.2 (total counts)
NSF	2000b	MF	Pilot	0.1 μm	treated surface water	3.4 to 4.5 (3 – 5 μm)
NSF	2000b	MF	Pilot	0.1 μm	treated surface water	3.2 to 4.6 (5 – 15 μ m)
NSF	2000g	UF	Pilot	150,000 – 180,000 MWCO	treated surface water	1.6 to 4.0 (3 – 5 μ m)
NSF	2000g	UF	Pilot	150,000 – 180,000 MWCO	treated surface water	1.4 to 3.8 (5 – 15 μ m)
NSF	2000e	UF	Pilot	100,000 MWCO	surface water	2.9 to 4.6 (3 – 5 μ m)
NSF	2000e	UF	Pilot	100,000 MWCO	surface water	2.8 to 4.4 (5 – 15 μ m)
NSF	2000b	MF	Pilot	0.1 μm	treated surface water	2.3 (total counts)
NSF	2000d	UF	Pilot	0.01 μm	treated surface water	1.5 (total counts)
NSF	2000d	UF	Pilot	0.03 μm	treated surface water	2.0 (total counts)
NSF	2000f	UF	Pilot	0.03 μm	surface water	3.1 to 4.6 (5 – 15 μ m)
Scanlan, et al.	1997	MF	Pilot	0.2 to 0.5 μm	surface water	2.6 (2 – 15 μ m)
Scanlan, et al.	1997	UF	Pilot	0.05 μm	surface water	3.3 (2 – 15 μ m)
Kothari, et al.	1997	MF	Pilot	0.2 μm	surface water	1.9 (2 – 100 μ m)
O'Connell, et al.	1997	UF	Pilot	100,000 MWCO	groundwater	Below detection limit for 2 μ m
Kothari, et al.	1997	MF	Pilot	0.2 μm	surface water	3.6 (2 – 5 μ m)
Clair, et al.	1996	MF	Pilot	0.2 μm	surface water	>2.5 (>2 μ m)

* indicates removed below detection limit.
+ indicates a broken seal.
++ indicates a potentially contaminated filtrate tank or line.

3.7   Summary

The studies cited in this section demonstrate that membrane processes are able to achieve significant removal of pathogens and other microorganisms. Integral MF and UF processes can often reduce protozoan cyst and bacteria concentrations to detection limits. Since the pore size of most membranes is typically at least an order of magnitude smaller than bacteria and protozoan cysts, the primary removal mechanism for these organisms is sieving. UF processes with pore sizes of approximately 0.01 µm and smaller can typically achieve virus removal to detection limits, while MF and UF processes with pore sizes greater than approximately 0.01 µm often exhibit partial virus removal. However, virus removal is a impacted by many factors, including the formation of a dynamic cake layer on the membrane surface. Thus it is difficult to make generalizations regarding virus removal efficiency based solely on membrane process classification.

Although MF and UF membranes are considered absolute barriers for many pathogens of concern to the water treatment industry, there are practical and operational concerns that should be addressed. Imperfections in the construction of the membrane module or degradation of the membrane system over time can lead to the passage of microorganisms into the treated water. These imperfections can include broken fibers, scratches in the membrane surface, pores larger than the nominal size, o-rings that do not seal properly, and glue joints that may be cracked. Potential integrity breaches such as these underscore the need for reliable integrity testing, even with the superior microbial removal performance demonstrated by numerous studies.   The following chapter describes the integrity monitoring techniques commonly used with membrane processes, including the applicability and limitations of various tests.

4.0 INTEGRITY TESTING

4.1 Overview of Integrity Testing

Integrity testing is a means of assessing whether a membrane system is completely intact or has been compromised, and it is a critical consideration for any membrane filtration plant. Although a MF or UF membrane represents a theoretical absolute physical barrier to particles (in the form of pathogens, turbidity, total suspended solids (TSS), etc.) that are larger than the membrane pore size, integrity testing represents a practical way of verifying the barrier effectiveness by detecting leaks or membrane breaches.

There are two general types of integrity test methods:

1) <u>Direct Methods</u>: Direct methods are applied specifically to the membrane or membrane module to detect integrity breaches and/or determine their sources.

2) <u>Indirect Methods</u>: Indirect methods are surrogate measures of integrity that involve monitoring filtrate water quality. A significant decline in water quality may indicate that membrane integrity has been compromised.

Both types of methods may be useful monitoring and/or diagnostic tools for membrane filtration systems, although there is a trade-off associated with each. Indirect methods have the advantage of continuous application while the system is in operation. However, indirect methods are only inferential techniques for detecting membrane integrity problems. The converse is true for the direct methods. While the direct methods specifically test the membranes for integrity problems, current methods cannot be applied continuously and must be conducted while the system is off-line. Direct and indirect testing methods are discussed in detail in Sections 4.2 and 4.3, respectively. Some of the advantages and disadvantages of the various direct and indirect methods are summarized in Table 13.

Integrity testing may be conducted with the intent of satisfying any one or more of several different objectives. These objectives include:

1) <u>Verification of high quality filtrate water</u>: Because the integrity of the membrane filter is essential to achieving filtrate water quality goals, integrity testing can serve as an indicator of water quality problems. Indirect methods are best suited for this objective, as they are designed to monitor water quality. However, an integrity breach detected using a direct method of testing would also indicate that the filtrate water quality has been compromised.

2) <u>Demonstration of regulatory compliance</u>: As discussed in Chapter 6, direct or indirect integrity test methods or a combination of both may be required by the primacy agency of jurisdiction to demonstrate that a membrane filtration system is successfully achieving its allocated pathogen removal credit and/or other water quality objectives. Generally, any detected compromise in membrane integrity must be promptly addressed, independent of the magnitude of the breach. The implications of membrane integrity testing for microbial risk and regulation are addressed in Chapter 5.

Table 13. Summary of Integrity Monitoring Methods

Integrity Test Method	Advantages	Disadvantages
Direct Methods		
Pressure Hold Test	• Ability to monitor entire rack of membranes simultaneously • Ability to detect single fiber breaks and small holes • Standard part of most membrane systems and highly automated • Can test both membranes and downstream plumbing for leaks • Ability to maintain aseptic quality of system if applied to filtrate side	• Need for increasingly sensitive pressure transducers when test is applied to increasingly large number of modules • Potential to yield false-positive results if the membrane is not fully wetted • Limitation in log removal equivalency (sensitivity)
Diffusive Air Flow Test	• Similar advantages as the pressure hold test, although typically not included as standard equipment • More sensitive than the pressure hold test as currently applied • Ease of conducting and accuracy of test (when measuring water displacement)	• Sensitivity to temperature (viscosity) • Limited full-scale applications to verify performance • Manual application as currently applied, though the test can be automated • Not included as standard equipment for most MF/UF systems
Bubble Point Test	• Ease of conducting and interpreting results • Ability to identify specific compromised fibers and leaking seals	• Labor intensive for large plants – manual application • Only able to pinpoint leaks identified by other test methods • Only practical as a diagnostic test for the repair of individual modules
Sonic Sensing Analysis	• Identifies compromised module and general location of integrity breach • Easy to use • Potential to be developed into a continuous, on-line monitoring method	• Manual application • Limited use in the water industry to date (primarily used as a diagnostic tool at current state of development) • Labor intensive for large plants • Subjective interpretation of results • Not practical for submersed systems
Indirect Methods		
Particle Counting	• Continuous monitoring of filtrate water quality • Sensitive to minor changes in water quality • Widespread use and familiarity in water industry	• Difficult to calibrate • Imprecision between different (even well-calibrated) instruments • Susceptible to sensor clogging • Susceptible to counting bubbles (entrained air) as particles, or particles resulting from microbial growth in instrument tubing • Relatively high cost
Particle Monitoring	• Continuous monitoring of filtrate water quality • Significantly lower cost than particle counters • No calibration required • More sensitive to integrity breaches than turbidimeters but less sensitive than particle counters	• Infrequent use in water industry • Less sensitive than particle counters • Susceptible to sensor clogging • Susceptible to counting bubbles (entrained air) as particles, or particles resulting from microbial growth in instrument tubing • Provides only a relative index of particle concentration
Turbidity Monitoring	• Continuous monitoring of filtrate water quality • Near comprehensive use at surface water plants as a result of filtered water turbidity standards • Significantly lower cost than particle counters	• Relative insensitivity to breaches in membrane integrity compared to other methods, although developing laser turbidimetry may result in comparable sensitivities • Susceptible to counting bubbles (entrained air) as particles

3) <u>Detection of equipment / filtration system problems</u>: Integrity testing, by design, is an indicator of whether some components of a membrane filtration system (i.e., the membrane, o-rings, seals, etc.) are operating properly. As a result, independent of water quality or regulatory concerns, an integrity test serves as a diagnostic tool to alert an operator to any problem with the system that needs to be corrected.

4.2 Direct Methods

The direct methods of integrity testing are non-destructive techniques that are applied specifically to the membrane or membrane module in order to identify and/or isolate leaks. The primary disadvantage of direct methods is that they cannot be conducted continuously while the membrane filtration system is in operation. Thus, the longer and more frequent the integrity testing, the greater the impact on system production capacity. The frequency of direct method integrity testing varies with the regulatory requirements of the primacy agency. Typically, five to ten minutes is necessary to conduct a routine direct integrity test, although the system may remain off-line much longer if a potential integrity breach is detected.

Direct testing methods also indicate nothing specific about filtrate water quality. Thus, if an integrity breach is detected, a direct method test will yield no information on the impact of that breach on the filtrate quality. However, direct methods are not designed to convey water quality information and are not applied with this objective in mind.

There are four direct integrity testing methods that are commonly employed to varying degrees:

1) Pressure Hold Test

2) Diffusive Air Flow Test

3) Sonic Sensing Analysis

4) Bubble Point Test

Each of these four types of direct methods is well suited for particular testing applications. For example, the pressure hold and diffusive air flow tests are both first-line integrity tests that are conducted on racks of membrane modules. Thus, while these tests are the most expedient and efficient means to directly test multiple membrane modules, they will not indicate the specific module or location within that module where a breach has occurred. Therefore, if either the pressure hold test or the diffusive air flow test detects a problem, follow-up diagnostic testing would be necessary to locate the breach. For example, a sonic test may be applied to individual modules within a rack that failed an integrity test to isolate the module with the integrity breach. Note that the pressure hold and diffusive air flow tests may require that the membrane rack under examination be taken off-line. Once the module is isolated and removed from the rack, the bubble point test can be used to identify the compromised fiber(s). The sonic sensing analysis can be conducted while a rack is on-line, but is not a continuous test.

The four direct testing methods outlined above are addressed in detail in the following sections. The tests are discussed as applicable to hollow-fiber membranes. Spiral wound MF and UF membranes, although commercially available, are uncommon for drinking water applications, and several of the direct methods of membrane integrity testing presented here are not directly applicable to spiral-wound elements.

4.2.1 Pressure Hold Test

A pressure hold test is conducted by applying pressurized air to the membrane and monitoring the rate of pressure decay over a specific duration of time. An outline of the test protocol is as follows:

1) Drain the water from one side of the membrane: Typically, the insides of the fiber lumens are drained, which may be the feed or the filtrate side of the membrane, depending on whether the system is operated in an "inside-out" or "outside-in" configuration.

2) Pressurize the drained side of the fully wetted membrane: The applied pressure must be lower than the bubble point of the membrane, which is the pressure required to overcome the capillary forces that hold water in the membrane pores. (Bubble point theory is further discussed in conjunction with the bubble point test in Section 4.2.4.) Pressures ranging from 4 – 30 psi are typically applied during the pressure hold test, depending on the type of proprietary system. (Membrane construction may limit the pressure at which a membrane can be tested.) As further discussed in Section 5.4.1, the applied pressure determines the smallest hole that can be detected by the pressure hold test. Vacuum systems, which have the feed side of the membrane simply submerged in basins, are typically tested without draining the basins. As a result, the hydrostatic pressure at the bottom of the basin must be considered in determining the net applied pressure during a pressure hold test performed on a vacuum-driven system.

3) Hold the pressure for about ten minutes and monitor the pressure decay: If there are no leaks in the membrane, process plumbing, or other pressurized system components, then the only way for air to escape is by diffusing through the water contained in the pores of the fully-wetted membrane. Estimates of an acceptable pressure decay for an intact membrane and leak-free system will vary somewhat by manufacturer. Typically, higher rates of pressure loss are considered acceptable for composite membranes since diffusion is significantly greater through a thin membrane film compared to a homogenous membrane of greater thickness. In general, a pressure greater than 0.1 to 0.5 psi per minute may indicate a leak or breach in membrane integrity. The specific threshold of acceptable pressure decay rate varies among the different proprietary membrane filtration systems and is a function of both membrane characteristics and the net applied test pressure.

When applied to a single membrane module, the pressure hold test has been shown to be very sensitive to leaks and integrity breaches. In one test, Adham, et al. (1995) reported that a considerable loss of pressure was observed for a 0.6 mm needle puncture in the lumen wall of one out of over 22,000 fibers in a membrane module. Typically, however, the pressure hold test

is applied to an entire rack of membranes simultaneously to test membrane integrity as efficiently as possible, diminishing the sensitivity of the test. The more membrane modules included in a single application of the test or the larger the number of fibers (or membrane area per fiber) per membrane module tested, the greater the number of pores through which the pressurized air can diffuse. This, in turn, results in more rapid pressure decay via diffusion, diluting the impact of one compromised fiber on the pressure decay rate. As a result, the greater the number of fibers tested, the more sensitive the pressure transducers need to be in order to differentiate between normal diffusive losses spread out over a larger membrane area and losses due to integrity breaches.

The dilution effect that occurs during the application of the pressure hold test to a rack of membranes is illustrated through comparison of the results of Adham, et al. (1995) with those from a fiber-cutting study conducted at the Kenosha, Wisconsin microfiltration water treatment facility. In summarizing the findings of the Kenosha study, Landsness (2001) cites that for a rack of 90 modules of the same type of membrane tested by Adham, et al., six fibers had to be cut before pressure hold test results exhibited any significant variation from the case in which all fibers were intact.

Note that the pressure hold test may also be applied to a single membrane module to help pinpoint the source of an integrity problem, although this is seldom done in practice in favor of bubble point testing.

<u>Advantages</u> of the pressure hold test include:

1) Ability to measure integrity directly

2) Ability to monitor an entire rack of membrane modules simultaneously

3) Sensitivity on the order of single fiber breaks and small holes in the fiber lumen wall (The ability of the pressure hold test to detect very small integrity breaches will vary with the total number of fibers (and hence total membrane area) to which the test is applied.)

4) Standard inclusion in most MF and UF systems

5) High degree of automation

6) Widespread use and acceptance by both utilities and primacy agencies

7) Ability to test both the membrane and downstream plumbing for leaks

8) Ability to maintain the aseptic quality of the system if conducted by pressurizing the filtrate side of the membrane

Some <u>disadvantages</u> are:

1) Inability to continuously monitor integrity

2) Need for increasingly sensitive pressure transducers when the test is applied to an increasing number of membrane modules

3) Potential to yield false-positive results if the membrane is not fully wetted
(This condition may occur with newly installed and very hydrophobic membranes that are difficult to wet, or when the test is applied immediately after a backwash process that includes air.)

4.2.2 Diffusive Air Flow Test

There are two different "diffusive air flow tests" described in the literature. Both tests are based on the same principle as the pressure hold test and are applied with the same objective of broadly detecting leaks in a rack of membrane modules. The diffusive air flow tests differ from the pressure hold test in that either air or water flow through the membrane pores is measured rather than pressure decay. Both types of diffusive air flow tests are described as being potentially more sensitive than the pressure hold test (Trimboli, et al. 1999). However, these tests have not been sufficiently developed to gain widespread acceptance by primacy agencies in the United States, and applications of these tests for integrity monitoring in full-scale water treatment plants worldwide are rare at this time.

The most commonly cited diffusive air flow test, discussed by Meltzer (1987), Vickers (1993), and Cheryan (1998), involves measuring the diffusion of air through the fully-wetted membrane pores. One potential difficulty associated with this test is the sensitivity of diffusion rates to temperature. Seasonal variations in temperature may cause the results of this test to fluctuate over the course of the year, although it is possible that the results could be normalized to a standard reference temperature. Currently, this test is not in common use in membrane water treatment plants, and available literature describing the application of this test to large-scale membrane filtration systems is relatively limited.

The other diffusive air flow test, described in a 1997 report by the American Water Works Association Research Foundation (AWWARF) as under development, measures the volume of water displaced by the pressurized air through compromised fibers. In this report, Jacangelo, et al. cite the advantages of this test as its ease and accuracy of measurement. Since that report was published, a membrane water treatment plant in New Zealand (Joyce Road Water Processing Plant, Tauranga, New Zealand) has adopted the use of this integrity test, which calls for simply using a graduated cylinder to measure the water flow that would pass through any compromised fibers or other integrity breaches in a membrane module (Trimboli, et al. 1999).

<u>Advantages</u> of the diffusive air flow test include:

1) Ability to measure integrity directly

2) Ability to monitor an entire rack of membrane modules simultaneously

3) Sensitivity on the order of single fiber breaks and small holes in the fiber lumen wall
    (The ability of the diffusive air flow test to detect small integrity breaches will vary with the total number of fibers (and hence total membrane area) to which the test is applied. However, the diffusive air flow test is more sensitive to small breaches than the pressure hold test.)

4) Ability to test both the membrane and downstream plumbing for leaks

5) Ability to maintain the aseptic quality of the system if conducted by pressurizing the filtrate side of the membrane

Some <u>disadvantages</u> are:

1) Inability to continuously monitor integrity

2) Need for increasingly sensitive flow monitoring equipment when the test is applied to an increasing number of membrane modules

3) Potential to yield false-positive results if the membrane is not fully wetted
    (This condition may occur with newly installed and very hydrophobic membranes that are difficult to wet, or when the test is applied immediately after a backwash process that includes air.)

4) Not included as part of standard equipment in most MF and UF systems

4.2.3   Sonic Sensing Analysis

A sonic sensing analysis is less of an independent testing method than a companion tool to pressure testing. If a breach is detected using a pressure hold test, a sonic sensing analysis may be used to isolate the particular module that contains the leak. The analysis is conducted by manually applying an accelerometer (an instrument used to detect vibrations) to one or more locations on each membrane module. Using headphones, the operator listens for vibrations generated by leaking air.

The sonic sensing analysis is most effectively administered by a skilled and experienced operator and is somewhat more subjective than the other forms of integrity testing, either direct or indirect. Adham, et al. (1995) reported that sonic sensing was able to detect a breach as small as a 0.6 mm needle puncture in the wall of one out of over 22,000 hollow fibers in one type of membrane, although some skill in strategically checking the module was required to identify this breach.

Advantages of the manually applied sonic sensing analysis currently in use include:

1) Ability to measure integrity directly

2) Identification of compromised module and general location of breach

3) Ease of use (assuming the test is conducted by a trained operator)

4) Potential to be developed into a method of on-line, continuous, direct testing

Some disadvantages are:

1) Inability to continuously monitor integrity

2) Manual application

3) Limited use in the water industry to date

4) Potential to be labor intensive for large plants

5) Potential for subjective interpretations of results

6) Not practical immersed membrane systems

An automated and computerized sonic testing system could have the potential to eliminate the subjectivity of this test and serve as an on-line, continuous, and direct means of integrity testing. The early-stage development and testing of such an automated sonic system was described in a paper by Glucina, et al. (1999). This new acoustic monitoring system utilizes a sensor on each membrane module to detect changes in noise caused by pressure fluctuations in a compromised fiber. Test results indicated that the automated acoustic system was capable of detecting a single compromised fiber, although performance was affected by the level of background mechanical noise associated with the membrane filtration system. In addition, greater noise was generated by higher flows through a compromised fiber, rendering the breach easier to detect relative to the background noise. The system described by Glucina, et al. (1999) remains under development by the manufacturer.

4.2.4 Bubble Point Testing

Bubble point testing, like sonic testing, is best employed in conjunction with the pressure hold test rather than as a separate and independent gauge of membrane integrity. For example, after a pressure hold test is used to detect an integrity problem and a sonic sensing analysis isolates the module containing the leak, the bubble point test can be applied to a identify the compromised fiber(s) following its removal from the rack.

