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**St. Johns River Water Supply Project
Literature Review of
Surface Water Treatment Technologies**

**ST. JOHNS RIVER WATER SUPPLY PROJECT
LITERATURE REVIEW OF SURFACE WATER TREATMENT TECHNOLOGIES**

BY

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CONTENTS

FIGURES.....	iii
TABLES.....	iv
ACRONYMS AND ABBREVIATIONS	v
INTRODUCTION.....	1
PURPOSE	4
TECHNOLOGIES.....	5
COAGULATION AND FLOCCULATION	5
CLARIFICATION TECHNOLOGIES.....	5
<i>Conventional Clarification.....</i>	6
<i>Inclined (Plate or Tube) Settlers</i>	6
<i>Upflow Blanket Clarifiers</i>	8
<i>Microsand Ballasted Clarifier-Actiflo®</i>	10
<i>Dissolved Air Flotation (DAF).....</i>	15
FILTRATION TECHNOLOGIES	18
<i>Granular Media Filters.....</i>	18
<i>Biologically Active GAC Filters (BAC).....</i>	21
<i>Membrane Filtration</i>	22
MEMBRANE DESALTING TECHNOLOGIES	26
<i>Membrane Treatment Waste Streams.....</i>	31
INTEGRATED MEMBRANE SYSTEMS (IMS) APPLICATIONS.....	33
<i>CSF Pretreatment Followed by RO.....</i>	33
<i>High-rate Clarification Pretreatment Followed by NF.....</i>	34
<i>MF Pretreatment Followed by NF</i>	34
<i>Riverbank Filtration Pretreatment Followed by NF</i>	35
<i>Pretreatment Comparison Studies.....</i>	36
<i>Fouling/Flux Considerations for IMS Applications</i>	37
OXIDATION AND DISINFECTION	38
CHLORINE	38
CHLORAMINES	40
CHLORINE DIOXIDE.....	44
OZONE	45
ULTRAVIOLET LIGHT (UV).....	49
POTASSIUM PERMANGANATE	51
TOC REMOVAL NEEDED FOR FREE CHLORINE AS A RESIDUAL DISINFECTANT.....	56
MEMBRANES.....	56
GAC CONTACTORS	56
ANIONIC RESINS.....	57
OCCURRENCE AND TREATMENT OF ALGAL TOXINS.....	58
BACKGROUND AND OCCURRENCE.....	58
TREATMENT.....	59
<i>Coagulation/Activated Carbon.....</i>	59
<i>Oxidation.....</i>	59
<i>UV.....</i>	60
<i>Membranes.....</i>	60
<i>Combined Treatment Techniques.....</i>	61
<i>Source Water Management Strategies</i>	61
SUMMARY.....	62
REFERENCES.....	63

FIGURES

1	Conventional Treatment, Partial Desalting.....	3
2	Inclined Plate Settles Installation	7
3	Superpulsator® Schematic.....	9
4	Actiflo® Schematic.....	12
5	High-Rate Conventional Treatment, Partial Desalting.....	16
6	DAF Schematic.....	17
7	Granular Media Filter Schematic	20
8	Pressure-Driven Membrane Process Application Guide	23
9a	Immersed Microfiltration Membrane Schematic.....	24
9b	Immersed Microfiltration Membrane Installation.....	24
10	Conventional with MF, Partial Desalting	25
11	Coagulation/MF, Partial Desalting	27
12	RO/NF Membrane Pressure Vessel Schematic	30
13	UV Disinfection Unit.....	52

TABLE

1	Superpulsator® Installations in the U.S. on Surface Waters.....	11
2	Actiflo® Installations in the U.S. on Surface Waters.....	14
3	DAF Installations in the U.S. on Surface Waters	19
4	Large MF/UF Installations in North America.....	28
5	Advantages and Disadvantages of Using MF/UF Filtration as Compared to Granular Media Filtration.....	29
6	NF/RO Installations in North America	32
7	Applicability of Oxidants/Disinfectants in Water Treatment.....	39
8	Advantages and Disadvantages of Using Chlorine	41
9	Advantages and Disadvantages of Using Chloramines.....	43
10	Advantages and Disadvantages of Using Chlorine Dioxide	46
11	Advantages and Disadvantages of Using Ozone	50
12	Advantages and Disadvantages of Using UV Disinfection	53
13	Advantages and Disadvantages of Using Potassium Permanganate.....	55

ACRONYMS AND ABBREVIATIONS

AOC	assimilable organic carbon
AWWA	American Water Works Association
BAC	biologically active carbon
Br ⁻	bromide
BrO ₃ ⁻	bromate
BW	brackish water
CA	cellulose acetate
Cl ₂ :N	chlorine to nitrogen (ratio)
CSF	coagulation/sedimentation/filtration (conventional treatment)
CT	contact time
D/DBP	Disinfectant/Disinfectant Byproduct
D/DBPR	Disinfectant/Disinfectant Byproduct Rule
DAF	dissolved air flotation
DOT	U.S. Department of Transportation
EC	enhanced coagulation
EPA	U.S. Environmental Protection Agency
ESWTR	Enhanced Surface Water Treatment Rules
GAC	granular activated carbon
gpm/ft ²	gallons per minute per square foot
HAA	haloacetic acid
HCl	hydrochloric acid
HOCl	hypochlorous acid
IMS	Integrated Membrane Systems
LOX	liquid oxygen
LT2	Long Term 2
MF	microfiltration
mg/L	milligrams per liter
MGD	million gallons per day
MIB	2-methylisoborneol
mm	millimeter

Table of Contents

MRDL	maximum residual disinfectant level
MTC	mass transfer coefficient
NCl_3	trichloramine
NH_2Cl	monochloramine
NHCl_2	dichloramine
nm	nanometer
NOM	natural organic matter
NTU	nephelometric turbidity unit
$^{\circ}\text{C}$	degrees Celsius
OCl^-	hypochlorite ion
OH^-	hydroxyl ion
PAC	powered activated carbon
RO/NF	reverse osmosis/nanofiltration
SW	surface water
SWTR	Surface Water Treatment Rule
T&O	taste and odor
TDS	total dissolved solids
TFC	thin film composite
TM	technical memorandum
TOC	total organic carbon
TTHM	trihalomethane
UF	ultrafiltration
UV	ultraviolet
WTP	water treatment plant
$\mu\text{g/L}$	micrograms per liter
μm	micrometer

INTRODUCTION

Selecting treatment technologies for any water treatment system is driven primarily by drinking water regulations and the meeting of consumer expectations. For surface water treatment, the primary regulations are the Enhanced Surface Water Treatment Rules (ESWTR) and the Disinfectant/Disinfectant Byproduct (D/DBP) Rules. The planning process for any treatment facility on the St. Johns River has a 5- to 10-year window. Therefore, upon construction of this facility, compliance will be required for the Long Term 2 (LT2) ESWTR and Stage 2 D/DBP rules. To meet these regulations, the following primary analytes need to be targeted for removal:

- Organics
- Turbidity
- *Giardia*
- Viruses
- *Cryptosporidium*

The approach to removing these analytes is multibarrier treatment involving the following unit processes:

- Coagulation and flocculation
- Clarification
- Granular media filtration
- Disinfection

This approach, termed conventional treatment, requires each process to remove water-borne pathogens, with each process operating at a high rate of efficiency. The effectiveness is cumulative, in that each unit process helps the subsequent unit process work more effectively than if operated alone. For instance, effective coagulation and flocculation will improve the performance of the clarification process, and effective clarification will improve the performance of filtration. After filtration, the filtered water is considered “clean,” which increases the effectiveness of disinfection. Disinfection is used to inactivate any of the pathogens that may have passed through the previous barriers. In this manner, each step plays an important role in the removal and inactivation of water-borne pathogens.

The St. Johns River water has typical surface water characteristics for Florida. The characteristic dark brown color of the water is due to the

organics in the water. These organics are mostly dissolved humic and fulvic matter. The turbidity in the water results from small particles that make the water “cloudy” and must be removed to low levels to increase the efficiency of disinfection. As in all surface water treatment systems, the target pathogens of concern for the St. Johns River are *Giardia lamblia*, *Cryptosporidium*, and viruses.

Additionally, the St. Johns River has unique characteristics due to the brackish content of the water. This brackish surface water has total dissolved solids (TDS) concentrations ranging from 400 milligrams per liter (mg/L) to 1,060 mg/L and chloride concentrations ranging from 139 mg/L to 455 mg/L. Because of these unique characteristics, partial desalting must be used with conventional treatment. The following major processes that would be associated with this integrated treatment system are illustrated in Figure 1.

Figure 1 illustrates pretreatment by conventional water treatment, integrated with reverse osmosis/nanofiltration (RO/NF) and followed by primary disinfection, and residual disinfectant. From Figure 1, the conventional treatment step consists of coagulation, flocculation/sedimentation, and granular media filtration (CSF). Following the granular media filters, some of the stream is applied to the RO/NF membranes with some bypassing the RO/NF stream to be blended. The bypass is used since 100 percent membrane treatment will not be required during less brackish conditions of the year. The process technologies in Figure 1 illustrate the basic treatment steps that would be applied to treat water from the St. Johns River. For the purposes of this report, the combination of pretreatment technologies (such as CSF) followed by membrane desalting for surface water treatment is termed Integrated Membrane Systems (IMS).