The bubble point test is based on capillary theory, in which the "bubble point" is defined as the gas pressure required to displace liquid from the pores of fully-wetted filtration media. In

conducting a bubble point test, the module to be tested is first removed from the rack. The external shell of the module is then drained and pressurized to a pressure below the bubble point of the membrane. Applied pressures are generally similar for the bubble point and pressure hold tests for the same type of proprietary membrane. A dilute surfactant solution is applied to the open ends of the membrane fibers at the end of the module. The formation of bubbles in the surfactant solution can be used pinpoint specific leaking fibers.

Advantages of the bubble point test include:

1) Ability to measure integrity directly

2) Ease of conducting and interpreting results

3) Ability to identify specific compromised fibers and leaking seals so as to facilitate repair

Some disadvantages are:

1) Inability to continuously monitor integrity

2) Manual application

3) Requires removal of a membrane module from the rack

4) Potentially labor intensive for large pressure-driven (i.e., encased) membrane systems

5) Only a useful tool for pinpointing leaks that have already been identified by other testing methods when applied to pressure-driven (i.e., encased) membrane systems

4.3   Indirect Methods

Indirect methods of integrity testing do not apply specifically to the membrane or module, but rather monitor some component of filtrate water quality as a surrogate measure of integrity. Because the membrane filtrate water quality is typically very consistent and is independent of the feed water quality, a marked decline in filtrate quality may indicate an integrity problem.

While the indirect methods have the disadvantage of only being able to suggest potential integrity problems, there are some benefits to using these methods. First, the most common methods of indirect testing operate in a continuous, on-line mode. In addition, the same indirect methods and testing instruments can be applied to any membrane system, independent of manufacturer, system configuration, or any other parameter intrinsic to a proprietary system. Moreover, indirect methods are likely to remain applicable to any new systems that are developed. It should be noted that systems that use air for backwash, or to control fouling in the case of some submerged systems, are more susceptible to interference by entrained air bubbles, which may make development of a stable baseline more difficult.

The three indirect testing methods that are employed in the majority of membrane filtration applications are as follows:

1) Particle Counting

2) Particle Monitoring

3) Turbidity Measurements

The above methods are listed in order of decreasing sensitivity to integrity breaches as determined in a study of integrity test methods conducted by Adham, et al. (1995). Each of these methods, as well as several less common indirect techniques for detecting integrity problems, are discussed as follows in Sections 4.3.1 – 4.3.4.

4.3.1 Particle Counting

Particle counters use a laser-based light scattering technique to count particles and group them according to size. Although Adham et al. (1995) determined that particle counting was the most sensitive of the three common on-line indirect methods, particle counting instruments have a number of well-established operational problems that can potentially distort both the accuracy and precision of their measurements.

Advantages of particle counting are as follows:

1) Sensitivity to relatively minor water quality changes that may result from a breach

2) Widespread use and familiarity in the water treatment industry

3) Continuous monitoring of filtrate quality

Some disadvantages are:

1) Difficulty to calibrate in the field

2) Imprecision between different instruments
   (Two identical, well-calibrated devices may yield significantly different readings for the same water source.)

3) Susceptibility to "coincidence error"
   (Two or more particles may pass through the sensor simultaneously, causing the count to be underestimated.)

4) Susceptibility to sensor clogging or obscuring, particularly in turbid waters

5) Susceptibility to counting bubbles as particles as a result of air entrainment

6) Susceptibility to counting particles shed from connective piping or tubing on the filtrate side of the membrane (i.e., from microbial growth, corrosion, etc.)

7) Unrepresentative (unstable) output during startup and shutdown

8) Cost of particle counters relative to other integrity monitoring instrumentation

These disadvantages have significant implications for the use of particle counters as a means of integrity monitoring. First, because particle counting is not an absolute measure of water quality, relative changes in particle concentration must be used to determine whether a breach of integrity has occurred. A baseline and relative deviations that would signal a potential breach would have to be established for each individual particle counter. If a particle counter is sufficiently sensitive, then small breaches would be easily detectable relative to baseline measurements. The factors affecting instrument sensitivity are discussed in Chapter 5.

Due to variability in particle counters, a specific instrument could only be used for the particular membrane rack filtrate to which it is attuned and for which the relative deviation of concern is known. Switching particle counters (or sensors) or recalibrating the instruments would require re-attenuation for each of the affected instruments to the particular filtrate waters to which they are applied. However, it would be feasible to multiplex a number of sensors to an individual particle count instrument if the individual sensors are attenuated to a specific rack.

The susceptibility of particle counters to coincidence error and sensor clogging may not present a significant problem for these instruments when applied to monitor membrane filtrate. The potential for both of these errors is heavily influenced by water quality. The higher the particle concentration and/or turbidity of the water, the more subject these instruments are to underestimating the particle counts. However, since MF and UF membrane filtrate typically has a very low particle concentration and turbidity, even under compromised conditions, coincidence or clogging errors are not likely to occur.

The potential for air entrainment to cause particle counters to report overestimated results presents a more substantial problem. Significant air may be introduced into the piping during the periodic membrane backwashing, particularly if air is used to scour or pulse the membrane during the backwash cycle. As a result, after backwashing, the effective use of particle counters as an integrity monitoring tool is somewhat diminished until the air is expelled and the particle counts return to baseline levels. The time required for this air purge varies with the particular membrane system and the backwash operating parameters. The implications of this error for integrity testing and microbial risk are discussed in Section 5.4.2.

The cost of particle counters can vary depending on the sensitivity of the instrument, i.e., the more sensitive an instrument is to small particle size ranges, the more expensive it is likely to be. The higher cost of particle counters (relative to other instruments used for indirect monitoring) also has implications for integrity testing. Generally, the more expensive an instrument is, the greater the motivation to develop a monitoring scheme that minimizes the number of instruments required. However, the fewer the number of particle counters in operation, the greater the number of membranes modules that will be monitored by each device. As a result, the impact of

an integrity breach is diluted, and the ability of a particle counter to detect the breach is diminished. The cost of implementing particle counting as means of integrity monitoring may be moderated somewhat by the use of a multiplexing system to connect sensors on a number of different membrane racks to a single instrument, however, this would prevent continuous monitoring of every rack. A similar cost-saving technique could also be applied in using particle monitors and turbidimeters, as well.

4.3.2   Particle Monitoring

Particle monitors operate on the principle of light obstruction, similar to particle counters. However, rather than counting particles and grouping them by size, particle monitors measure particulate water quality on a dimensionless scale relative to an established baseline.

Particle monitors are significantly less expensive than particle counters and were determined to be more sensitive to integrity breaches than turbidimeters (Adham, et al., 1995). However, particle monitors are seldom used by utilities, and thus the water industry has limited experience with these devices. Moreover, particle monitors are subject to some of the same disadvantages as particle counters. The advantages and disadvantages of particle monitors are summarized below:

Advantages of particle monitors include:

1) Lower cost than particle counters

2) Greater sensitivity to integrity breaches than conventional turbidimeters

3) Continuous monitoring of filtrate quality

Some disadvantages of particle monitors are:

1) Infrequent use in the water industry

2) Lower sensitivity to integrity breaches than particle counters

3) Susceptibility to "coincidence error"

4) Susceptibility to sensor clogging or obscuring, particularly in turbid waters

5) Susceptibility to counting of bubbles as particles as a result of air entrainment

6) Provides only a relative index of particle concentration

4.3.3 Turbidity Measurements

Conventional turbidimeters measure light scatter due to the presence of particulate matter in water. These instruments have been shown by Adham, et al. (1995) to be less sensitive than both particle counters and particle monitors for detecting integrity breaches; however, a newly developed laser turbidimeter may hold more promise for indirect integrity monitoring. Manufacturer specifications indicate that the laser turbidimeter has increased sensitivity in excess of two orders of magnitude over conventional turbidimeters and is optimized to measure very low turbidities, in the range of $0 - 1$ NTU. These abilities have been documented in a study conducted by Banerjee, et al. (1999a). Since most MF and UF systems produce filtrate water consistently in the range of $0.01 - 0.05$ NTU, the laser turbidimeter may be well suited to monitor membrane filtrate.

In another study conducted by Banerjee, et al. (1999b) with different collaborators, the laser turbidimeter and one type of particle counter (from the same manufacturer) tracked changes in water quality caused by particles larger than 2 μm with similar success, although the data collected by the laser turbidimeter appeared to exhibit greater resolution. In addition, a third study conducted by Banerjee et al. (2000), with still a different set of collaborators, demonstrated that the ability of the laser turbidimeter to detect changes in water quality caused by cutting a single membrane fiber in a test module was on par with that of a particle counter. The results of at least one recent study, however, indicate that the laser turbidimeter is somewhat less sensitive to integrity breaches than particle counters (Colvin, et al., 2001).   Thus, although the effectiveness of the relatively new laser turbidimeter as an indirect method of integrity testing is still being evaluated by the water industry, research conducted to date generally indicates that these devices are more sensitive to integrity problems then conventional turbidimeters and seem to be comparable to particle counters.

Like particle counters, continuous, on-line turbidimeters may also be subject to air entrainment error. Typically, bubble traps are employed with turbidimeters (both conventional and laser) to minimize or eliminate this error. However, neither conventional nor laser turbidimeters share the same accuracy and precision difficulties that are problematic for particle counters. Two well-calibrated turbidimeters are likely to yield similar results for the same water. Conventional turbidimeters, which are employed in vastly greater numbers in water treatment plants than the relatively new laser turbidimeter, are also significantly less expensive than particle counters. In addition, turbidimeters have the added advantage of measuring a parameter that is both absolute (as opposed to a relative measure, as with particle monitors) and widely recognized as a meaningful gauge of water quality from a regulatory perspective.

Advantages of conventional turbidimeters are summarized as follow:

1) Near comprehensive use at surface water treatment plants throughout the country as a result of surface water treatment regulations

2) Lower cost then particle counters or particle monitors

3) Consistency of measurement
(Two well-calibrated turbidimeters will yield similar results for the same water.)

4) Ability to measure water quality with respect to particulate matter in absolute terms (as opposed to particle counters)

5) Continuous monitoring of filtrate quality

Some <u>disadvantages</u> are:

1) Relative insensitivity to breaches in membrane integrity compared to other indirect methods

2) Susceptibility to air entrainment error

The advantages and disadvantages associated with laser turbidimeters are similar to those listed for conventional turbidimeters. However, the sensitivity of laser turbidimeters to changes in filtrate water quality is significantly greater than that of conventional turbidimeters.

4.3.4 Other Indirect Methods

Other indirect methods of integrity testing include seeding studies, silt density index (SDI) tests, and batch particle count tests. These tests cannot be conducted continuously or on-line, are logistically more difficult to implement than the on-line methods, and require substantially more time to complete. Thus, these tests lack the primary advantages of both the direct and indirect tests. As a result, these tests are not considered practical for integrity monitoring at full-scale water treatment plants.

One recently developed method of indirect integrity testing is a variant of particle counting that involves periodically spiking the membrane feed water with powdered activated carbon (PAC) (van Hoof, et al., 2001). Because the addition of the chemically inert PAC increases the concentration of particles in the feed water, the resulting filtrate will also be higher in particle counts under conditions of compromised integrity. This increase in particulate concentration facilitates detection of an integrity breach by particle counters, particle monitors, or turbidimeters. (The effect of feed water quality and other parameters on the sensitivity of integrity testing methods is further discussion in Chapter 5.) Like other common methods of indirect integrity testing, particle spiking is an on-line test but not continuous. In addition, the more frequently a particle spiking test is conducted, the greater the usage and associated cost of the spiking agent. The particular particle spiking method utilizing PAC as described by van Hoff, et al. (2001) was applied to a UF water treatment plant in Europe. This page intentionally left blank.

5.0   MEMBRANE INTEGRITY AND MICROBIAL RISK

5.1   Driving Force for Integrity Testing

Microfiltration and ultrafiltration membranes have been demonstrated to be effective barriers to particles and microorganisms that are larger than the membrane exclusion characteristic, as discussed in Chapter 3. In addition, it has been shown that even with an integrity breach that is sufficiently small, membrane filtration systems have the ability to achieve pathogen removal above that normally possible with conventional treatment processes. For example, an AWWARF study (Jacangelo, et al., 1997) demonstrated that with one of 22,400 fibers cut, a specific MF membrane was still able to achieve 3.9-log *Giardia* and 4.6-log *Cryptosporidium* removal. However, primacy agencies in general have chosen not to link various degrees of integrity loss with incremental reductions in log removal credit. Instead, primacy agencies typically require any identifiable integrity breach to be promptly addressed, independent of the magnitude of the breach or its particular implications for risk of microbial passage. While a utility may have confidence that its membrane filtration system has an implicit factor of safety for the protection of public health even with a small degree of integrity loss, it is still obligated take steps to correct the problem immediately. One exception to this general approach to membrane regulation has been developed in the state of Wisconsin, which requires membrane filtration plants to correlate degree of integrity loss with reduction in log removal capability. The state then uses this data to establish facility-specific action levels for integrity loss based on the results of regular integrity monitoring. An overview of nationwide state regulatory policies is presented in Chapter 6.

Both direct and indirect test methods are used to monitor membrane integrity and detect defects or breaches that could allow feed water to bypass membrane filtration. Most new membrane filtration systems are factory-equipped with the ability to automatically conduct this test at operator-defined intervals. In some cases, primacy agencies require utilities with membrane filtration systems to conduct a pressure hold test as frequently as every four hours, an interval that corresponds with the turbidity monitoring frequency for conventional media filters. In addition, commonly employed indirect methods, such as particle counting and turbidity measurements, are applied on-line to continuously monitor for water quality changes as a surrogate measure of membrane integrity. These indirect methods can also detect small integrity breaches under certain conditions. Thus, the tools are readily available to identify compromises in the membrane filtration system with a frequency as often as a pressure hold test is conducted, and potentially almost instantaneously depending on the sensitivity of the on-line indirect test methods that are utilized and the magnitude of the breach.

With an obligation to repair any compromise in membrane integrity promptly and the means to quickly detect breaches readily available, the primary driving force for membrane integrity testing has been less related to the microbial risk associated with various levels of integrity loss than on the potential for any microbial risk at all. As a result, the regulatory community has in general directed its efforts toward the minimization of microbial risk by focusing on the immediate detection and elimination of any breach in membrane integrity.

Therefore, the optimization (i.e., maximizing the efficiency and effectiveness) of membrane integrity testing, in terms of the applicability of the various tests, ease of testing, minimization of off-line time, test sensitivity, etc., is of primary importance. This section addresses the factors that affect the optimization of membrane integrity testing, as well as the implications of these factors with respect to the water treatment industry's confidence in the ability of membranes to reliably remove pathogens.

5.2 Integrity Breaches

Most membrane integrity problems result from factory defects (e.g., in the processes of fiber spinning, potting, or sealing) or damage incurred during shipping. These integrity problems may become manifest during normal operation, system pressurization, or backwashing and are likely to be detected shortly after the installation of the membranes. Integrity problems may also be caused by improper maintenance (e.g., failing to properly seal the module, improper chemical cleaning, or careless handling of the membrane) or structural creep of the fibers over the life of the membrane. Chemical degradation may create integrity problems as well, which may result from filtering water outside the recommended pH range, cleaning the membranes with solutions outside the recommended pH range, or the accidental exposure of an oxidant-intolerant membrane to a pre-oxidant or disinfectant used upstream in the treatment process.

Integrity breaches may occur in any of several locations in the membrane module, including the seals, the membrane potting, or in the fibers. In general, there are two types of compromised fibers: broken or punctured. Broken fibers are completely compromised across the entire fiber diameter, while punctured fibers have holes in the fiber wall.

Once compromised fibers have been identified using integrity test methods, they can be individually isolated and taken out of service by inserting specially designed pins or epoxy into one or both ends, depending on whether filtrate is withdrawn or feed is fed from both ends. These pins effectively seal off the damaged fiber. Addressing seal leaks may be a matter of replacing the o-rings, while cracks in the potting or other problems, such as structural defects in the module headpieces which connect a module to the rack, may require factory service or module replacement.

5.3 Factors Affecting Direct Methods

5.3.1 Pressure-Driven Methods

All three of the pressure-driven methods for direct integrity testing – the pressure hold test, the diffusive air flow test, and the bubble point test – are governed by capillary theory as described by the bubble point equation. The bubble point is defined as the gas pressure required to displace liquid from the pores of a fully wetted membrane. The bubble point equation is derived from a balance of static forces on the liquid meniscus in a capillary tube, and is expressed as follows:

$$P = k \cdot \left(\frac{4 \cdot s \cdot \cos q}{D} \right)$$

where: P = bubble point pressure
k = pore shape factor
σ = surface tension of the capillary liquid
θ = liquid-capillary tube contact angle (or the "wetting angle")
D = capillary (or pore) diameter

The bubble point test was originally developed to characterize pore sizes in membranes. When bubbles are first detected at a certain threshold pressure, the bubble point equation can be used to calculate the diameter of the largest pore. As a conservative example, by assuming a water temperature of 20°C (implying a surface tension of 73 dynes/cm), a shape factor of 1 (i.e., a perfectly cylindrical hole), and a wetting angle of 0°, rearranging the variables, and applying the proper conversion factors to yield convenient units, the bubble point equation may be simplified as follows (Cheryan, 1998):

$$D\,(\mu m) = \frac{41.6}{P\,(psig)}$$

Note that the pressure required to displace air from the capillary tube is inversely proportional to the size of the pore. Therefore, the smaller the pore size, the greater the required pressure to force air through the pore. Applying this equation to integrity testing, the smallest size hole in a fiber that can be detected is limited by the maximum rated transmembrane pressure of the membrane. Conservatively assuming that a commercially available membrane would be able to withstand a maximum test pressure of 100 psi (although this will vary from product to product), the smallest size hole that would be able to be detected using the pressure hold or bubble point tests is just over 0.4 µm. A hole this size is near the low threshold of bacteria sizes (~ 0.7 µm) and about an order of magnitude smaller than the smallest protozoan cyst (~ 3 µm).

A typical test pressure range specified by membrane manufacturers for conducting pressure hold tests is approximately 15 – 20 psi, which translates into minimum detectable hole sizes of about 2 – 3 µm. Although the membrane may be completely intact and contain no holes smaller than this range, a pressure-driven test conducted in this range would not be able to demonstrate integrity on a finer scale. While holes smaller than 2 – 3 µm would allow the passage of virus and some bacteria through the membrane, demonstrating integrity to this size pore should indicate the removal of *Giardia* (~ 6 – 20 µm) and *Cryptosporidium* (~ 3 – 8 µm).

Demonstrating integrity to the degree necessary to remove viruses is more problematic. Extending this conservative example, in order to physically demonstrate that a membrane is intact to a degree such that even the largest size virus (~ 0.1 µm) is completely removed, a pressure hold test would have to be conducted at over 400 psi, well-above the pressure rating for any MF and UF membrane in use for water treatment.

Applying the bubble point equation with parameters that may be more typical of commonly used membranes (k = 0.25 and θ = 45°), only about 75 psi would be necessary to detect a breach comparable in size to the largest virus using the pressure hold test; however, a prohibitive

~ 750 psi would be required to detect a breach on the order of the smallest virus (~ 0.01 µm). Conversely, at typical test pressures of 15 – 20 psi, the smallest breach that can be detected is about 0.4 – 0.5 µm, a range well exceeding the size of even the largest virus particles. Thus, at these applied pressures, a successful pressure hold test would provide no indication of whether smaller breaches, still capable of allowing significant virus passage, were present in the membrane module.

The limitations of the pressure-driven integrity test have significant regulatory implications. If the ability to demonstrate continued removal capability on a regular basis via integrity testing is the criterion by which primacy agencies judge whether to grant pathogen removal credit commensurate with the performance specifications of the system, then significant virus removal credit is difficult to justify. Thus, even though challenge studies have demonstrated that UF membranes are capable of removing viruses, without the means to continually, consistently, and practically verify this removal over the course of system operation, primacy agencies may be unwilling to grant virus removal credit. Cheryan (1998) noted this issue in his text, *Ultrafiltration and Microfiltration Handbook*, indicating that the lack of an integrity validation test largely prevents UF membranes from being accepted as "sterilizing filters."

However, the bubble point equation can be used to illustrate why the pressure hold test can be effective for detecting integrity breaches as small as a single cut fiber. Applying the equation with conservative parameters ($k = 1$ and $\theta = 0^o$) to a membrane fiber with a diameter as small as 100 µm demonstrates that a pressure of only 0.4 psi is necessary to demonstrate integrity on the order of a single cut fiber. Thus, at typical test pressures of 15 – 20 psi, a single cut fiber would readily produce a response. However, the inability of integrity testing to detect a hole on the order of 0.1 µm may be a significant factor in the reluctance of state agencies to grant virus removal credit to UF membranes.

The vacuum hold test is variation of the pressure hold test in which a vacuum is applied to the drained side of a fully wetted membrane and the vacuum pressure decay rate monitored. The vacuum hold test is limited to test pressure of -1 atmosphere (-14.7 psi), which corresponds to a minimum detectable breach size of approximately 0.5 µm applying the bubble point equation and typical operating parameters ($k = 0.25$ and $\theta = 45^o$). At this applied vacuum pressure, the vacuum hold test could detect leaks smaller than *Giardia, Cryptosporidium*, and most bacteria, but would not be able to verify integrity in the size range of virus particles.

Another factor limiting the maximum test pressure or vacuum at which a pressure- or vacuum-driven test can be applied is the trans-wall symmetry of the membrane fiber (see Section 2.2.1). For composite membranes, the rate of diffusion through liquid filled pores can be significant, resulting in increased pressure loss during a pressure-driven test that would still be considered indicative of an integral membrane. Homogeneous membranes face a different concern during pressure hold testing. When air is applied to the permeate side it can become trapped in the small pores near the dense outer layer of the membrane and may not be displaced when normal operation is resumed. This effectively reduces the thickness of the dense outer layer, resulting in increased strain on the fiber, potentially resulting in fiber damage. This is less of a concern in composite membranes where the air-water interface is maintained at the outer thin film resulting in less air binding in the membrane pores (Cote, 2001).

5.3.2   Sonic Methods

As a manually applied test, one significant limitation of the sonic sensing analysis is the potential subjectivity of the test when employed to identify very small leaks (i.e., on the order of a pin-sized hole in the fiber wall, or smaller) that may be difficult for an operator to identify. The ability of the test to detect such membrane integrity problems may be dependent the operator's skill in interpreting the sounds transmitted by the sensor.

At its current state of development, the sonic sensing analysis is not employed as a primary means of detecting leaks, but rather as a diagnostic tool for helping to isolate a leak that has already been detected. As a result, optimization of current sonic sensing technology as an integrity monitoring tool does not have significant implications for the minimization of microbial risk.

However, sonic testing techniques may have the potential to be developed into an integrity test method that is direct, on-line, and continuous. An automated sonic test could continually monitor sound waves emanating from the membrane module and compare them to a baseline established on a module that is known to be integral. If the results were to vary significantly from preset baseline parameters, an alarm could provide instant notification. This test would eliminate any subjectivity of current sonic sensing analysis, and, if sufficiently sensitive to very small leaks uniformly throughout the membrane module, it could be used as a first line integrity monitoring tool. The development of such an on-line, continuous sonic integrity testing method is described by Glucina, et al. (1999) and is summarized in Section 4.2.3.

5.4   Factors Affecting Indirect Methods

5.4.1   Common Factors Affecting Indirect Method Sensitivity

Although particle counters, particle monitors, and turbidimeters do not directly test membrane integrity, they are on-line methods which continuously monitor filtrate quality. These methods, if sufficiently sensitive, can be an effective integrity monitoring tool and complement direct integrity testing.

Since each of these methods provides an indication of integrity through excursions in filtrate water quality relative to a baseline value, the sensitivity of each method depends on the impact of the breach on filtrate water quality. Water from a breach will have elevated levels of particles and turbidity; however, these high concentrations will be diluted by the filtrate, potentially to levels that would be indiscernible to indirect monitoring instrumentation. The amount of dilution that occurs is a direct function of the flow and particle concentration from the breach relative to the flow and particle concentration from all intact fibers. The greater the flow and particle concentration from a breach, i.e., the greater the severity of the breach, the more likely an indirect method will be capable of detecting the breach. This link between filtrate water quality and method sensitivity also implies a link between sensitivity and microbial risk, in that higher particle concentrations and/or turbidity imply higher pathogen concentrations.

The following factors impact the flow or particle concentration from a breach, relative to intact fibers, and thus the sensitivity indirect integrity methods:

1) Feed Water Quality: A higher concentration of particles (i.e., pathogens, TSS, turbidity, etc.) in the membrane feed water will result in a greater concentration of particles from an integrity breach. Thus, indirect integrity monitoring instruments are more sensitive to integrity breaches at higher feed water particle concentrations.

2) Mode of Operation: Although mode of operation has been used primarily to indicate whether a membrane filtration system is configured in a dead-end or cross flow pattern, the diversification of proprietary system types and configurations necessitates that a broader definition be used. Thus, for the purposes of this analysis, the two modes of interest are differentiated as: a) those systems that concentrate particulate matter in the bulk feed solution; or b) those systems that do not concentrate particulate matter in the bulk feed solution to an appreciable extent. Two types of systems that concentrate particles in the bulk feed solution are cross-flow systems and vacuum systems operated in the direct mode with feed and bleed.

   The effect of operating mode on instrument sensitivity is illustrated by the example of cross flow operation, in which the concentration of particles/turbidity in the bulk feed solution continuously increases over the course of a filtration cycle (i.e., between backwashes). The 1997 AWWARF study conducted by Jacangelo, et al. demonstrated that this artifact of operating in a cross flow mode could impact the sensitivity of indirect integrity monitoring methods. In this study, the sensitivity of particle counters to a single fiber break was consistently found to increase over the course of a filtration cycle. A similar effect was not observed for the dead-end flow mode of operation, in which particulate matter in the bulk feed solution is not concentrated to an appreciable extent. Thus, the mode of operation can affect the particle concentration from a breach, which in turn affects the sensitivity of the instruments used for indirect integrity monitoring.

3) Location of Fiber Break: For systems that concentrate particulate matter in the bulk feed solution, the particle concentration gradients will increase from the process influent to the process effluent. As a result, a break near the process effluent will result in greater contamination of the filtrate relative to a break near the influent. Consequently, indirect methods are more sensitive to integrity breaches near the process effluent.

4) Number of Fibers per Module: The greater the number of fibers in a given membrane module, the smaller the flow contribution and resulting impact on filtrate quality from a single broken fiber. Consequently, indirect methods are more sensitive to fiber breaks in modules with a smaller number of fibers.

5) Fiber Diameter: The smaller the diameter of a broken membrane fiber, the smaller the flow contribution and resulting impact on filtrate quality from a single broken fiber. Thus, indirect methods are less sensitive to fiber breaks in modules with small diameter fibers.

6) <u>Transmembrane Pressure</u>: As the TMP is increased, the permeation of water through the pores of intact fibers increases, as does the flow from integrity breaches. However, in the majority of cases, an increase in TMP will result in a greater relative increase in the filtrate flow from intact fibers. This will lead to further dilution of particles from the breach, resulting in decreasing indirect method sensitivity with increasing TMP.

7) <u>Membrane Fouling</u>: As the membrane fouls, resistance to water permeation through the pores of intact fibers increases, and the TMP is typically increased to maintain production. This will result in increased flow through broken fibers relative to flow through intact fibers, assuming that foulants are not large enough to plug broken fibers. The increased flow through broken fibers will have a greater impact on filtrate water quality. As a result, indirect methods become more sensitive to integrity breaches as the membrane fouls.

For each application of an indirect integrity monitoring technique, there is a minimum change in water quality resulting from an integrity breach that can be reliably detected. Using a theoretical calculation as applied to two types of proprietary membranes, researchers conducting the 1997 AWWARF study tried to determine the smallest breach, or threshold, that could be detected by three indirect monitoring instruments. The threshold is expressed in terms of the largest number of fibers that can be monitored using an indirect monitoring technique while still being capable of detecting a single fiber break. For both turbidimeters and particle monitors, the threshold was smaller than the number of fibers contained in a single module of one type of membrane, indicating that these devices were ineffective for detecting a single fiber break. For particle counters, on the other hand, it was shown that for this type of membrane one instrument could monitor 29 modules and still detect a single cut fiber. However, for another type of membrane with an order of magnitude more fibers per module, a particle counter would only be able to detect a single cut fiber over two modules. This apparent discrepancy was attributed to the mode of operation. The module with the most fibers was operated in a dead-end mode (i.e., no significant concentration of particles on the feed side), where as the module with fewer fibers was operated in a cross-flow mode (i.e., significant increase in the concentration of particles on the feed side over a filtration cycle). Thus, if it is necessary to detect a single cut fiber over a membrane rack to minimize microbial risk, particle counters may not be an economically feasible means of integrity testing for at least some types of membranes. Furthermore, turbidimeters and particle monitors, which are less sensitive instruments, may be neither a technically nor an economically feasible means of monitoring to this level of integrity.

Although indirect monitoring techniques have sensitivity limitations, there is still utility in the application of these techniques to membrane filtration systems. Due to the current lack of continuous, direct methods of integrity testing for widespread application at MF and UF facilities, indirect methods are the only available means for monitoring system performance between periodic applications of more sensitive direct testing methods. Thus, indirect methods may complement direct integrity testing even if they cannot detect single fiber breaks in most full-scale water treatment plant applications. Also, it is important to note that the dilution effect that makes it difficult to detect small breaches using indirect methods also reduces the impact of these small breaches on filtrate quality and microbial risk.

Some specific issues associated with particle counters and turbidimeters are addressed in Sections 5.4.2 and 5.4.3, respectively.

5.4.2 Particle Counters

One factor endemic to particle counters that hinders the ability of these devices to detect integrity breaches is their susceptibility to false positive readings from bubbles resulting from air that may be entrained during some backwash procedures. The particle count spikes that occur after backwashing may confound the ability of an operator to distinguish backwashing effects from a fiber break for a period of time after the backwash cycle, particularly if other factors have minimized the sensitivity of the particle counters. This potential inability to detect leaks may increase the microbial risk from a regulatory perspective.

However, a prudent monitoring protocol may allow an operator to distinguish fiber breaks from air entrainment error. First, it may be possible to define the periodic particle count profile associated with the backwash cycle and effectively use that profile as a baseline. Adham, et al. (1995) observed that the phantom particles detected following a backwash cycle generally ranged from 0.5 – 1.0 µm, whereas particle counts in the size range of 1.0 – 2.0 µm were most affected by cutting one fiber in a simulated integrity breach. The success of this technique is dependent on the ability of a skilled operator to distinguish the normal backwash profile from aberrations that may occur and is dependent on the magnitude of the backwash profile relative to elevated particle counts caused by an integrity breach. Alternatively, depending on the degree of system automation, the software controlling the particle counters may be programmed to ignore the data spikes attributable to air entrainment during backwashing.

The variety of potential problems associated with particle counters, including air entrainment error, coincidence error, particle shedding error, clogging, instrument variability, and calibration difficulties (as discussed in Section 4.3.1), as well as questions about the sensitivity of the instruments, cast significant uncertainty on the utility, reliability, and practicality of using these devices as a sole means of membrane integrity monitoring. Furthermore, the applicability of particle counters for systems that use air for backwashing or to prevent fouling is a concern. Moreover, there is some doubt regarding the usefulness of particle counters in general throughout the water industry. However, the requirement of some primacy agencies that particle counters be used to monitor membrane filtrate makes the use of the devices an important concern in some states, and a significant factor in efforts to minimize microbial risk through integrity monitoring.

5.4.3 Turbidimeters

Although Adham, et al. (1995) determined that in general conventional turbidimeters are not as sensitive as particle counters (or particle monitors) for detecting integrity problems, a recently developed laser turbidimeter may have the potential to meet or exceed the performance of the other indirect integrity test methods (Banerjee et al., 1999b, Banerjee et al., 2000). Manufacturer specifications indicate that the laser turbidimeter is optimized to measure very low turbidity (i.e., in the 0 – 1 NTU range) and has a twofold increase in sensitivity over conventional turbidimeters, factors which may make the laser turbidimeter well-suited for membrane filtrate

monitoring. Moreover, while a laser turbidimeter is still subject to the same factors that influence the sensitivity of the other indirect monitoring devices, it may not be subject to the various accuracy and precision problems that are endemic to particle counters.

5.5 Regulatory Implications of Integrity Testing

5.5.1 Framework for Minimizing Microbial Risk

As with conventional treatment technologies, the allocation of pathogen removal credit to a membrane filtration system by a primacy agency is driven by the ability of the system to minimize microbial risk. In practical terms, the minimization of microbial risk means demonstrating that the membrane system can adequately remove pathogens and the periodic and/or continual verification that the membrane barrier is intact. Generally, under the current regulatory climate, any identifiable compromise in membrane integrity must be promptly addressed, irrespective of the level of microbial risk represented by the integrity breach. An overview of the approaches adopted by the state regulatory agencies is presented in Chapter 6.

To ensure that microbial risk is minimized, there are three criteria that membrane systems have generally had to satisfy: a theoretical, a practical, and an operational criterion. These are as follows:

1) Classification of Pore Sizes (theoretical criterion): Pore size classification is an important first step in classifying membranes in terms of the microbial removal capabilities, as it serves as a gauge for the size of pathogens that can be removed. Typically, the standard specifications of the membrane manufacturer are accepted and this criterion is tacitly satisfied. However, Cheryan (1998) notes that research has shown that it is common for membrane pores at the upper end of the size distribution to be much larger than the rated size. This is due, at least in part, to the lack of an industry standard for determining and reporting pore size information for membranes. Nevertheless, Cheryan cites additional studies showing that membranes may be capable of removing particles as much as three times smaller than the pore size, and that membranes consistently demonstrate particle removal according to their reported pore sizes when subjected to challenge studies.

2) Demonstration of Particle Removal (practical criterion): Once a pore size classification provides an indication of the exclusion characteristic of a particular type of membrane, microbial challenge studies are conducted to demonstrate this ability. The acceptance of prior challenge studies varies among utilities and regulators, which may require additional demonstration testing as applied to a particular water quality or an additional challenge study conducted under the guidelines of the primacy agency of jurisdiction.

3) Verification of Membrane Integrity (operational criterion): Even after a membrane has been certified by regulators and installed, periodic integrity testing is necessary to confirm that there are no compromises that would jeopardize the allocated pathogen removal credits.

5.5.2 Implications of Current Integrity Test Methods

Integrity testing is a critical factor in ensuring the minimization of microbial risk. Without methods to determine whether or not a membrane is integral, there would be no operational means to verify that a membrane system is continually removing pathogens according to its rated ability. However, both the direct and indirect methods of integrity testing have limitations that inhibit confidence in their ability to detect integrity problems and which must be considered in the overall context of risk management. Pressure-driven and manual sonic tests are not continuous monitoring methods. Furthermore, the pressure-driven tests are not on-line methods, and the more frequently they are conducted the greater the impact on water production. While indirect methods are continuous and on-line, they are less sensitive and some instruments are subject to errors affecting accuracy and/or precision. And although pressure-driven tests (i.e., those based on bubble point theory) are more sensitive than the indirect methods, both share an inability to detect very small leaks that have implications for microbial risk assessment.

While Adham, et al. (1995) demonstrated that both the pressure hold test and the various indirect methods (under certain conditions) have the ability to detect holes as small as 600 μm in a single module, an examination of the bubble point equation illustrates that the pressure hold test, as typically applied to pressurized systems, can detect integrity breaches on the order of about 0.5 μm. The ability of the pressure hold test to detect much smaller holes in these systems is limited only by the maximum rated TMP of the membranes. It is largely this limitation – the inability of membranes to be tested at pressures that would allow breaches smaller than 0.1 μm to be detected – that prevents UF from receiving significant virus removal credit. The vacuum hold test is similarly limited in its ability to detect breaches smaller than 0.5 μm since the maximum test pressure at which the vacuum test can be applied is –15 psi.

Similarly, indirect integrity monitoring techniques lack the ability to characterize breaches in the size range of viruses. Turbidimeters and particle monitors lack the ability to characterize the size range of particles that are detected, while particle counters are not widely used to measure the concentration of particles in the 0.01 μm to 0.1 μm range. However, particle counters are commonly used to measure the concentration of particles in the 1 μm to 10 μm size range and larger. Thus, particle counters could be used to monitor for breaches in integrity that could pass particles in the size range of *Cryptosporidium* oocysts and *Giardia* cysts, but sensitivity limitations of this technology may require a significant number of particle counters to detect a small number of broken fibers in a rack of modules. This may preclude the use of indirect monitoring techniques as the only means of integrity testing when removal credits in excess of those granted to conventional media filters are considered. Nonetheless, indirect methods may serve as a useful means of continuous monitoring for larger membrane breaches between the periodic application of more sensitive direct integrity tests.

5.5.3 Implications of Potential Future Integrity Test Methods

The development of an on-line, continuous, direct method of integrity testing could have a substantial impact on the minimization of microbial risk with respect to membrane filtration. Such a test, if sensitive enough, could facilitate the allocation of significant virus removal credit for UF and perhaps additional *Giardia* and *Cryptosporidium* credit for both MF and UF.

However, even an increase in pathogen removal credits for membrane filtration is unlikely to shift the long-standing paradigm of multiple barrier protection. The multiple barrier concept is grounded more in the desire for reliable and consistent treatment rather than a means of compensating for inefficient treatment. It is important to note that improved methods of integrity testing will not enhance the ability of membranes to remove pathogens, but instead provide a means of verifying removal capabilities that are demonstrated during challenge testing. Thus, improved integrity monitoring may justify increased removal credit, but would not completely compensate or eliminate the need for multiple barriers through the combination of physical removal and chemical disinfection.

As new integrity test methods are developed with the potential to increase pathogen removal credits for membranes, it is important that a standard framework be developed for integrity testing. Although the idiosyncrasies associated with each proprietary membrane filtration system may complicate development of this framework, integrity testing standards would lend some consistency to the process of allocating pathogen removal credits and improve the precision with which integrity tests are conducted and interpreted.

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6.0 REGULATORY APPROACHES TO MICROFILTRATION AND ULTRAFILTRATION

6.1 Introduction

As discussed in Section 2.1.1, the current regulation that requires the removal/inactivation of pathogens during drinking water treatment is the SWTR. This rule primarily considers conventional filtration plants and, to a lesser extent, other media filtration technologies such as direct, slow sand, and diatomaceous earth filtration. All other filtration technologies are considered alternate filtration technologies and are not explicitly addressed in the SWTR. Guidance for AFT is provided in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (EPA, 1990), also referred to as the SWTR Guidance Manual.

In general, AFTs can be used if the utility demonstrates that the technology, in combination with disinfection, achieves at least 3-log *Giardia* and 4-log virus removal/inactivation. Utilities are typically required to demonstrate the ability of AFT to remove pathogens through pilot studies. However, the SWTR Guidance Manual does make an exception to the pilot testing requirement for RO, since the technology was considered effective for removal of *Giardia* and viruses by the authors of the manual. The other AFTs that were specifically addressed in this manual include package plants and cartridge filtration units. Since the application of MF/UF to surface waters for pathogen removal was still a novel concept at the time the SWTR was developed, these processes were not mentioned in the rule or the SWTR Guidance Manual.

As discussed in Section 2.2, MF/UF technology has experienced a phenomenal rate of growth over the past decade, and upcoming regulations that specifically address *Cryptosporidium* will continue to drive this growth. As a result, many states had to develop an approach for permitting and regulating membrane filtration technologies. The only formal guidance available from EPA was the AFT provision of the SWTR Guidance Manual, which does not adequately address the removal capabilities and specific requirements of MF/UF. Some states have chosen to treat MF/UF as AFT as defined under the SWTR, while other states have developed procedures and requirements that are specific to membrane filtration technology. This disparity has resulted in a wide range of regulatory requirements across the states, which has made it more challenging to implement this technology in a consistent manner.

Although there is variability among state regulatory approaches, there are some common elements such as, demonstration of treatment efficacy, determination of removal credits, and integrity monitoring requirements. Demonstration of treatment efficiency is typically achieved through an initial process evaluation, site specific pilot testing, or full-scale testing. An initial product evaluation may include an analysis of existing performance data or certification testing. Pilot testing is the most common method of demonstrating treatment efficiency, and is recommended by the SWTR Guidance Manual for AFT. In some cases, full-scale demonstration testing is required by the primacy agency, and typically involves increased monitoring to verify that the process performs as expected. These three approaches for demonstrating treatment

efficacy are not mutually exclusive, and many primacy agencies use these tools in combination during the permitting process.