These treatment steps, as well as IMS technology applications, are discussed in greater detail in this technical memorandum (TM). The subsequent sections will focus on the following treatment steps:

- Coagulation and flocculation
- Clarification technologies (conventional and high-rate)
- Filtration technologies (granular media filtration, microfiltration, and ultrafiltration)
- Membrane desalting technologies (nanofiltration and reverse osmosis)

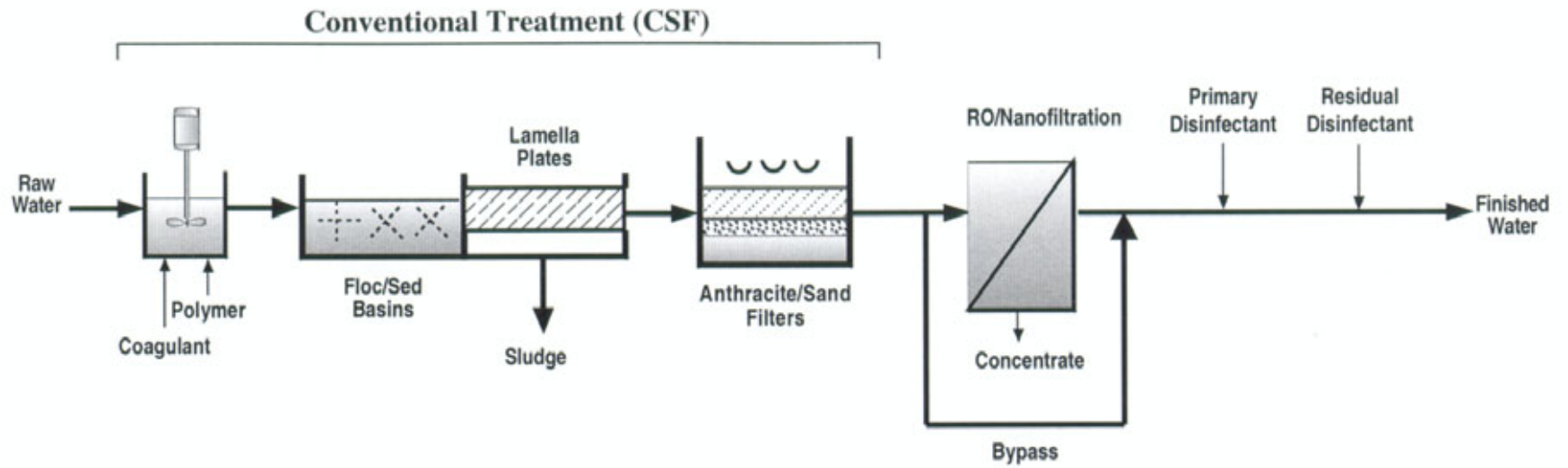


Figure 1. Conventional Treatment, Partial Desalting

- Integrated Membrane Systems (IMS) applications
- Primary disinfection (ozone, chlorine, chlorine dioxide, and ultraviolet [UV])
- Residual disinfection (chloramines)

PURPOSE

This treatability study is being conducted by the St. Johns River Water Management District (SJRWMD) and CH2M HILL to quantify the treatment requirements and costs for a potential surface water treatment facility to be located along the reach of the St. Johns River between the southern end of Lake Monroe in Sanford and De Land. Currently, the public supply utilities in this area have been relying on groundwater supply for their treatment facilities.

The requirements and treatment technology for groundwater treatment differ significantly from those for surface water treatment. Therefore, the purpose of this TM is to provide a general overview and basic summary of the different types of treatment technology that could potentially be applied to this surface water source. In addition to a general overview, this TM will also reference recent studies that are applicable to treatment of surface water from the St. Johns River.

It is also intended that the stakeholders use this summary to become more familiar with surface water treatment technology during the technology evaluation and selection process of this project.

TECHNOLOGIES

COAGULATION AND FLOCCULATION

The first step in water treatment is coagulation. The coagulation step is necessary to reduce the organics and turbidity in the water and consists of a rapid mixing with coagulant addition.

Particles and organics in natural water systems are negatively charged and subsequently repel one another. Coagulants added to the water form positively charged complexes that neutralize (destabilize) the negatively charged particles.

The purpose of the rapid mixer is to achieve the initial contact between the water and coagulant to form the positively charged coagulant complexes.

Enhanced coagulation (EC) is typically performed in the conventional coagulation process to increase total organic carbon (TOC) removal in the process. EC consists of adjusting the coagulation pH and coagulant dose to optimize TOC removal.