The removal credits awarded to a membrane filtration process are based on a variety of factors, including total removal/inactivation requirements, multiple barrier requirements, experience with the technology, and results of demonstration testing. As discussed in Chapter 3, most MF/UF challenge studies demonstrate very high removals of protozoan cysts and cyst sized particles, often to below detection limits. However, state primacy agencies do not award these high removal credits due to other factors considered when making the determination. In many cases, states require a minimum level of chemical inactivation regardless of the demonstrated removal efficiency of the process in order to enforce multiple barrier treatment. Also, states rarely grant removal credits in excess of the federal requirements for removal/inactivation of pathogens.

Integrity monitoring, using methods discussed in Chapter 4, is typically required to ensure some level of process performance. Integrity monitoring requirements for membrane filtration range from the turbidity monitoring requirements of the SWTR to comprehensive monitoring programs that utilize a variety of integrity testing techniques.

This chapter provides an overview of the state regulatory requirements for membrane filtration at the time of this report. A summary of the various regulatory approaches for MF/UF is presented, followed by a discussion of the key components of these approaches.

6.2 Summary of State Regulatory Approaches

Figure 10, presented in Section 2.2.2.4, shows the 27 states that have MF/UF plants treating surface waters or ground water under the direct influence of surface water at the time of this report. These states were contacted regarding their approach for permitting membrane filtration technologies. Ohio and Maine were also contacted since these states have begun to develop a process for permitting this technology, although they did not have any operating MF/UF systems at the time. The remaining 21 states were not contacted since there were no MF/UF plants operating in these states and no information was available regarding their approach towards permitting membrane filtration.

Table 14 presents a summary of the state regulatory requirements for membrane filtration. The table shows the number of MF/UF plants in the state; the maximum removal credits awarded for *Giardia*, viruses, and *Cryptosporidium*; minimum chemical inactivation requirements; pilot testing requirements; and integrity monitoring requirements. This information represents the regulatory status of membrane filtration at the time of this report, and many of the primacy agencies indicated that their process is evolving as more experience with this relatively new technology is developed. Additional information on the policies of a particular state may be obtained by contacting a representative from that state's drinking water program. A list of state drinking water programs can be found on the Association of State Drinking Water Administrators (ASDWA) homepage (*www.asdwa.org*).

Table 14. Summary of State Primacy Agency Regulatory Requirements

State	# MF/UF Plants	Maximum Removal Credits[1]			Minimum Chemical Inactivation Requirements	Pilot Testing Requirements	Integrity Monitoring Requirements[2]
		Giardia	*Virus*	*Crypto*			
AK	8	No specific credits granted			0.5-log *Giardia* inactivation	Some cases	Not required
AZ	2	3	0.5 MF 4 UF	NA	Balance of SWTR requirements	Not required	Varies – monitoring requirements are linked to removal credits
CA[3]	28	4	0.5 MF 4 UF	4	Maximum of 0.5-log *Giardia* or 2-log virus inactivation	Some cases	Varies – may include PC/PM and/or physical integrity testing
CO	8	No specific credits granted			0.5-log *Giardia* inactivation	Not required	Continuous – may include PC/PM or pressure drop
CT	2	2.5	0	NA	Balance of SWTR requirements	All cases	Not required
FL	1	2.5	0	NA	Balance of SWTR requirements	All cases	Not required
HI[4]	7	1	0	NA	Balance of SWTR requirements	Some cases	Not required
ID[5]	4	3	0	NA	Balance of SWTR requirements	Some cases	Periodic – physical integrity test
KS	2	No specific credits granted			Balance of SWTR requirements	Some cases	Continuous – pressure drop Periodic – physical integrity test
ME	0	1.5	0	NA	Balance of SWTR requirements	All cases	Not required
MA	3	2	0	2	Balance of SWTR requirements	All cases	Not required
MI[6]	8	3	0	NA	Balance of SWTR requirements	Some cases	Continuous – PC/PM Periodic – physical integrity test
MO	1	2.5	0	NA	Balance of SWTR requirements	All cases	Not required
NV	4	2.5	0	NA	Balance of SWTR requirements	All cases	Not required
NJ	1	No specific credits granted			0.5-log *Giardia* inactivation	All cases	Periodic – physical integrity test
NY	2	No specific credits granted			Balance of SWTR requirements	Some cases	Not required
NC	2	No specific credits granted			0.5-log *Giardia* inactivation	Some cases	Periodic – physical integrity test
OH	0	2.5	0	NA	Balance of SWTR requirements	All cases	Continuous – PC/PM Periodic – physical integrity test

Table 14. Summary of State Primacy Agency Regulatory Requirements (continued)

State	# MF/UF Plants	Maximum Removal Credits[1]			Minimum Chemical Inactivation Requirements	Pilot Testing Requirements	Integrity Monitoring Requirements[2]
		Giardia	Virus	*Crypto*			
OK	2	No specific credits granted			Balance of SWTR requirements	All cases	Not required
OR	3	2.5	0	NA	Balance of SWTR requirements	Not required	Not required
PA[7]	4	3	4 UF	2	Balance of SWTR requirements	All cases	Continuous – PC/PM Periodic – physical integrity test
SD	2	2.5	0	NA	Balance of SWTR requirements	All cases	Not required
TN	1	3	0	2	Balance of SWTR requirements	Some cases	Not required
TX	5	3	0	2	Balance of SWTR requirements	All cases	Continuous – PC/PM/LNTU Periodic – physical integrity test
UT	2	3	0.5	NA	Balance of SWTR requirements	Some cases	Continuous – PC/PM Periodic – physical integrity test
VA	12	2	0 MF 1 UF	NA	Balance of SWTR requirements	Some cases	Continuous – PC/PM Periodic – physical integrity test
WA	2	3	0 MF 4 UF	3	0.5-log *Giardia* inactivation	Some cases	Periodic – physical integrity test every 4 hours
WI	4	3	0 MF 3 UF	3	Balance of SWTR requirements	All cases	Periodic – physical integrity test every 8 hours
WY	1	No specific credits granted			Balance of SWTR requirements	Some cases	Not required

1. These are the maximum removal credits awarded to a membrane filtration process, and lower credits may be awarded in some cases.
2. All plants are required to monitor turbidity under the SWTR – additional integrity monitoring requirements are shown in this table.
3. California awards removal credits based on the results of microbial/particulate challenge studies for specific products.
4. Hawaii is considering increasing the *Giardia* removal credit to 3-log. A plant in HI indicated that it was awarded 2.5-log credit for *Giardia* and *Crypto*.
5. A plant in Idaho indicated that it was awarded 3-log credit for *Giardia* and *Crypto* and 4-log credit for virus.
6. A plant in Michigan indicated that it was awarded 3.5-log credit for viruses.
7. Requirements for Pennsylvania are based on the application of UF to finished water in Pittsburgh. Different requirements may apply to MF/UF applications treating raw or pretreated surface waters, but information was not available from these sites.

The maximum removal credits awarded to membrane filtration processes are shown for each state in Table 14, although site specific factors may lead some states to award lower credits than those listed. The removal credits reported in Table 14 are applicable to both MF and UF processes, except for viruses, where different removal credits may be awarded for the two technologies. Eight of the 29 states do not award specific removal credits to membrane filtration processes; rather the state evaluates the entire treatment plant as a whole to determine whether or not the combined barriers of removal and disinfection meet the SWTR requirements.

The *Giardia* and *Cryptosporidium* log removal credits granted to membrane filtration are summarized in Figure 14. In general, states did not make a distinction between MF and UF processes when determining removal credits for these pathogens. This is consistent with the fact that the exclusion characteristic of both MF and UF membranes is small enough to provide removal to below the detection limits of these organisms. Of the 21 states that have awarded specific removal credits to MF/UF, California awards up to 4-log *Giardia* credit, nine states award up to 3-log *Giardia* credit, seven states award up to 2.5-log *Giardia* credit and four states award 2-log *Giardia* credit or less. Only seven states have awarded specific removal credit for *Cryptosporidium*, four of which grant the 2-log *Cryptosporidium* removal credit required by the recently promulgated IESWTR and proposed LT1ESWTR (63 FR 69477, 65 FR 19045). Two states grant up to 3-log removal credit and California grants up to 4-log removal credit for *Cryptosporidium*.

The virus log removal credits granted to membrane filtration are summarized in Figure 15, and unlike the case for *Giardia* and *Cryptosporidium* removal, some states do make a distinction between MF and UF processes for the case of virus removal. This approach is consistent with the results of several studies, some of which are summarized in Chapter 3, which demonstrate virus removal to below detection limits by most membrane processes classified as UF, compared to the variable removals observed for membrane processes classified as MF. Virus removal credits awarded to UF processes range from 0-log to 4-log, while the maximum virus removal credit awarded to a MF process is only 0.5-log. The majority of states did not grant any virus removal credit to either MF or UF processes. One of the primary reasons that full virus removal credit is not typically granted is the inability of integrity monitoring techniques to detect breaches or pores that could pass viruses, as discussed in Chapter 5. Also, several states indicated that other treatment requirements result in disinfection levels that exceed the 4-log virus inactivation requirement.

The removal credits shown in Table 14 do not meet the 3-log *Giardia* and 4-log virus removal/inactivation requirements of the SWTR, with the possible exception of UF applications in California and Arizona. In cases where full removal credits are not awarded, chemical inactivation would be required to make up the balance of the SWTR requirements. Furthermore, Alaska, California, Colorado, New Jersey, North Carolina, and Washington have minimum chemical inactivation requirements regardless of the removal credits awarded to any process. The end result is that almost every membrane filtration plant operating in these 29 states is required to provide some level of primary disinfection with chemical inactivation, which is consistent with the multiple barrier approach to drinking water treatment.
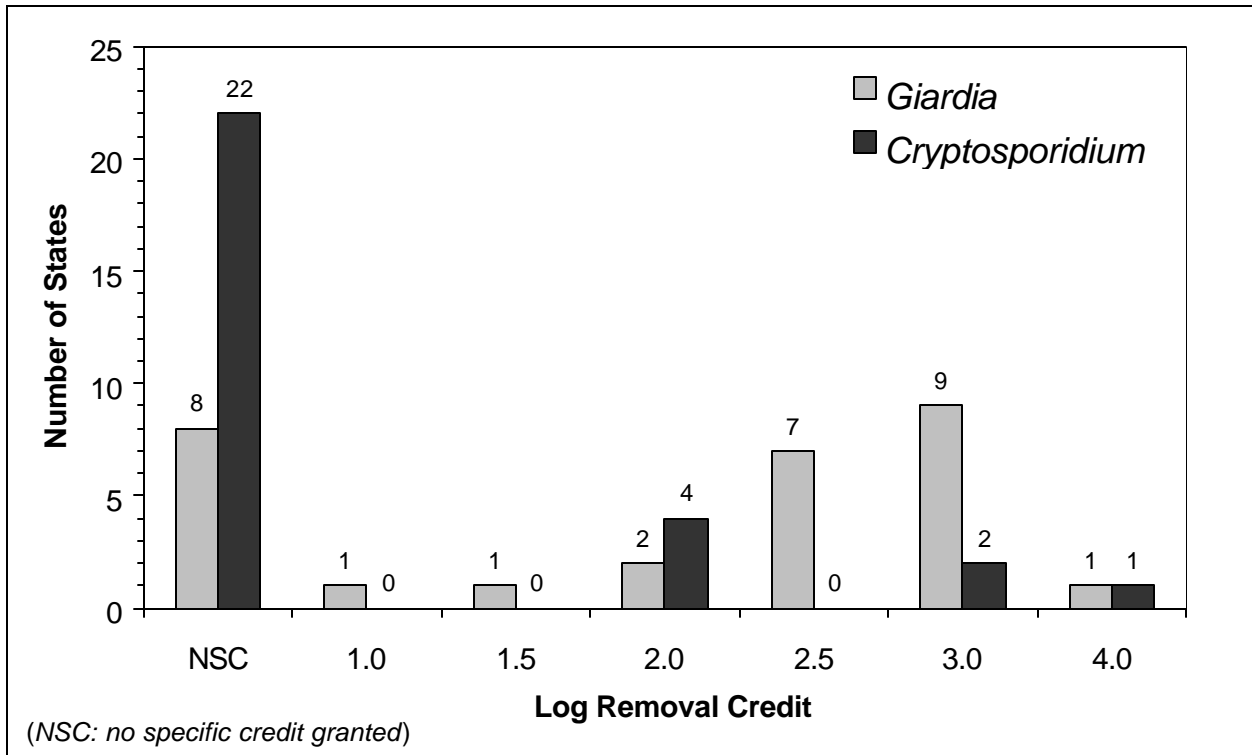
Figure 14. Maximum Log Removal Credits for *Giardia* and *Cryptosporidium* for 29 States
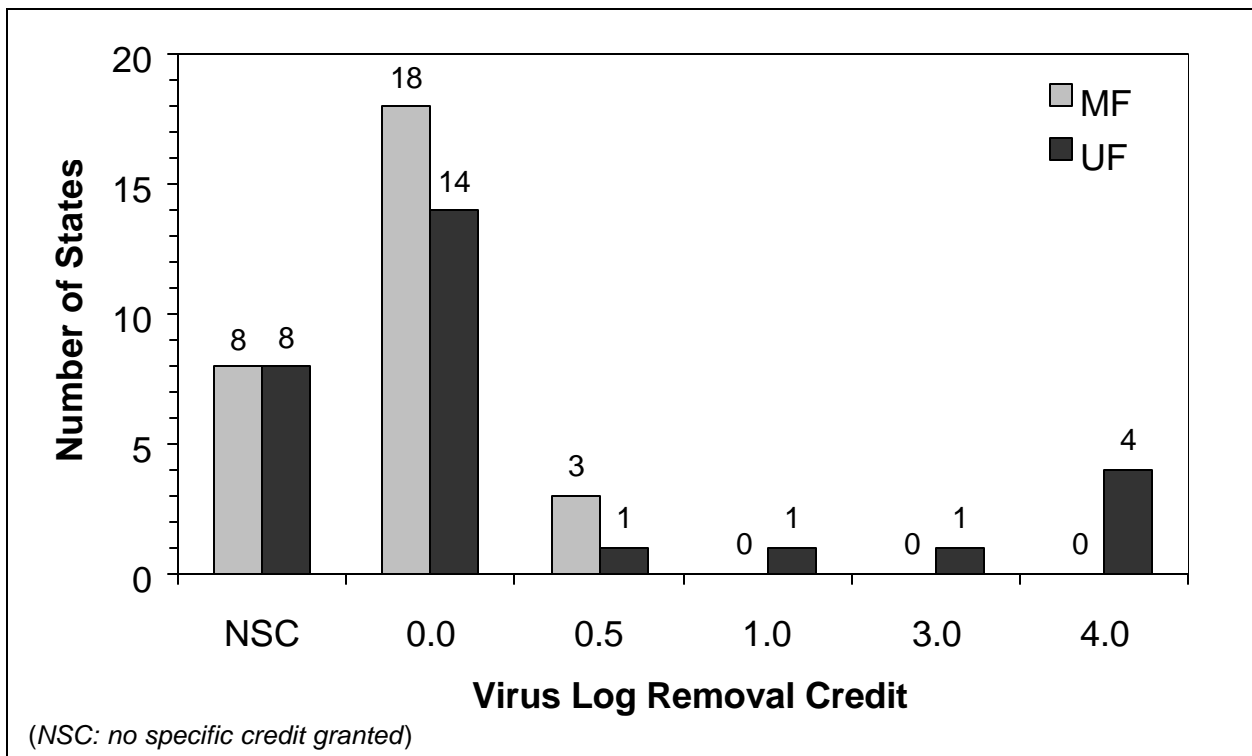
Figure 15. Maximum Virus Log Removal Credits for MF and UF for 29 States

Pilot testing requirements have been consolidated into three categories in Table 14: not required, required in some cases, or required in all cases. Thirteen of the 29 states (45%) require pilot testing in all cases, 13 states (45%) require it in some cases and 3 states (10%) do not require pilot testing for membrane filtration. States that do not require pilot testing or require testing in only some cases typically offer alternatives for demonstrating process performance in lieu of pilot studies, such as prior tests conducted at another site or full-scale demonstration testing.

Integrity testing requirements are summarized in Table 14 using five categories: not required, continuous testing, periodic testing, both continuous and periodic testing, or variable requirements. Figure 16 summarizes the integrity monitoring requirements for the 29 states contacted during this project. Continuous monitoring typically uses one of the following methods: particle counting (PC), particle monitoring (PM), laser turbidimetry (LNTU), or pressure drop across the membrane, while periodic monitoring typically consists of physical integrity testing using the pressure hold test. One state requires only continuous monitoring, five states require only periodic, physical integrity testing, seven states require both continuous and periodic monitoring, and two states determine the integrity monitoring requirements on a case-by-case basis. Fourteen states do not require any type of integrity monitoring beyond the turbidity monitoring required under the SWTR.
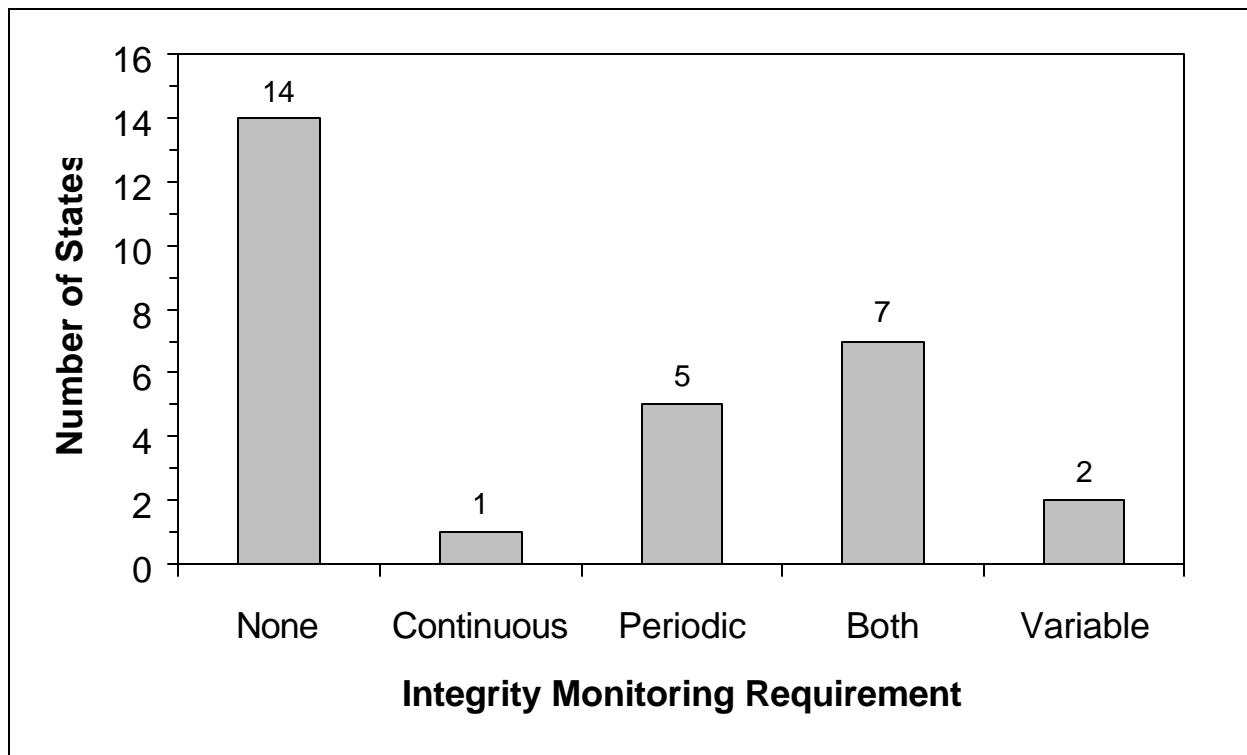
Figure 16. MF/UF Integrity Monitoring Requirements for 29 states

In this summary, the components of state regulatory approaches for membrane filtration have been discussed independently; however, it is important to consider how these components work together to establish a comprehensive framework for this technology. For example, states that require utilities to develop an integrity monitoring program were found to be more likely to award higher removal credits to a membrane filtration process. The use of sensitive integrity monitoring techniques provides increased confidence in the membrane barrier, thus reducing the need to rely entirely on chemical inactivation as a safeguard. In the following sections, these components will be discussed in greater detail, including specific examples that demonstrate the synergy between the various components.

6.3   Initial Product Evaluation

Due to the proprietary nature of membrane filtration systems and limited experience with the technology, most states require MF/UF systems to undergo an initial product evaluation prior to design and construction of a facility. A product evaluation can range from a desktop analysis of manufacturer specifications and data from previous studies to a testing and certification program administered by the state or a third party.

At a minimum, most states require that chemicals and materials that come in contact with drinking water meet National Sanitation Foundation (NSF) Standards 60 and 61, respectively. These standards are in place to ensure that harmful chemicals are not introduced into drinking water through either direct addition or leaching. Both membrane materials and chemical cleaning agents are covered under these standards. Many membrane systems and proprietary cleaning chemicals are certified under the appropriate NSF standard. However, some states have reported problems due to a lack of certification for a specific product and had to resort to alternate criteria to verify that the material in question met the intent of the NSF standards.

As part of the initial product evaluation, most states require manufacturers to supply data for the proposed membrane system, including system specifications, basic design information, pore size distribution, and absolute/nominal pore size cutoff. A few states require data beyond this basic information. For example, Virginia requires certification that the membrane has an absolute cutoff of 1 μm or less, where the absolute cutoff is demonstrated by 7-log removal. As another example, Wisconsin requires manufacturers to supply theoretical calculations relating the results of integrity testing to a known number of broken fibers. As discussed in Chapter 5, an understanding of this fundamental relationship is necessary to establish control limits for integrity test results that are based on risk of microbial passage.

In addition to manufacturer information, data from previous demonstration studies may be used during initial product evaluation, and some states will use this information in lieu of site specific pilot studies or certification studies. For example, Tennessee used existing data to permit the first installation in the state without pilot testing. During initial product evaluation, Arizona has considered removal credits awarded to a specific membrane filtration process by other state agencies. Also, a number of states used information developed by California and Virginia to support permitting of the first installations in their respective states.

Some states require products to be certified within the state or by an independent third party before a system can be approved for use in the state. The objective of certification testing is to demonstrate the ability of a membrane process to remove pathogens such as *Giardia*, *Cryptosporidium*, and viruses. This is typically accomplished through microbial or particulate challenge studies. Additionally, fiber-cutting studies may be performed during certification testing to evaluate the ability of integrity monitoring procedures to detect a failure.

There are a variety of general certification programs used by various state agencies. Both Alaska and Idaho require demonstration of *Giardia* removal by membrane filtration through third party testing according to the Western States Protocol (Bruce Barrett & Associates, 1992). Wisconsin requires bench-scale testing to demonstrate pathogen removal for each proprietary membrane system used in the state. In some cases, states will allow a pilot study conducted at the first installation in the state to be used for the purpose of certification. For example, manufacturers have used pilot studies conducted at the first installations in California, Virginia, and Texas for the purpose of obtaining certification within each respective state, in addition to meeting the requirement to perform site specific studies. Some states that have just started to address this technology are requiring all utilities to conduct site specific pilot tests to demonstrate pathogen removal, effectively rendering these tests certification studies.

In addition to state specific certification programs, there are independent, third party certification programs. A national certification program is attractive since it provides a standard, transparent testing program that can be used by all manufacturers, regulatory agencies and utilities for the purpose of process certification. The NSF ETV program is an example of a national program that tests membrane filtration processes according to a standard protocol. For membrane processes, the NSF ETV program evaluates removal of *Giardia* cysts and *Cryptosporidium* oocysts through challenge studies. The results are published in a report and made available to stakeholders and other interested parties. The LT1ESWTR (IV, A, 1, a, ii) suggests the NSF ETV program as a potential means of verifying the performance of membrane technology (65 FR 19045).

Some states have indicated that they would consider using NSF ETV certification to meet the requirements of their own certification program or pilot testing requirements. Use of NSF ETV results in lieu of site specific pilot testing is especially attractive for small systems that may find MF/UF technologies cost prohibitive with the added expense of an extended pilot study. However, a few states have indicated that they may not be willing to rely solely upon NSF ETV certification for process approval. One state specifically expressed a concern over the role that manufacturers have played in the development of acceptance criteria for NSF ETV testing. Furthermore, NSF ETV testing does not replace the need for site specific pilot testing conducted to develop design and operational criteria as well as demonstrate the economic feasibility of implementing the technology. Pilot testing conducted for this purpose is discussed in the following section.

6.4 Pilot Testing Requirements

As discussed in Section 6.2, 26 of the 29 states contacted during this project require pilot testing in at least some cases. The purpose of pilot testing varies from state to state, but in general the objectives of testing can be divided into two broad categories: testing to demonstrate pathogen removal or testing to assess site specific performance of the MF/UF system. The former objective is typically associated with certification testing, and many states that require demonstration of pathogen removal during pilot testing use these results for the purpose of certification or determining removal credits. For example, pilot testing at some of the first installations in California, Virginia, and Texas were used for the purpose of product certification. States that require pilot testing to assess site specific performance are more concerned with process feasibility and system operation. Some states require certification testing of proprietary systems as well as site specific pilot testing to demonstrate process feasibility.

Most pilot testing required by state agencies is conducted for the purpose of evaluating site specific design and operational issues. These issues may include the determination of pretreatment requirements to control fouling, acceptable fluxes, and cleaning intervals and efficiencies. For example, Texas uses pilot testing to determine the adequate level of pretreatment to ensure acceptable productivity under a range of influent water quality conditions. Several states use the results of pilot testing to establish constraints on these operating parameters. At some of the early MF installations in California, the state established a TMP that triggered chemical cleaning, treating TMP analogous to headloss in a media filter. California also uses pilot testing to establish the maximum flux at which a specific product can be operated at full-scale. States that use pilot study results to establish operational criteria for MF/UF typically provide utilities with the option to conduct additional testing to demonstrate that the process can safely operate outside of the previously established operational criteria.

Thirteen states contacted during this project require pilot testing in all cases. Many of these states treat MF/UF as AFT as defined in the SWTR Guidance Manual which recommends pilot testing these processes (EPA, 1990). However, some states with a more progressive view of the technology also require pilot testing in all cases. For example, Texas requires pilot testing to gather critical process design data, and Wisconsin requires testing to further demonstrate particle removal and determine full-scale operating parameters. Also, there are at least two states, New Jersey and Ohio, which require all new drinking water treatment facilities to be pilot tested regardless of the technology being implemented.

Thirteen states require pilot testing in only some cases. In general, these states require new products to be piloted at least once in the state, and after the technology has been demonstrated, other utilities in the state using the same technology may not be required to conduct pilot studies. States such as California, Virginia, and Hawaii that have been dealing with membrane filtration for several years initially required all utilities installing new membrane filtration facilities to conduct pilot testing prior to construction; however, as these states gained experience with this technology, the pilot testing requirements were relaxed. Under certain conditions, all three of these states may waive the pilot testing requirement if the membrane system under consideration has already been tested in the state. States with fewer installations have adopted a similar philosophy to the pilot testing requirement. For example, Kansas, Idaho, and Michigan require

the first installation of a given proprietary system to be pilot tested but may waive the pilot testing requirement for subsequent installations using the same technology.

Some states offer alternatives to pilot testing for the purpose of verifying system performance. Alaska and Washington allow full-scale testing to be used for the purpose of process demonstration. Although, in the case of Washington, full-scale testing has historically been limited to very small systems proposing to install bag or cartridge filtration where the size of the pilot system was comparable to the size of the full-scale plant. Virginia has a mandatory, 30-day shakedown period during which increased monitoring is required, and this full-scale evaluation period may be used in lieu of pilot testing in some cases. Arizona does not require pilot testing, but does require plants to go through a startup phase during which increased monitoring and increased chemical disinfection are required.

Only three states do not require pilot testing of membrane filtration processes – Arizona, Colorado, and Oregon. These states cited two primary reasons for not requiring pilot studies: the large amount of existing data demonstrating effective pathogen removal by MF/UF, and the fact that many utilities will conduct pilot testing to develop design information and bidding criteria regardless of the state requirements. In fact, most utilities in states without a pilot testing requirement did perform pilot studies for use in membrane procurement and system design. The risk of economic failure of the system, given the cost of the technology, drives the decision to conduct pilot studies as opposed to regulatory requirements.

6.5   Determination of Removal Credits

As discussed in Chapter 3, there is a substantial amount of data demonstrating that MF/UF membranes can achieve pathogen removal to below detection limits if the exclusion characteristic of the membrane is smaller than the size of the target organism, assuming an integral membrane system. Much of this data was obtained from bench- or pilot-scale microbial challenge studies in which seeded concentrations of microorganisms in the membrane feed were much higher than typical pathogen concentrations in surface waters. The high levels of seeded organisms result in log removals as high as 5-, 6- and 7-log. Researchers have observed that log removal of pathogens by an integral membrane process is a function of the concentration of organisms in the influent (Jacangelo, et al., 1997). In a similar manner, the use of seeded surrogates such as particles or indigenous spores results in high log removals since the concentrations of these surrogates are higher than naturally occurring pathogen levels.

The log removal credits awarded by state agencies, summarized in Section 6.2, are less than the log removals observed during pathogen challenge studies. Many states have adopted a conservative approach to awarding removal credit to provide a factor of safety on the process. However, the most common reason for this approach is the reluctance of most state agencies to award removal credits beyond the federal SWTR requirements of 3-log *Giardia* and 4-log virus removal/inactivation to any technology.

Under the federal SWTR, a well operated conventional treatment plant that meets the turbidity requirements of the rule may receive up to 2.5-log *Giardia* and 2-log virus removal credit. The remaining 0.5-log *Giardia* and 2-log virus credit must be achieved through chemical

disinfection, and some states award less than the suggested removal credit to conventional filtration and require higher levels of disinfection. Removal credits are awarded in this manner to enforce the long-standing practice of multiple barrier protection through a physical barrier and a disinfection barrier. The physical treatment barrier is provided by the combination of coagulation, sedimentation, and filtration. The disinfection barrier is provided through the application of chemical disinfectants or potentially ultraviolet irradiation.

Relative to the benchmark of 2.5-log *Giardia* removal credit for conventional treatment, Figure 14 indicates that 10 states treat MF/UF as a superior barrier to pathogens and award up to 4-log *Giardia* removal credit. Seven states award up to 2.5-log removal credit, essentially treating membrane filtration as equivalent to conventional filtration with respect to pathogen removal. Finally, four states (Hawaii, Maine, Massachusetts, and Virginia) award less than 2.5-log removal credit to MF/UF, although there are special circumstances in each case. Hawaii's initial experience with membrane filtration dealt with unfiltered systems that were required to install filtration technology. These utilities had more than 3-log *Giardia* disinfection capacity which allowed the state to be conservative and grant only 1-log of *Giardia* removal credit to MF/UF; however, the state is considering increasing the credit to 3-log. Maine does not have any full-scale MF/UF plants, and currently treats MF/UF as an AFT along with bag and cartridge filtration, which are granted 1.5-log *Giardia* removal credit. Virginia, which was one of the first states to permit membrane filtration processes, grants 2-log *Giardia* removal credit to MF/UF but is in the process of revising the requirements for membrane plants and may increase the removal credits. Eight states with operating MF/UF facilities do not award specific removal credits to membrane filtration, but rather evaluate all treatment barriers as a system to determine whether or not the SWTR requirements are met.

An evaluation of the maximum removal credits listed in Table 14 shows that currently only two states, Arizona and California, would potentially award all removal credits required under the SWTR to an UF process. However, California does require some level of chemical inactivation regardless of the removal credit awarded to the process. (The Pittsburgh plant in Pennsylvania was also awarded full removal credits for the IESWTR; however, this is a unique application in that UF is being used to re-treat finished water.) In all other cases, states require MF/UF plants to provide at least enough chemical disinfection to meet the balance of the SWTR requirements. This typically amounts to 4-log virus inactivation and/or 0.5-log *Giardia* inactivation, but is as high as 2-log *Giardia* inactivation in Hawaii. Furthermore, Alaska, California, Colorado, New Jersey, North Carolina, and Washington require a minimum level of chemical inactivation regardless of the technology used or the associated removal credits. In some cases, the primacy agencies in these states may grant the complete 3-log removal credit for *Giardia*, yet may still require the plant to provide some level of *Giardia* inactivation. For states with a minimum inactivation requirement, the minimum level is typically 0.5-log of *Giardia* inactivation, which will provide in excess of 4-log virus inactivation when free chlorine is used as the disinfectant. Other minimum inactivation requirements that have been implemented, or are under consideration by state agencies, include 0.25-log for *Giardia* and 2- to 4-log for virus.

These minimum disinfection requirements impact the use of MF and UF as compliance technologies for the DBP regulations. In cases where membrane filtration is awarded most or all of the required removal credit, the plant may be able to reduce free chlorine contact time to meet

the DBP MCLs. However, when a high post-filtration contact time is necessary to meet disinfection requirements, significant levels of DBPs can form, limiting the potential of MF/UF as a DBP control strategy. Many researchers suggest that some disinfection after MF/UF is necessary to control bacterial regrowth on the filtrate side of the membrane (AWWA, 1999). However, the different inactivation requirements of state agencies demonstrate the range of opinions with respect to the level of disinfection necessary after membrane filtration, and in a more general sense, how the multiple barrier concept applies to membrane filtration.

The manner in which primacy agencies assign removal credits also varies from state to state. Some states will assign the same removal credits to all membrane filtration process, while others will assign the same removal credits to all plants using a specific proprietary system. However, a number of states make case-by-case determinations regarding removal credits, regardless of whether or not the system is being used at another plant in the state. These removal credits are often based on the results of microbial or particulate challenge studies; however, since removal to below detection limits is typically observed in these studies, most MF/UF plants in the state end up receiving the same or similar credits. A few states consider additional factors when determining removal credits. For example, Arizona will award higher removal credits to utilities that use more sensitive and reliable integrity monitoring procedures relative to those that rely on turbidity monitoring. In at least one case, California considered operating parameters when assigning removal credits and reduced the virus removal credit when the plant elected to operate at a higher flux. Although there are exceptions, by far the general practice has been to award partial removal credits to MF/UF and require plants to make up the balance of the SWTR requirements through inactivation.

As discussed in Chapter 2, the IESWTR will require most surface water plants to achieve 2-log *Cryptosporidium* removal, and the LT2ESWTR could require plants with high influent *Cryptosporidium* concentrations to achieve up to 5.5-log *Cryptosporidium* removal/inactivation. Figure 14 shows that only seven of the 29 states have awarded removal credits to membrane filtration for *Cryptosporidium* at this time. Massachusetts, Pennsylvania, Tennessee, and Texas have awarded the 2-log credit required under the IESWTR to membrane filtration; Wisconsin and Washington have granted 3-log credit; and California has granted up to 4-log credit. The Agreement in Principle for the LT2ESWTR currently proposes granting a minimum 2.5-log *Cryptosporidium* removal credit to membrane processes if specific performance criteria are met (65 FR 83015). State primacy agencies will need to address *Cryptosporidium* removal by membrane filtration since it is likely that a number of utilities will consider this technology to comply with the upcoming regulations. States will also need to make a determination with respect to *Cryptosporidium* removal for existing membrane plants, and in some cases may require additional testing.

6.6 Integrity Testing Requirements

As discussed previously, states rarely award all of the removal credit required under the SWTR, and require some level of chemical disinfection. One reason that multiple barrier protection is required for membrane filtration is the concern regarding membrane integrity. Even though membranes have demonstrated very high levels of pathogen removal, there is a potential for microorganisms to contaminate the filtrate if there is an integrity breach. Chemical disinfection

can serve as an additional barrier in the event of a failure. However, integrity monitoring can be used to verify the integrity of the system and thus reduce the need for a large disinfection barrier.

At the time of this report, 14 of the 29 state agencies contacted did not require integrity testing. These states do require turbidity monitoring, but as discussed in Chapter 4, current turbidity technology lacks the sensitivity to detect small breaches in integrity that are of concern. The remaining 15 states require periodic physical integrity testing and/or continuous integrity monitoring. All states that require periodic physical integrity testing stipulate use of the pressure hold test. States that require continuous integrity monitoring permit use of one of the following methods: particle counting, particle monitoring, laser turbidimetry, or pressure drop across the membrane. At the time of this report, only Texas has expressly permitted the use of laser turbidimeters for membrane integrity monitoring; however, other states are considering this monitoring technology.

As discussed in Section 4.2.1, the pressure hold test is a direct method of verifying system integrity; however, it requires the system to be taken off-line, and thus can only be used for periodic testing. Twelve states require periodic integrity testing using the pressure hold test, some of which have established a testing frequency. Washington requires pressure hold testing at 4-hour intervals to be consistent with the 4-hour turbidity monitoring requirement of the SWTR and to compensate for the lack of a continuous monitoring technique capable of detecting breaches that are of concern. Wisconsin requires pressure hold testing at 8-hour intervals. Most states that require pressure hold testing specify daily testing, and a few require less frequent testing. For example, Texas and Oregon require pressure hold testing to be conducted at weekly intervals, and Kansas requires testing to be performed when the system is taken off-line for cleaning. Seven of the twelve states that require periodic pressure hold testing also require continuous monitoring.

Continuous monitoring provides a real-time measure of system performance, but the methods currently available only provide an indirect assessment of membrane integrity. Eight states require continuous testing beyond the turbidity monitoring requirements of the SWTR, and six of these states require particle counting, particle monitoring, or laser turbidimetry in the case of Texas. One state, Kansas, requires pressure drop monitoring while Colorado allows the use of particle counting, particle monitoring, or pressure drop, and is considering laser turbidimetry. States that require continuous monitoring typically require one monitoring unit per membrane rack, or in some cases only require monitoring of the combined filtrate.

In addition to periodic and continuous testing, most membrane filtration plants need to perform diagnostic testing to isolate problems identified during integrity testing. As discussed in Chapter 4, methods commonly used for diagnostic testing include the pressure hold test, the bubble point test and sonic testing. A few states do require plants to conduct periodic diagnostic test independent of routine integrity monitoring results.

Regardless of the integrity monitoring technique used, it is necessary to establish control limits that trigger a specific action when exceeded. For periodic testing using the pressure hold test, manufacturers often specify the pressure decay rate below which the system is considered integral; however, as discussed in Chapter 5, there are a number of factors that impact the

relationship between pressure hold test results and risk of microbial passage. A few states, such as Wisconsin and Virginia, require manufacturers to provide a theoretical basis for the specified control level. The theoretical relationship between the results of the pressure hold test and the number of broken fibers can be used to establish control limits that ensure the system is capable of achieving the removal credit granted by the primacy agency.

For continuous testing using particle counters or particle monitors, relative counts are typically used to establish control limits due to the difficulties associated with measuring absolute particle counts. In order to develop control levels for relative particle counts, it is necessary to establish a baseline during operation with integral membranes, where the integrity is typically verified through the pressure hold test. A control level is established at some value above the baseline, and particle counts above this control level trigger a response. Since there is not a standard methodology for establishing a control limit for particle counts, states typically set the limit at a conservative value.

The individual tools available to monitor membrane integrity can be combined into a comprehensive monitoring program. Two states that have developed such programs are Texas and Wisconsin. Texas based its monitoring program on continuous particle counting and requires particle counters on each rack of membrane modules. A baseline particle count level is established with integral membranes (verified through direct integrity testing), and the control limit is set at two standard deviations above the mean baseline value. If the particle counts from a rack of membranes exceed the control limit, a direct integrity test must be conducted on the rack of membranes, and sonic testing is used isolate compromised modules as necessary. Utilities are also required to conduct direct integrity testing once per week independent of the particle count monitoring.

Wisconsin's monitoring program is based on the pressure hold test conducted at 8-hour intervals. Fiber-cutting studies are performed at all full-scale installations to determine the relationship between pressure hold test results and the number of cut fibers, and to ensure that the test is sufficiently sensitive to detect a breach that would compromise the level of removal credit awarded with a 1-log factor of safety. This relationship is used to establish two control limits for pressure decay rates during pressure hold testing. Results below the lower control limit require no action. Results between the lower and upper control limits require sonic testing of the suspect modules. Results above the upper control limit require the suspect modules to be taken off-line for repair/replacement. Utilities are also required to conduct sonic testing every 30-days independent of the pressure hold test results.

The comprehensive monitoring programs for Texas and Wisconsin demonstrate how either continuous indirect monitoring or direct integrity testing can be used to evaluate membrane integrity and establish control limits for the monitoring results.

6.7 Summary

The results of this state survey demonstrate the significant differences that exist among various approaches to regulating MF/UF for pathogen removal. There are a range of requirements with respect to product certification and pilot testing. At one extreme, states rely on existing data and do not require further demonstration of product performance. At the other end of the spectrum, some states require product certification, site specific pilot testing and full-scale process demonstration. With respect to removal credits, states awarded 1- to 4-log *Giardia* removal credit for MF and UF membranes, with most states granting 2.5- or 3-log credit. With only three exceptions, states did not award virus removal credit to MF processes, and in no case was the virus removal credit greater than 0.5-log. Seven states awarded virus removal credit to UF membranes, with credits ranging from 0.5- to 4-log. Only seven states have awarded *Cryptosporidium* removal credit to membrane filtration, with credits of 2-, 3-, or 4-log. Eight of the 29 states did not award specific removal credits to membrane filtration processes. A commonality among the various regulatory approaches is that in almost all cases some level of chemical disinfection was required for MF/UF filtrate.

There were also significant differences in the monitoring required by different states. Fourteen of the 29 states did not require any integrity monitoring for membrane filtration plants aside from turbidity. Of the remaining 15 states, seven require both continuous indirect monitoring and periodic direct integrity testing, five require only direct integrity testing, one requires only continuous indirect monitoring, and two approve integrity monitoring plans on a case-by-case basis. All states that require direct integrity testing stipulate use of the pressure hold test, while states that require continuous indirect monitoring specify particle counting, particle monitoring, laser turbidimetry, or pressure drop monitoring.

Much of the variability in state requirements for membrane filtration is a result of factors such as different approaches to multiple barrier treatment, different levels of experience with membrane processes, the lack of standardization in this technology field, and a lack of formal guidance from USEPA that adequately addresses this technology. This variability present challenges for the implementation of this technology.

During this project, several states raised outstanding issues related to the regulation of membrane filtration for pathogen removal, including:

- Failure to adequately address membrane filtration in the federal regulations

- Consistent determination of removal credits for membrane filtration processes

- Defining appropriate multiple barrier protection for a membrane filtration process

- Reliability, sensitivity and transparency of integrity testing methods

- Increased understanding of the relationship between integrity testing results and a breach in integrity and risk of microbial passage

- Appropriate use of particle counting, particle monitoring and turbidity monitoring in an integrity monitoring program

- Product certification, and the impact of certification on site specific pilot testing requirements

- Appropriate cross-connection control for CIP systems

- Longevity of membrane elements, and changes in performance with time

- Operator certification for membrane filtration processes

Of these unresolved issues, one of the most important may be the first, the failure of federal regulations to adequately address membrane filtration technology. If this issue were to be resolved in a sound and defensible manner, it would go a long way towards resolving some of the other outstanding issues listed above. This would ultimately lead to greater consistency among the various regulatory approaches and would make it easier to implement membrane filtration technology for pathogen removal.

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7.0   UTILITY PRACTICES

7.1   Introduction

A representative sample of twenty-four utilities was selected from the installation lists provided by MF/UF manufacturers and contacted to obtain information regarding their membrane facilities. This information included operating parameters and the factors that contributed to the decision to utilize membrane filtration. Utilities were selected based on location (i.e., state), installation date, and the manufacturer of the proprietary membrane system. The information received from the utilities is summarized in Table 15, while the decision drivers and operational practices are discussed in more detail in Sections 7.2 and 7.3, respectively.

7.2   Decision Drivers

The utilities contacted cited a number of reasons for choosing membranes as part of their respective treatment schemes, ranging from regulatory considerations to addressing consumer concerns. The drivers for installing membrane filtration are listed below in order of frequency cited.

1) Membrane filtration facilitates compliance with existing and future regulatory requirements

2) An intact membrane provides an absolute barrier to protozoan cysts and bacteria, and in the case of UF, can achieve significant virus removal

3) Membrane filtration systems are easy to operate, less susceptible to changes in source water quality, and highly automated

4) The footprint for a membrane plant is small compared to other technologies

5) Membranes provide another treatment barrier to protect public health

6) The cost of membrane filtration is competitive with other technologies

7) Membranes are economical for unfiltered systems that are concerned about losing their unfiltered status

8) Membrane filtration is an effective pretreatment for nanofiltration and reverse osmosis

9) Membrane filtration alleviates consumer concerns regarding source water quality

Regulatory requirements were most frequently cited as a reason for installing MF/UF technology by the utilities contacted. Several utilities were concerned that their existing facilities would not be sufficient to meet the CT (disinfectant residual $\times$ contact time) requirements of the SWTR. One utility noted that MF/UF made it possible to meet CT requirements and reduce disinfectant dosages, putting the utility in a better position to comply with the Stage 1 D/DBP Rule.

Table 15. Summary of General Information for the Utilities Contacted

State	Water Type	Capacity (MGD)	System	Install. Date	Process Configuration	Feed Water Quality Characteristics	Decision Driver	Log Credits Given by State[1]	Monitoring Requirements[2]
Alaska	Reservoir	0.43	US Filter	Fall 1999	MF→ Chloramination → Nanofitration → Chlorination	- Turbidity = 4 NTU - TOC > 30 mg/L - *Giardia* & *Crypto* present	- Pretreatment - Removal of *Giardia* and *Crypto* - Reduce DBPs	NR	NR
Arizona	Lake	3.0	Zenon	June 1999	Equalization (PAC and $KMnO_4$) → UF → Chlorination	- Central Arizona Project Water (Colorado River)	- Space limitations - Low capital costs	- *Giardia*: 3-log	- Particle Counting
California	Reservoir	0.144	Aquasource	Feb 1995	UF → Chemical disinfection	- Turbidity = 10 NTU - Total Coliform = 0.8 MPN	- Current regulatory compliance - Appropriate technology for small system	- *Giardia*: 3-log - Viruses: 4-log	- Particle Counting (SR)
California	NR	5.0	US Filter	Feb 1994	Strainer → MF → Chlorination	NR	- Current regulatory compliance - CT limitations	- *Giardia*: 3-log	- Pressure Hold Test (SR) - TMP Limit (SR)
Colorado	Lake	30[3]	Pall	June 2001	Coagulation & Sedimentation (PAC, $KMnO_4$ & Ferric) → MF → UV → Chloramination	- Turbidity = 11.6 NTU - TOC = 1.9 mg/L - Alk = 49 mg/L - Hard = 53 mg/L	- Low manpower required - Removal of *Giardia* and *Crypto*	- *Giardia*: 3-log	- Particle Counting (SR)
Florida	NR	1.67	Zenon	Fall 2000	Softening & Sedimentation (H_2SO_4) → UF	- pH = 8.3 - Turbidity = 2-20 NTU	NR	- *Giardia* 2.5-log	- Particle Counting
Hawaii	Impounded Direct Runoff	3.1	US Filter	May 1997	Pre-sedimentation → MF → Chlorination	- Turbidity ~ Low-High - Alk ~ Low	- Current regulatory compliance - Removal of *Giardia* and *Crypto*	- *Giardia* and *Crypto*: 2.5-log	- Particle Counting (FSR)
Hawaii	Impounded Direct Runoff	2.2	US Filter	May 1997	Pre-sedimentation → MF → Chlorination	- Turbidity ~ Low-High - Alk ~ Low	- Current regulatory compliance - Removal of *Giardia* and *Crypto*	- *Giardia* and *Crypto*: 2.5-log	- Particle Counting (FSR)

Table 15. Summary of General Information for the Utilities Contacted (continued)

State	Water Type	Capacity (MGD)	System	Install. Date	Process Configuration	Feed Water Quality Characteristics	Decision Driver	Log Credits Given by State	Monitoring Requirements
Hawaii	Impounded Direct Runoff	9.9	US Filter	May 1998	Pre-sedimentation → MF → Chlorination	- Turbidity ~ Low-High - Alk ~ Low	- Current regulatory compliance - Removal of *Giardia* and *Crypto*	- *Giardia* and *Crypto*: 2.5-log	- Particle Counting (FSR)
Hawaii	Impounded Direct Runoff	2.2	US Filter	May 1998	Coagulation & Sedimentation → MF → Chlorination (ammonia facilities mothballed)	- Color ~ 180 TCU (High)	- Current regulatory compliance - Removal of *Giardia* and *Crypto*	- *Giardia* and *Crypto*: 2.5-log	- Particle Counting (FSR)
Idaho	Mountain Runoff	1.6	Koch	Jan 1997	Rock Filter → UF → Chlorination	- Turbidity = 0.2-0.4 NTU	- Space limitations - Future unfiltered regulations compliance	- *Giardia* and *Crypto*: 3-log - Viruses: 4-log	- Pressure Hold Test (SR)
Kansas	River	3[3]	Koch	Feb 2001	Coagulation & Sedimentation →UF	- Turbidity = 1-5 NTU	NR	NR	NR
Michigan	Lake	7.0	US Filter	Sept 1997	Strainer → MF → Chlorination	- Turbidity = 0.2-6 NTU - pH = 7.8 - Hard = 45 mg/L	- Future regulatory compliance	- *Giardia*: 3-log - Viruses: 3.5-log	- Particle Counting (SR) - Pressure Hold Test (SR)
Missouri	Lake	1.0	Koch	Jul 1999	Pre-sedimentation → Lime & Polymer Addition → Rapid-rate Sedimentation → Equalization → UF	- Turbidity = 0.7-0.9 NTU	NR	NR	- Particle Counting (FSR)
New Jersey	NR	0.5	Aquasource	1997	Screen → MF → Chlorination	- Turbidity < 2 NTU	- Current regulatory compliance	NR	NR
New York	River	0.14[4]	Aquasource	1993	NR	NR	NR	NR	NR
Oregon	River	0.5[3]	Pall	Sept 2001	NR	- TOC < 1 mg/L - pH 7.0 - Alk =30 mg/L	- Future unfiltered regulations	- Pathogens: 3-log	- Pressure Hold Test (SR)
Pennsylvania	Reservoir	20[2]	Pall	Spring 2001	MF → Chlorination	- Turbidity = 0.02-1 NTU - pH = 7.6 - 8.7 - TSS = 0 -2 mg/L - Hard = 78 - 184 mg/L	NR	- *Giardia*: 4-log - Viruses: 0-log	- Particle Counting (SR) - Pressure Hold Test (SR)

Table 15. Summary of General Information for the Utilities Contacted (continued)

State	Water Type	Capacity (MGD)	System	Install. Date	Process Configuration	Feed Water Quality Characteristics	Decision Driver	Log Credits Given by State	Monitoring Requirements
Texas	River	9.0	Aquasource	Jan 2000	Ferric sulfate → Clarifier → Pre-filter → UF	- Turbidity ~ High	- Customer preferences	- *Giardia*: 3-log - Viruses: 2-log	- Particle Counting (SR) - Pressure Hold Test (SR)
Texas	Lake & River	7.8	Pall	Dec 1999	Sedimentation → MF → Chlorination	- Turbidity ~ High - TOC ~ High	- High THM levels - Removal of *Crypto* - Variable water quality	- *Giardia* and *Crypto*: 3-log - Viruses: 0-log	NR
Utah	River	1.2	US Filter	June 1999	Pre-sedimentation → Pre-filter → MF → Chlorination	- Turbidity = 5-10 NTU - TOC = 2 mg/L - Alk = 230 mg/L - Hard = 220 mg/L	- Remote location - Low costs	- *Giardia*: 3-log - Viruses: 0.5-log	- Pressure Hold Test (SR)
Virginia	GWUDI	2.5	Koch	Aug 1999	Pre-filter → UF → Chlorination	- Turbidity = 0.5 NTU	NR	- *Giardia*: 2-log	- Pressure Hold Test (SR) - Particle Counting (SR)
Washington	River	6.5	US Filter	June 2000	Pre-screens → MF → Chlorination → Caustic & Fluoride	- Turbidity < 2 NTU - TOC < 2 mg/L - pH = 7.0	- Ease of operation - Future unfiltered regulations	- *Giardia* and *Crypto*: 3-log	- Pressure Hold Test (SR)
Wisconsin	NR	14	US Filter	Oct 1998	Strainer → MF → Chlorination → Fluoride & Corrosion Inhibitor	- TOC = 2-3 mg/L - pH = 7.5 - Alk = 100 mg/L - Hard = 140 mg/L	- Removal of *Crypto* - Future regulatory compliance	- *Giardia*: 3-log	- Pressure Hold Test (SR) - Sonic Test (SR)

1 –Several utilities indicated that they were awarded credits different from the credits that the state indicates that they grant to MF/UF processes.

2 - The monitoring requirements are listed as the utilities reported them. Some of the requirements may not be state requirements as indicated.

3 - Pilot studies with future capacities listed

4 - Only pilot study completed

NR - Not reported

TSS - Total Suspended Solids

Alk - Alkalinity (mg/L as CaCO₃)

Hard - Hardness (mg/L as CaCO₃)

MPN - Mean Probable Number

TCU - True Color Units

NTU - Nephelometric Turbidity Units

PC - Process Configuration

GWUDI – Ground Water Under Direct Influence

Crypto - *Cryptosporidium*

SWTR - Surface Water Treatment Rule

CT - (Disinfection) Contact Time

DBPs - Disinfection Byproducts

SR - State Requirement

FSR- Future State Requirement

MF/UF can remove protozoa, specifically *Cryptosporidium* and *Giardia*, to below detection limits. UF has been demonstrated to be capable of removing viruses (see Chapter 3), though the results are variable and dependent upon the exclusion characteristic of the specific membrane. The fact that these technologies provide a barrier to pathogenic microorganisms makes membrane filtration an attractive treatment alternative to conventional technologies. Several utilities contacted consider membranes to be a barrier capable of providing a long-term solution to future microbial contaminants of concern. For example, the SWTR included standards for only *Giardia* and viruses, while the IESWTR added *Cryptosporidium* removal/inactivation requirements. Since membrane filtration removes most pathogens larger than viruses via size exclusion, this technology represent a barrier to pathogens that would potentially be considered under future regulations. It is worth noting that the Unregulated Contaminant Monitoring Rule will gather occurrence data on eight microorganisms that have the potential to be addressed under future regulations.

As a stand-alone technology, membrane filtration is easier to operate than conventional treatment processes, which require more operator knowledge and are susceptible to changes in water quality. A number of utilities, particularly small utilities, cited automation as a key factor in the decision-making process. One utility stated that it did not want to hire additional treatment plant staff and consequently selected a process that was "as automated as possible."

Membrane filtration requires less land area than conventional treatment processes and can be retrofitted to existing facilities where little space is available. Submersible membranes can be installed in existing filter beds, after removal of the granular media and underdrain; however, this can be difficult in some plant configurations. One utility in Idaho sited its location in a mountainous region and indicated that the space requirements for slow sand filters made membranes a more attractive treatment option. Another utility in Utah chose membrane treatment over conventional treatment due to the problems associated with receiving chemical shipments at the remote location of the plant. MF/UF requires little chemical use other than periodic cleaning and post-membrane disinfection for virus inactivation and secondary disinfection.

Membranes are commonly used as a physical barrier in a multiple-barrier approach to treatment for microbial contaminants. When used in conjunction with chemical disinfection, and other physical barriers (such as conventional treatment), membranes provide an additional level of public health protection. Additionally, several utilities applied membrane filtration to reduce the level of chemical disinfection required. One utility in Pennsylvania opted to use membrane filtration to treat water in an uncovered finished water reservoir rather than cover it to maintain the aesthetic quality of the open reservoir (States, et al., 2000).

Capital and operating costs associated with membrane treatment are becoming increasingly competitive with conventional technologies. Total costs for a 1-MGD MF/UF plant with full backwash treatment (coagulation, sedimentation, dewatering, and sludge disposal) are estimated at $1.39 to $2.06 per 1000 gallons (depending upon the interest rate and average feed water temperature (EPA, 2000b). Costs for similar sized package conventional plants are estimated at $0.73 to $0.87 per 1000 gallons (EPA, 1999d), and those costs do not include the treatment of

filter backwash solids. Several of the utilities contacted installed membranes after they failed to meet filtration avoidance criteria. MF/UF offered an economically feasible alternative to conventional treatment or media filtration.

A few utilities use MF/UF as a pretreatment for NF or RO in dual membrane treatment applications. NF and RO membranes, designed to remove dissolved contaminants, are particularly susceptible to fouling when applied to surface waters. MF and UF remove particulate matter, and thus minimize particulate fouling of NF and RO membranes. MF/UF are able to remove suspended particles and pathogens, while NF/RO remove selected salts, synthetic organic chemicals, and DBP precursors. A utility in Alaska with source water TOC as high as 30 mg/L was able to reduce finished water TTHM levels to $10 - 20$ µg/L through dual membrane treatment. This utility uses chloramines prior to NF to control biological fouling on the NF membranes. Following NF, chlorine is added to achieve breakpoint, allowing free chlorine to be used as the residual disinfectant (Lozier, et al., 1997). However, ammonia facilities are available should this utility decide to use chloramines for residual disinfection in the future.

A utility in Texas installed UF to address public concern over the use of surface water as a drinking water supply. The customers of this utility had historically been served by ground water, and were apprehensive when a nearby river was proposed as an alternate source to alleviate some of the burden on the aquifer. The utility determined membrane filtration was best suited for treating the river water and addressing public concerns.

7.3 Operational Practices

Utility operational practices varied based on the source water quality, process configuration, and regulatory requirements. A summary of the utilities' operational information is presented in Table 16. Note that utilities in Westminster, Colorado; Astoria, Oregon; New Rochelle, New York; Parsons, Kansas; and Pittsburgh, Pennsylvania are not included in the table because those systems are pilot facilities. This section discusses operational practices reported by the utilities contacted, including pretreatment, flux and transmembrane pressure, backwash practices, clean-in-place (CIP) practices, monitoring and integrity testing, and observed treatment challenges.

7.3.1 Pretreatment

Pretreatment is used by MF/UF facilities for four general reasons: 1) to control fouling, 2) to provide additional treatment, 3) to meet manufacturer warranty requirements, or 4) to meet state regulatory requirements. The majority of installations use pretreatment to improve feed water quality and reduce fouling; however, it was not clear what fraction of the utilities contacted do so as part of a warranty requirement. States that require pretreatment, generally do so because of concerns over economic failure of the system that could result from inadequate pretreatment to control fouling.

Table 16. Summary of Operating Practices for Utilities Contacted

State	Water Type	Capacity (MGD)	System Type	Membrane Configuration	TMP$_{Max}$ (psi)	Flux (gfd)	Backwash Procedures	Backwash Treatment	Cleaning-in-Place Procedures	Pressure Hold Test Frequency	Treatment Challenges
Alaska	Reservoir	0.43	MF	OI	15	NR	Every 30 min or TMP$_{Max}$	NR	- Every 2-3 weeks at 0.5*Q$_{Design}$	Every 24 hrs	Poorer WQ during winter
Arizona	Lake	3.0	UF	OI	NR	38.5	Every 15 min (30 sec duration)	- Discharged to WWTF	- Every month with Chlorine and NaOH	NA	NR
California	Reservoir	0.144	UF	IO	NR	NR	Time-based	- Chlorine → Unlined pond	- Every year	NA	Seasonal WQ variation
California	NR	5.0	MF	OI	17	NR	TMP$_{Max}$ -based	NR	NR	Every 4 hrs	Seasonal WQ variation (after winter storms)
Florida	NR	1.67	UF	OI	20	NR	Every 15 min (30 sec duration)	NR	- NaOCl, Citric acid, NaOH, Na$_2$SO$_4$ treatment	NA	NR
Hawaii	Runoff	3.1	MF	OI	NR	67	Total of 90 min/day	NR	NR	Every 24 hrs	Seasonal WQ variation
Hawaii	Runoff	2.2	MF	OI	NR	88	Total of 90 min/day	NR	NR	Every 24 hrs	Seasonal WQ variation
Hawaii	Runoff	9.9	MF	OI	NR	67	Total of 90 min/day	NR	NR	Every 24 hrs	Seasonal WQ variation
Hawaii	Runoff	2.2	MF	OI	NR	88	Total of 90 min/day	NR	NR	Every 24 hrs	Seasonal WQ variation, Color
Idaho	Runoff	1.6	UF	IO	NR	NR	Every 60 min	- Settling Tank → Infiltration pond	- Every month with Chlorine and NaOH	NR	Variable WQ, algae, operator skills
Michigan	Lake	7.0	MF	OI	17	20 - 65 (30 Avg)	Every 60 min	- Discharged to lake	- Every 6 weeks with Memclean	NA	NR
Missouri	Lake	1.0	UF	IO	25	96	Every 60 min	- Discharged to reservoir	- Every 90 days or TMP>15 psi with NaOH and Chlorine	NA	TOC
New Jersey	NR	0.5	UF	IO	NR	72 (D) 66 (Max)	Every 30-60 min	NR	- Every month	NA	Iron, microbiological fouling
Texas	River	9.0	UF	IO	NR	60	Time/Temp/Flux/ Turbidity-based	- Evaporative lagoon	- Every 15-20 days with Citric acid - Short-term chemical cleaning schedule	Every 10 days	Turbidity spikes

Table 16. Summary of Operating Practices for Utilities Contacted (continued)

State	Water Type	Capacity (MGD)	System Type	Membrane Configuration	TMP$_{Max}$ (psi)	Flux (gfd)	Backwash Procedures	Backwash Treatment	Cleaning-in-Place Procedures	Pressure Hold Test Frequency	Treatment Challenges
Texas	Lake & River	7.8	MF	OI	20	52	Every 20 min	NR	- Citric acid and NaOH treatment	NR	WQ highly variable, TOC
Utah	River	1.2	MF	OI	18	100	Every 20 min (air and raw water)	- Holding pond → River	- Every 4-6 weeks (or <100 LMH/bar) with Memclean and Citric acid	NR	NR
Virginia	GWUDI	2.5	UF	IO	25-30	101	Every 30-90 min	- Discharged to stream	- Chlorine, Citric acid, Sulfuric acid, NaOH treatment	Every 24 hrs	Turbidity spikes following storms, Fouling problems
Washington	River	6.5	MF	OI	15	50-70	Every 40 min	- Recovery System Membrane → WTP Headworks - Waste Basin → Land application	- Every month with Citric acid and NaOH	Every 4 hrs	Turbidity spikes following storms
Wisconsin	NR	14	MF	OI	NR	NR	Every 40 min	- Discharged to WWTF	- Every 6 days at Q$_{Design}$	Every 8 hrs	Turbidity spikes following storms, *Crypto* removal

NR – Not reported
NA – Not applicable
D - Design
W - Winter
S - Summer
OI – Outside-in
IO – Inside-out

Pretreatment reduces the solids load applied to the membrane, permitting use of a higher flux and thus reducing the required membrane area. Alternatively, the lower solids loading could allow a lower transmembrane pressure to be applied, which would reduce operating costs. Another benefit of pretreatment is that it results in longer runtimes between backwash and cleaning events. All of these factors can allow systems to achieve a higher system recovery, maximizing water production and lowering overall costs.

Pretreatment is also used to protect the membrane from contaminants that could damage the system. Prefilters are necessary to remove large suspended solids and some bacteria, and provide protection against fiber and pore plugging as well as biological fouling and degradation. Pre-sedimentation, with or without coagulation, can remove suspended solids and microorganisms, reducing the solids load to the membrane.

Pretreatment may also be applied to remove contaminants that would otherwise not be removed by membrane filtration alone. Oxidation, coagulation and sedimentation can remove dissolved contaminants (e.g., iron, manganese, TOC, etc.) that may otherwise pass through a MF/UF membrane. Coagulation may also result in agglomeration of particles and microorganisms that would normally be too small to be retained by MF/UF membranes.

The utilities contacted can be divided into two categories with respect to pretreatment: those that use only pre-filtration prior to membrane treatment, and those that use sedimentation. Seven of the utilities contacted use only pre-filtration. Most use strainers, but several use alternate filtration technologies. For example, one plant in Idaho also uses a rock filter. Three others use 400 to 500 µm strainers to remove larger particulate matter and debris from the feed water. Twelve utilities use sedimentation as pretreatment, and seven of these utilities use coagulation in conjunction with sedimentation.

It is worth noting that pretreatment chemicals must be evaluated for compatibility with membrane materials. For example, cationic polymers are frequently used to enhance the coagulation and flocculation processes in a conventional treatment plant; however, most membranes are anionic in nature and are incompatible with these polymers. Failure to completely remove the polymer from the membrane feed water can result in substantial fouling of the membrane. Another consideration is the coagulant itself. Most membranes are compatible with ferric salts, but alum has resulted in significant fouling with some membranes.

Two of the utilities contacted use no additional pretreatment prior to MF or UF membranes. There was no apparent correlation between the source water for these utilities and their decision to not include additional pretreatment. The two remaining utilities provided no information regarding their treatment practices.

Two other utilities took advantage of retrofit situations to incorporate pretreatment. In both cases, new membrane facilities were installed following coagulation and sedimentation. One of these plants added UF to expand treatment plant capacity. The other replaced conventional media filtration with UF, but has mothballed the media filters for emergency use. Another retrofit option involves using existing media filter basins to house immersed membranes. This allows utilities to take advantage of existing plant piping and basins with minimal modification.

7.3.2 Flux and Transmembrane Pressure

The operating fluxes reported by these utilities ranged from 30 to 100 gfd and averaged approximately 75 gfd, varying with manufacturer specifications, membrane configuration and level of pretreatment. The average flux for outside-in configurations was approximately 65 gfd and ranged from 30 to 100 gfd.   The average flux for inside-out configurations was approximately 80 gfd and ranged from 60 to 100 gfd.

Maximum TMP is primarily dependent upon membrane configuration and manufacturer specifications. The utilities contacted were asked to provide the maximum TMP at which their system operates. The maximum TMP ranged from 15 to 30 psi with an average of 20 psi for all of the utilities contacted that utilize positive pressure membrane systems. The average maximum TMP for outside-in configurations was 17 psi and ranged from 15 to 20 psi. The average maximum TMP for inside-out configurations was 30 psi and ranged from 25 to 35 psi. Two of the utilities contacted utilize vacuum pressure systems, and the maximum TMP for these systems was –12 psi.

7.3.3 Backwash Practices

Periodic backwashing is necessary to remove the solids that accumulate at the membrane surface during a filtration cycle. For most systems, backwashing is fully automatic, and is initiated: 1) when the TMP reaches a programmed setpoint, 2) after a programmed period of operation, regardless of the TMP, or 3) after a given volume of filtrate is produced. Both liquid and air backwashing are employed with MF/UF technology.

Of the utilities contacted, 16 initiated backwashing based upon operation time at a frequency ranging from 15 to 90 minutes. One utility based backwashing on a combination of operational time and TMP, and another based its decision to backwash solely on TMP. A new facility in Texas had a much more complex approach that considered feed water temperature and turbidity levels, as well as time and flux.

Six utilities operate in an inside-out mode and use purely hydraulic washes, and 13 utilities operate in an outside-in configuration and use an air/water combination. Of those 13 utilities, 11 feed air from the filtrate side of the membrane and water on the feed side only during the backwash period. The remaining two are submerged membrane systems, and use continuous feed side aeration to prevent solids build-up on the membrane surface and minimize flux decline or increasing TMP during operation.

Backwash water will typically have elevated concentrations of suspended solids and microorganisms. Since this may potentially include high concentrations of pathogens, backwash water must be treated and/or disposed of in a proper manner. The backwash water from conventional filtration plants will be regulated under the proposed Filter Backwash Rule (see Section 2.1.4); however, it is unclear at this time whether or not membrane backwash water will need to comply with the requirements of this rule.

The utilities contacted were asked to provide information regarding the disposal of backwash water. Disposal practices ranged from direct discharge to a receiving body of water to treatment by additional membranes and recycle to the treatment plant headworks. The reported disposal practices, from most to least frequently cited, are as follows:

1) Discharge to a receiving body of water (stream, river, lake, or pond) other than the raw water source with or without additional treatment

2) Discharge to sanitary sewer

3) Recycle to the head of plant

4) Discharge to evaporation pond

5) Discharge to raw water source

6) Use for irrigation/land application

Five of the utilities contacted reported that they discharged MF/UF backwash to a receiving body. Two utilities provide no additional treatment of the backwash and discharge directly to a nearby stream and lake, respectively. Two other utilities clarify backwash before discharging to a nearby river and unlined pond, respectively. Still another utility chlorinates the backwash before it is discharged to an unlined pond.

The backwash from two utilities is treated at municipal wastewater treatment facilities. One of these utilities discharges spent backwash directly to the sanitary sewer; the other pumps backwash to the wastewater plant. Neither utility reported any pretreatment requirements for their backwash stream.

One utility in Washington treats spent backwash water from eight primary production MF units with a ninth MF unit. During the first nine months of operation, filtrate from the ninth unit was recycled to the primary production raw water line. Based on filtrate water quality and integrity test data from the ninth unit, the state now allows discharge of the ninth unit filtrate to the clearwell, along with the filtrate from the eight primary production units. Backwash from the ninth unit is stored in a waste basin until it is discharged over an open field using spray nozzles. The waste stream is not disinfected prior to disposal. A second basin captures CIP waste streams, which are pumped and trucked to the city's wastewater treatment facility.

The use of evaporation ponds may be an option for treatment of spent backwash for utilities in warm climates. However, it may be advantageous to have an alternative, such as discharge to a sanitary sewer, available for emergency situations. A utility in Texas reported that evaporation ponds have been sufficient to handle their entire backwash flow, and after one year of operation it had not yet had to discharge to the sanitary sewer.

A utility in Missouri discharges spent backwash to the raw water reservoir. No treatment was reported prior to discharge to the reservoir. Contaminant loading was not a concern for this

utility, primarily due to the extensive level of pretreatment, including pre-sedimentation, lime and polymer addition, and rapid-rate filtration.

Another backwash disposal practice reported by the utilities contacted was land application for irrigation. Only one utility reported this as its sole method of disposal, although another utilized a combination of recycle flow and land application. Neither of these utilities reported disinfecting backwash prior to land application.

7.3.4 Clean-in-Place Practices

When foulants can no longer be removed from the membrane surface by backwashing, chemical cleaning is required. Chemical cleaning of MF/UF membranes is typically referred to as a clean-in-place operation. The frequency with which CIPs must be performed is affected by pretreatment, feed water quality, mode of operation, manufacturer specifications, nature of the foulant, and other operating parameters. A CIP may be initiated based upon a scheduled cleaning interval, at a specific TMP or flux, or based on a rate of increase in TMP. CIP practices can include the use of detergents, acids, bases, oxidizing agents, chelating agents, and enzymatic cleaners.

The CIP frequency varied from once every two weeks to once per year for the utilities contacted. The most common practice was to perform CIPs at least once per month as part of standard operating practices. Eight utilities perform CIPs as part of a routine operating schedule. Five of those utilities perform cleaning at least once per month, one performs cleaning every 1000 hours (i.e., approximately 6 weeks), one is a new facility that expects to clean quarterly, and one cleans annually. One of the utilities that cleans at least once per month varies the frequency depending upon plant production. At design flow, cleaning is conducted every six days. However, when production is at approximately 70 percent of design capacity, the frequency is reduced to every 18 to 22 days. The utility that cleans annually takes the system off-line for cleaning and uses distribution system storage to satisfy demand during a CIP event.

Four of the utilities contacted initiate cleaning based upon a loss in membrane flux or an increase in TMP. The frequency of cleaning for these utilities ranged from every two to three weeks to approximately 90 days. The two remaining utilities that provided CIP information initiate cleaning based on a combination of time and TMP. That is, cleaning is initiated if TMP reaches a maximum value or if some period of operation time passes, whichever occurs first. This reflects the fact that most plants operate to achieve a constant production to meet demand, and the TMP is increased to maintain production as the membranes foul.

The types of chemicals used for CIP varied depending on the degree of fouling as well as the membrane manufacturer's requirements. Citric acid followed by sodium hydroxide was the most frequently reported combination of chemical cleaners and was used by five of the utilities contacted. Two of those utilities also used chlorine for cleaning. Three utilities soaked their membranes in a high strength chlorine solution followed by cleaning with caustic. Finally, two utilities used proprietary surfactants that were recommended by the manufacturer.

An adequate rinse period (similar to a filter-to-waste cycle in a conventional granular media filter) is necessary following a CIP to ensure the removal of residual cleaning agents. Spent cleaning solution may be acidic or basic in nature, contain high levels of free chlorine, or contain other constituents of concern. As a result, proper disposal of cleaning solutions is necessary. The most common disposal method for spent cleaning solution was neutralization followed by discharge to a sanitary sewer or receiving body (i.e., river, stream, or lake). One utility reported that it collected spent cleaning solution and delivered it to the wastewater treatment facility by truck. Another utility neutralized spent cleaning solution and then pumped it to an evaporation pond.

7.3.5 Monitoring and Integrity Testing

In addition to the turbidity requirements of the SWTR, there were a number of integrity testing and monitoring requirements imposed by the state regulatory agencies as discussed in Chapter 6. These ranged from continuous monitoring methods, such as particle counting, to periodic direct integrity tests.

Only two of the utilities contacted conducted monitoring in excess of that required by the state regulatory agency. Both are conducting particle counting as a method of ensuring membrane integrity. When continuous monitoring was conducted, either voluntarily or to meet state requirements, particle counting was the method employed by all of the utilities contacted. Other methods are available, such as laser turbidimetry, but none were used by the utilities contacted.

No utility reported conducting direct integrity testing in excess of that required by the state. Of the nine required to conduct direct integrity testing, all nine used the pressure hold test. The frequency of the test varied by utility from once every four hours to once every ten days.

The data collected indicate that very few of the utilities and state agencies have implemented monitoring programs or regulatory requirements that link integrity monitoring to risk of microbial passage. For example, in many states there are no integrity monitoring requirements beyond turbidity monitoring which lacks the sensitivity to detect small breaches that could pose a significant risk of microbial passage.

Particle counting methods are more sensitive than turbidity monitoring for detecting breaches in membrane integrity, although, these methods are not without limitations. Using particle counters on combined effluent (i.e., filtrate from a number of different skids) may not provide sufficient sensitivity to detect small breaches of concern, and this difficulty increases with the number of skids to which a particle counter is applied. A breach in integrity can be masked by dilution when the filtrate from several skids is combined.

7.3.6 Treatment Challenges

The most commonly reported treatment challenge was variable raw water quality. Utilities frequently noted increases in raw water turbidity following rain or winter storm events, a phenomenon characteristic of many surface water supplies. While many utilities cited the ability of membrane filtration to handle variations in feed water quality as a significant influence for selecting the technology, the high solids load associated with these events accelerates fouling and increases the frequency at which systems must be backwashed or cleaned.

The second most common challenge reported was algae growth and microbial fouling of the membranes. Most of the utilities contacted were able to use chlorinated water for backwashing, or use chlorine as part of the CIP process, and eliminate biological activity on the membrane. However, this challenge may be more significant for utilities that employ membranes that are sensitive to chlorine.

Two utilities reported TOC as a treatment challenge. MF and UF are not capable of removing TOC without additional treatment. However, significant TOC reductions can be achieved through the inclusion of treatment processes specifically designed for this purpose (i.e., coagulation and sedimentation, or PAC). One utility reported a 30 percent reduction in raw water TOC through coagulation, sedimentation, and rapid-rate filtration as pretreatment to MF/UF. This same utility also has the ability to bring granular activated carbon (GAC) contactors on-line following MF/UF if TOC reduction is insufficient through conventional treatment. To date, this utility has not had to use its GAC contactors.

One utility experienced problems with iron fouling early in the technology demonstration phase. Adding chlorine to the backwash water oxidized the iron and reduced the effect of fouling. However, they still experience some problems during cold weather, and as a result the plant is taken off-line during winter months.

Other issues raised include equipment problems and operator training. One utility noted it had difficulty with its vacuum pumps, another cited recurring fiber breakage. These are issues that can be resolved by improved equipment specifications and improved quality control during the manufacturing process. Finally, one utility reported operator skill level as a challenge. Many utilities install MF/UF technology because it is almost entirely automated. However, this particular utility was once an unfiltered source, and thus did not have significant experience with the operation of water treatment processes. As a result, operator skill was a very real challenge at this utility. The membrane supplier in this case provided extensive operator training to eliminate this barrier.

7.4 Summary

A utility may choose to install membranes for a variety of reasons. In the majority cases the decision was influenced by current or future regulatory requirements. However, concern over microbial contaminants, independent of the regulations, is also frequently cited as a reason for selecting membrane filtration. In addition, membrane filtration systems are easier to operate, less susceptible to changes in source water quality, and require fewer operators than conventional

treatment plants. As membrane filtration becomes more cost-competitive, its use continues to grow, and membranes are being used in an increasingly proactive manner to improve drinking water quality and comply with new drinking water regulations.

Pretreatment is used for four general reasons: 1) to reduce the foulant load applied to the membrane, 2) to provide additional treatment, 3) to meet manufacturer warranty requirements, or 4) to meet state regulatory requirements. There was no apparent correlation between raw water quality and the level of pretreatment applied by the utilities contacted. Pretreatment was most commonly used to improve membrane feed water quality and reduce fouling, resulting in longer run times between backwashing and CIP events. Reducing the solids load can also lower the TMP requirements resulting in lower operating costs. In addition to solids removal, pretreatment processes such as coagulation and sedimentation have the ability to remove dissolved contaminants that may otherwise pass through MF/UF. Regulatory requirements to implement pretreatment are often based on a concern regarding economic failure of membrane system due to excessive fouling and cleaning requirements.

Manufacturer specifications and membrane system configuration are two critical factors in determining key design and operational variables like flux and TMP. However, feed water quality, pretreatment conditions, and economic considerations will also impact the optimal design and operational parameters for a given application.

Backwash and CIP operations are generally initiated based upon operating time or TMP. The interval between membrane backwashes typically ranges from 15 to 90 minutes regardless of the criteria used to initiate backwash, while CIP frequency ranges from once every two weeks to once per year. Backwashing is a physical scouring of the membrane that generally uses water or a combination of air and water; however, some plants employ chlorine during backwash to control biological fouling. A CIP is a more involved cleaning procedure in which chemical agents, such as acids, bases, oxidants or surfactants, are used to remove foulants that are not typically removed during a backwash event.

Monitoring and integrity testing requirements vary by state and can include continuous monitoring and/or periodic direct integrity testing. The majority of the utilities contacted did not conduct monitoring or testing beyond the state requirements; however, a few utilities do conduct discretionary indirect monitoring. When direct integrity testing was conducted, the pressure hold test was most commonly used. Some utilities supplemented the pressure hold test with sonic testing or the bubble point test to pinpoint breaches in integrity.

The most commonly reported treatment challenge facing the utilities contacted is dealing with fouling events caused by water quality fluctuations. However, most utilities did not feel this was a major concern and generally noted that one of the benefits of membrane filtration is its ability to handle influent water quality fluctuations. Microbial fouling was frequently reported, but easily remedied through backwashing with chlorinated water or chemical cleaning. Dissolved contaminants, such as iron, may be the most difficult foulants to address, although the use of oxidants has been used to control iron fouling with some success. Pretreatment by coagulation and sedimentation may also be used to reduce fouling caused by some dissolved contaminants.

Generally, the utilities contacted reported few operational issues with their membrane systems. Most agreed that membranes provided higher quality finished water and required less operator skill than conventional treatment. In addition, MF/UF offered these utilities a competitively priced, long-term solution for compliance with existing and future regulatory requirements.

8.0   SUMMARY AND CONCLUSIONS

One of the greatest health risk management challenges facing drinking water suppliers today is the control of microbial contaminants, such as bacteria, viruses and protozoa (e.g., *Giardia* and *Cryptosporidium*).   This point is emphasized by recent drinking water regulations that have focused on the control of waterborne pathogens.   The SWTR mandates filtration for all surface water systems that do not meet filtration avoidance criteria, requires minimum levels of removal and/or inactivation for viruses (4-log) and *Giardia* (3-log), and set a turbidity standard for combined filter effluent.   The IESWTR establishes more stringent filtered water quality standards for turbidity and sets a MCLG of zero for *Cryptosporidium* for large systems utilizing filtration.   The LT1ESWTR extends the requirements of the IESWTR to small systems.   Most recently, the LT2ESWTR agreement in principle proposes to use influent *Cryptosporidium* concentrations to determine any additional treatment requirements for this organism.

MF and UF are low-pressure membrane filtration technologies that have gained considerable acceptance in the drinking water industry over the past ten years.   Both have consistently demonstrated the ability to remove suspended particulate matter, including many regulated and unregulated pathogens.   These processes can be used effectively to meet the turbidity standards and disinfection/removal requirements of the various surface water treatment rules.

Membrane filtration systems are relatively easy to operate, less susceptible to changes in source water quality, and require fewer operators than conventional treatment plants.   Utilities contacted during this project pointed out that membranes provided higher quality finished water and required less operator skill than conventional treatment.   As membrane filtration becomes more cost-competitive, it is applied more frequently in a proactive manner to maintain and improve drinking water quality rather than in a reactive manner simply to comply with new drinking water regulations.

The decision to install membrane filtration is primarily influenced by existing and anticipated regulatory requirements, with secondary considerations given to site specific issues such as space constraints, manpower issues, and chemical use.   Concern over microbial contaminants, independent of the regulations, is also frequently cited as a reason for selecting membranes. A thorough examination of available literature indicates that MF and UF processes can greatly reduce protozoan cyst and bacteria concentrations, often to detection limits.   In addition, UF processes have demonstrated the ability to remove viruses to detection limits in many cases.

The predominant removal mechanism for protozoan cysts and bacteria is sieving, since the pore size of most membranes is typically at least an order of magnitude smaller than the size of these organisms. A number of membrane challenge studies reported *Giardia* removals ranging from 4- to 7.3-log, and *Cryptosporidium* removals ranging from 4.2- to greater than 8-log. In nearly every study, *Giardia* and *Cryptosporidium* were removed to below detection limits, and variations in reported log removals were a function of feed concentration.

Unlike protozoa removal, virus removal is impacted by factors other than the pore size, such as membrane surface charge, solution pH, and cake layer formation. This is due to the small size of

viruses, which are smaller in size than all MF, and some UF, membrane pore sizes. Reported virus removals ranged from 0- to 7.9-log.

Although MF and UF represent a physical barrier to particles and organisms that are larger than the exclusion characteristic of the membrane, a breach in integrity resulting from a broken or damaged fiber or seal can compromise this barrier. The risk of microbial passage due to a breach in integrity results in a need for a reliable, routine method of verifying membrane integrity. There are a number of direct and indirect methods that provide a practical means of verifying the integrity of a membrane system; however, there is a range in sensitivity among the various methods.

Direct methods are non-destructive techniques that are applied to the physical elements of the membrane module and system components to identify and/or isolate leaks. The primary disadvantage of existing direct methods is that they cannot be applied continuously while the membrane filtration system is in operation, although future innovations may allow continuous, on-line direct integrity testing. A secondary disadvantage for all direct methods except the pressure hold test is the current lack of automation for these tests. Direct methods also indicate nothing specific about filtrate water quality. However, results of most direct integrity test methods can be related to a breach of a specific size, which can be correlated to a certain level of contamination. The four most commonly applied direct monitoring methods are the pressure hold test, diffusive air flow test, bubble point test, and sonic sensing analysis.

The pressure hold and diffusive air flow tests are typically applied to a rack of modules, allowing a rapid assessment of integrity over a large number of fibers. Furthermore, these methods are very sensitive, and can detect a small number of broken fibers over a rack of modules. Depending on the manner in which these tests are applied, they can verify integrity at a level that would achieve greater than 5-log removal of *Cryptosporidium*. Based upon the manner in which these tests have been applied in the past, the diffusive air flow test has demonstrated greater sensitivity to ensure removal greater than 5-log. However, limits on the pressure that can be applied during these tests will determine the smallest hole that will produce a response during the test. Manufacturers typically specify that pressure hold tests be conducted in the range of approximately 15 to 20 psi, which corresponds to a hole size of approximately 0.5 µm. Similarly, a vacuum hold test is limited to a test pressure of –15 psi, which corresponds to a minimum detectable breach size of approximately 0.5 µm. Testing at these levels will produce a response from holes smaller than protozoan cysts and many bacteria, but would not produce a response from a hole the size of even the largest virus (~ 0.1 µm).

Indirect methods are not applied to the membrane module, but rather monitor some aspect of filtrate water quality as a surrogate measure of integrity. These methods typically monitor for deviations in filtrate water quality relative to an established baseline to provide an indication of a potential integrity problem. While the indirect methods have the disadvantage of only being able to suggest potential integrity problems, there are some benefits to using these methods. First, the most common methods of indirect testing operate in a continuous, on-line mode. In addition, the same indirect methods and testing instruments can be applied to any membrane system, independent of manufacturer, system configuration, or any other parameter intrinsic to a proprietary system. However, there are some potential implementation issues associated with

particle counting and air entrainment in systems that utilize air backwashes or air scour to minimize fouling of the membrane surface. The three most commonly applied indirect monitoring methods are particle counting, particle monitoring, and turbidity monitoring.

Indirect methods can be valuable integrity testing tools if sufficiently sensitive. The sensitivity of an indirect method as an integrity monitoring tool is dependent upon its ability to detect fluctuations in filtrate quality relative to a baseline established for an integral system. A breach in integrity will result in increased particle concentrations; however, the contribution of particles from a breach will be diluted by filtrate from intact fibers. This dilution effect will mask small breaches unless indirect methods are sufficiently sensitive to detect the resulting infinitesimal change in filtrate quality. The impact of this dilution effect on method sensitivity is a function of the flow and particle concentration from the breach relative to the flow and particle concentration from intact fibers.

Of the three commonly used indirect methods, particle counters are the most sensitive, followed by particle monitors and then turbidimeters. Although the sensitivity of these methods will vary from site to site, in general it is acknowledged that current indirect methods lack the sensitivity necessary to detect small breaches over a rack of modules that could compromise removal at levels of concern. However, indirect methods can complement direct integrity testing since they provide some level of continuous assurance against catastrophic failure between direct integrity test events.

In regulating membrane filtration technologies, state agencies have had to consider the factors previously discussed related to process performance, removal efficiencies, and integrity monitoring techniques. Current federal surface water treatment regulations do not specifically address membrane filtration technology; thus the twenty-seven states with operational membrane filtration plants have had to develop an approach for regulating this technology. This has resulted in variable requirements across the states; however, there are three common elements of most state regulatory approaches to membrane filtration: demonstration of treatment efficacy, determination of removal credits, and monitoring requirements.

Although most states require some demonstration of treatment efficiency, there is a range of approaches to performing this demonstration. At one extreme, states rely on existing data and do not require further demonstration of product performance. At the other end of the spectrum, some states require product certification, site-specific pilot testing and full-scale process demonstration. Pilot testing has been the most common approach to performance demonstration, with 90% of the states contacted during this project requiring pilot testing in some or all cases. However, as experience is gained with this technology and national certification programs are developed, some states have indicated a willingness to relax pilot testing requirements.

Determination of removal credits is based on a variety of factors including demonstration of treatment efficiency, total removal/inactivation requirements, experience with the technology, and approach to multiple barrier treatment. The literature contains a vast amount of data from challenge studies demonstrating very high removals of cysts and cyst-sized particles by membrane filtration, in many cases to below detection. However, state primacy agencies do not award these high removal credits due to other factors considered when making the determination,

and in many cases they require a minimum level of chemical inactivation regardless of the demonstrated removal efficacy. Also, states rarely grant removal credits in excess of the federal requirements for removal/inactivation of pathogens.

Most of the states contacted during this project grant between 2.5- and 3-log of *Giardia* removal credit for MF/UF membranes. Only seven states have awarded removal credit for *Cryptosporidium* ranging from 2- to 4-log. In most cases, states granted the same protozoa removal credits to MF and UF membranes, which is consistent with the results from challenge studies that demonstrate removal of protozoa to below detection by both MF and UF processes. With only a few exceptions, states did not grant virus removal credits to MF processes, and in no case was the virus removal credit greater than 0.5-log. Seven states awarded virus removal credit to membranes classified as UF processes, with credits up to the 4-logs required under the SWTR. A commonality among the various regulatory approaches is that in almost all cases some level of chemical disinfection was required for MF/UF filtrate.

There were also significant differences in the monitoring required by different states. Fourteen of the 29 states did not require any integrity monitoring for MF/UF plants aside from turbidity. Of the remaining 15 states, 12 require physical integrity testing with or without continuous monitoring and one state requires only continuous testing. All states that require periodic physical integrity testing stipulate use of the pressure hold test, while states that require continuous testing permit use of particle counting, particle monitoring, laser turbidimetry, or pressure drop.

The response from commonly used integrity tests can be related to the level of contamination, and thus the microbial risk, resulting from an integrity breach. This relationship can be used to demonstrate that even with an integrity breach that is sufficiently small, membrane filtration systems have the ability to achieve pathogen removal above that normally possible with conventional treatment processes (Jacangelo, et al., 1997). However, the philosophy that most state agencies have adopted with respect to integrity monitoring is that any integrity breach detected must be immediately addressed, regardless of the impact of the breach on removal efficiency. Few states have considered the sensitivity and detection limit of integrity monitoring methods in granting removal credits and establishing monitoring requirements.

Integrity testing is a key component in a membrane filtration application, both from a regulatory and public health perspective. However, both direct and indirect methods have limitations as integrity testing tools. Pressure-driven tests are extremely sensitive and can verify integrity to very high levels; however, these methods are not continuous, and provide no measure of filtrate water quality. Indirect methods are continuous and on-line, but cannot verify integrity to the levels necessary to ensure high removal efficiency. However, direct and indirect methods can complement each other in a comprehensive monitoring program. Seven of the states contacted during this project do require a two tier approach for integrity monitoring: periodic direct testing to verify integrity to the required level, and indirect monitoring to ensure that a minimum level of performance is achieved on a continuous basis.

Many of the differences in the various approaches adopted by state agencies are a result of differences in the philosophical approach to drinking water treatment, different levels of

experience with membrane processes, and a lack of formal guidance that adequately addresses this technology. These differences present challenges to the implementation of this technology. However, the development of formal federal guidance regarding pathogen removal by membrane filtration may go a long way towards standardizing the application and regulation of this technology.

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APPENDIX A

LIST OF FULL-SCALE MF/UF FACILITIES IN THE UNITED STATES
(AS OF JUNE 2000)

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Appendix A. List of Full-Scale MF/UF Facilities in the United States (as of June 2000)

State	Owner	City	Capacity (mgd)	Manufacturer	Installation Year[2]
AK	Barrow Utilities and Electric Coop, Inc	Barrow	0.06	Memcor	1995
AK	Barrow Utilities and Electric Coop, Inc	Barrow	0.06	Memcor	1998
AK	Barrow Utilities and Electric Coop, Inc	Barrow	0.36	Memcor	1999
AK	No. Slope Borough	Wainwright	0.35	Pall	1999
AK	No. Slope Borough	Point Hope	0.35	Pall	1999
AK	No. Slope Borough	Nuiqsut	0.35	Pall	2000
AK	No. Slope Borough	Point Lay	0.12	Pall	2000
AK	No. Slope Borough	Atqasuk	0.12	Pall	2000
AZ	Cholla WTP	Glendale	0.85	Aquasource	1998
AZ	Desert Hills		1	Zenon	1999
CA	Olivehain Municipal Water District		25	Zenon	2000
CA	East Bay MUD	Valley Springs	0.05	Aquasource	1995
CA	California Department of Parks - Van Damme State Park	Mendocino	0.026	Memcor	1991
CA	City of Santa Cruz	Felton	0.019	Memcor	1992
CA	San Jose Water Company	Saratoga	3.6	Memcor	1993
CA	US Forest Service	Barton Flats	0.01	Memcor	1993
CA	Cherry Hill/Hetch-Hetchy	Mocassin	0.026	Memcor	1993
CA	Imperial School District	Imperial	0.019	Memcor	1993
CA	Metropolitan Water District - Intake WTP		0.019	Memcor	1994
CA	Metropolitan Water District - Iron WTP		0.04	Memcor	1994
CA	Metropolitan Water District - Gene WTP		0.04	Memcor	1994
CA	Metropolitan Water District - Hinds WTP		0.019	Memcor	1994
CA	Metropolitan Water District - Eagle WTP		0.019	Memcor	1994
CA	El Dorado Irrigation District - Strawberry WTP	Placerville	0.132	Memcor	1994
CA	Alleghany County Water District	Nevada City	0.04	Memcor	1995
CA	Butano Canyon Water Company - Cathedral Grove WTP	Pescadero	0.03	Memcor	1995
CA	Inverness Public Utility District - Third Valley WTP	Inverness	0.03	Memcor	1995
CA	Pacific Gas and Electric - Tiger Creek WTP	Amador	0.03	Memcor	1996
CA	Bolinas Community Public Utility District	Bolinas	0.16	Memcor	1996
CA	Inverness Public Utility District - First Valley WTP	Inverness	0.12	Memcor	1996
CA	Lompico County Water District	Felton	0.06	Memcor	1996
CA	California Department of Parks - Portola State Park	La Honda	0.03	Memcor	1996
CA	Cucamonga County Water District	Rancho Cucamonga	4	Memcor	1997
CA	Applegate Water System	Applegate	0.08	Memcor	1997

Appendix A. List of Full-Scale MF/UF Facilities in the United States (as of June 2000) - continued

State	Owner	City	Capacity (mgd)	Manufacturer	Installation Year[2]
CA	California Department of Parks - Van Damme State Park	Modesto	0.03	Memcor	1998
CA	Lake Canyon Mutual Water Company	Los Gatos	0.03	Memcor	1999
CA	Solano Irrigation District	Vacaville	1.4	Pall	2000
CA	Santa Monica	Santa Monica	0.75		NR
CO	Keystone Ski Resort	Keystone	0.06	Memcor	1987
CO	City of Ft Lupton/Hudson	Ft Lupton	2.7	Memcor	1997
CO	Pine Brook Water District	Boulder	0.24	Memcor	1997
CO	Climax Molybdenum Company	Henderson	0.06	Memcor	1997
CO	Town of Dillon	Dillon	0.438	Memcor	1999
CO	Town of Erie	Erie	4	Memcor	1999
CO	Uppper Eagle Regional Water Authority	Vail	5	Pall	2001
CO	City of Westminister	Westminister	12	Pall	2001
CT	Mashantucket Pequot Tribe - Foxwoods Casino	Ledyard	1.8	Memcor	1996
CT	Mashantucket Pequot Tribe - Foxwoods Casino	Ledyard	0.9	Memcor	1999
FL	Marco Island	Marco Island	1.6	Zenon	2000
HI	Hawaii Deparment of Public Safety - Waiawa Correctional Facility	Oahu	0.12	Memcor	1996
HI	City of Maui - Lahaina WTP	Maui	2.7	Memcor	1997
HI	County of Maui - IAO Ditch	Maui	1.8	Memcor	1997
HI	Mililani Memorial Park	Oahu	0.08	Memcor	1997
HI	County of Maui - Kamole WTP	Maui	7.2	Memcor	1998
HI	County of Maui - Olinda WTP	Maui	0.9	Memcor	1998
HI	Honolulu Board of Water Supply - NUUANU Lower Aerator	Honolulu	2	Memcor	1998
ID	Oden Water District	Sand Pointe	1.2	Aquasource	1999
ID	Mullan	Mullan	0.6	Koch	1997
ID	Shoshone Water District	Wallace	1.6	Koch	1997
ID	Boise	Boise	4	Koch	2000
KS	Parsons	Parsons	3	Koch	2000
KS	Public Wholesale Water Supply District #18	Public Wholesale Water Supply District #18	2	Koch	2001
MA	Littleton Water Dept	Littleton	1.5	Koch	1997
MA	Gardner	Gardner	3	Koch	2000
MA	Seekonk	Seekonk	4.3	Zenon	NR
MI	Daviess County	Daviess County	0.288	Koch	2001
MI	Fayette State Park	Fayette	0.03	Memcor	1997
MI	City of Marquette	Marquette	7	Memcor	1997

Appendix A. List of Full-Scale MF/UF Facilities in the United States (as of June 2000) - continued

State	Owner	City	Capacity (mgd)	Manufacturer	Installation Year[2]
MI	Mackinac Island	Mackinac Island	2	Memcor	1998
MI	Linwood Metropolitan Water District	Linwood	0.216	Memcor	1999
MI	St. Clair County Water Supply System - City of Algonac WTP	Algonac	2	Memcor	1999
MI	East China	East China	2.7	Zenon	2000
MI	Caseville	Caseville	1.5	Memcor	NR
MO	Cass County - Public Water Supply District #7	Cass County	1	Koch	1999
NC	King Mountain Club	Highlands	0.03	Memcor	1998
NC	Town of West Jefferson	West Jefferson	0.12	Memcor	1998
NJ	Clyde Potts WTP	Southeast Morris County	0.5	Aquasource	1997
NV	Douglas County	Cave Rock	0.96	Memcor	1997
NV	Douglas County	Cave Rock	0.16	Memcor	1997
NV	U.S. National Park Service - Echo Bay	Lake Mead	0.259	Memcor	1999
NV	U.S. National Park Service - Overton Beach	Lake Mead	0.259	Memcor	1999
NY	New Rochelle	New Rochelle	0.09	Aquasource	1993
NY	City of White Plains	White Plains	1.6	Memcor	1999
OK	Hulah, OK - Water District #20	Hulah	0.08	Koch	1999
OK	Noble County	Lucien	0.12	Memcor	1997
OR	Oregon Parks and Recreation Department	Beverly Beach	0.1	Pall	1999
OR	Oregon Parks and Recreation Department	Bullards Beach	0.1	Pall	1999
OR	Youngs River/ Lewis & Clark District	Astoria	0.5	Pall	2000
PA	Pittsburgh Water & Sewer Authority	Pittsburgh	20	Pall	2000
PA			0.36	Zenon	2000
PA	Littlestown Borough Authority	Littlestown Borough	0.36	Zenon	2000
PA	Newport Borough	Newport Borough	0.18	Zenon	NR
SD	Aberdeen Area Indian Health Service	Ft Thompson	0.5	Memcor	1999
SD	Lower Brule Sioux Tribe	Lower Brule	0.96	Memcor	1999
TN	Lincoln Memorial University	Harrogate	0.3	Koch	1995
TX	Bexar MET	San Antonio	9	Aquasource	1999
TX	Canyon Regional Water Authority	Hays/ Caldwell	1	Koch	2000
TX	Canyon Regional Water Authority	Lake Dunlop	4	Koch	2001
TX	San Patricio Municipal WD	San Patricio	7.8	Pall	1999
TX	Travis County	Austin	2	Pall	2000
UT	Castle Valley Special Service District	Castle Dale	1.2	Memcor	1999
UT	Holliday, UT	Holliday	2.5	Pall	1999

Appendix A. List of Full-Scale MF/UF Facilities in the United States (as of June 2000) - continued

State	Owner	City	Capacity (mgd)	Manufacturer	Installation Year[2]
VA	Washington County Services Authority	Chilhowie	2.5	Koch	1999
VA	Nelson County Public Utility District - Schuyler WTP	Schuyler	0.08	Memcor	1994
VA	Tomsbrook	Tomsbrook	0.12	Memcor	1997
VA	Flying J Travel Pizza	Clear Brook	0.06	Memcor	1997
VA	Augusta County Service Authority - Coles Run WTP	Verona	0.96	Memcor	1998
VA	Town of Rural Retreat	Rural Retreat	0.42	Memcor	1998
VA	Botetourt County - Vista Corp Park WTP	Fincastle	0.06	Memcor	1998
VA	Edinburg	Edinburg	0.18	Memcor	1998
VA	Town of New Market	New Market	1	Memcor	1998
VA	Bedford County Public Service Authority	Bedford	0.06	Memcor	1998
VA	Giles County Public Service Authority	Pembroke	2	Memcor	1999
VA	Town of Dayton	Dayton	2.2	Memcor	1999
WA	City of Aberdeen	Aberdeen	7.11	Memcor	1999
WA	City of South Bend	South Bend	0.84	Memcor	2000
WI	Appleton	Appleton	24	Koch	2001
WI	City of Kenosha	Kenosha	14	Memcor	1998
WI	Manitowoc Public Utilities	Manitowoc	11	Memcor	1999
WY	Meeteetse, WY	Meeteetse	0.6	Pall	2000

1. This list includes only MF/UF installations that are subject to the requirements of the SWTR. It does not include ground water or other applications (such as industrial processes) which are not subject to the provisions of the SWTR. It is based upon information provided by the manufacturers and is believed to be complete and accurate, however, the information provided was not verified and discrepancies may exist.
2. The year of installation was provided by the manufacturers. In some cases this is the project start date, in others it may be the plant start-up date, and in others it may only be an approximation.