Once the negatively charged particles have been destabilized, these particles begin to stick together and form *floc*. As more particles stick together, the *floc* grows and becomes dense enough to settle from the water as sludge in the clarification step. Without proper coagulation, the subsequent clarification and filtration steps can not function properly.

This project will evaluate four coagulants for organic and turbidity removal by conducting bench-top experiments. Based on the results, one coagulant will be chosen and used for the remainder of the study.

Three previous studies on similar high TOC surface water (City of Tampa, Florida, 1998; City of Cocoa, 1995; and City of Melbourne, 1999) found that coagulation with ferric sulfate coagulant at a pH range of 4 to 4.5 achieved higher TOC removals than coagulation with aluminum sulfate. In all three cases, the new facilities were constructed using ferric sulfate as the coagulant for TOC removal.

CLARIFICATION TECHNOLOGIES

The next step in conventional water treatment is the clarification (or sedimentation) step. Clarification is used to remove the floc formed in

the coagulation/flocculation step as sludge. Clarification has been used at water treatment plants (WTPs) for many years as an effective means of treatment to produce a clarified effluent for further treatment by filtration.

The major types of clarification that will be discussed include:

- Conventional clarification
- Inclined settlers
- Upflow blanket clarifiers
- Microsand ballasted clarifiers
- Dissolved air flotation clarifiers

Conventional Clarification

Conventional sedimentation uses very large basins and allows the settling of the floc to occur by gravity. These conventional tanks have long detention times (3 to 4 hours for gravity settling).

Conventional clarification requires a large area to build the tanks for sedimentation. Surface loading rates must be low (0.3 to 1.0 gallons per minute per square feet [gpm/ft²]) to achieve proper operation and an acceptable effluent. Mechanical equipment, such as rakes, is required to withdraw sludge from the sedimentation basin.

Inclined (Plate or Tube) Settlers

Inclined plates can be installed in a sedimentation tank to improve clarification. Many high-rate clarifiers, including the Superpulsator[®] and Actiflo[®] (both to be discussed later), use inclined settlers.

Typical inclined settlers apply the flocculated water upward through the channels formed by the inclined surfaces. Tube settlers are generally used in this arrangement, and are the most popular method of inclined settling.

Figure 2 illustrates inclined plates (lamella plates) installed in a sedimentation basin. The advantage of inclined settlers is that increased surface loading rates (1 to 5 gpm/ft²) can be used to achieve proper settling. Also, the plates or tubes can be retrofitted to an existing sedimentation tank.

The material costs for the plates or tubes can vary, depending on the materials required for installation. The surface loading rates are higher than conventional clarification. Based on the configuration of the

plates/tubes, removal of solids that attach to the plates can be a



maintenance issue in some configurations.

Figure 2. Inclined Plate Settles Installation

For similar high TOC surface waters, pilot studies conducted by the City of Cocoa, Florida (1995) and City of Tampa (1998) found that inclined plate settlers provided adequate clarification and also provided low turbidity levels for subsequent filter runs.

Plate and tube settlers have been in use for many years in water treatment, and are a widely accepted technology for clarification. For the purposes of this study, any new facility applying conventional treatment, at a minimum, would have plate/tube settlers. Therefore, conventional treatment referred to in this report (see Figure 1) will assume a sedimentation basin installed with plate settlers.

Upflow Blanket Clarifiers

Upflow blanket clarifiers, also known as solids contact units, combine rapid mixing, flocculation, and sedimentation in one unit. These clarifiers are designed to maintain a large volume of flocculated solids within the unit, which enhances flocculation by encouraging interparticle collisions. The flocculated solids (solids blanket) are usually maintained at a set volume in the contactor, and cohesion of the blanket is achieved through the use of a polymer in addition to the coagulant.

Upflow clarifiers are popular because of their reduced size, which occupies less land space. Higher surface loading rates in these units can be used to produce more water per unit area than conventional sedimentation. One such unit is the Superpulsator[®], manufactured by Infilco Degremont, Inc. Figure 3 illustrates a schematic of the Superpulsator[®].

In the Superpulsator[®], rapid mixing occurs upstream of the unit where coagulant is added to begin the formation of floc. After rapid mixing, a polymer is added to promote sludge blanket cohesion. The coagulated water then enters the unit. The Superpulsator[®] uses a vacuum pump and vacuum chamber to produce a pulsing effect within the flocculation zone. The pulsing of the solids blanket expands the blanket and increases the rate of interparticle collisions. Clarification occurs with the use of inclined plates above the sludge blanket that settle the remaining floc. The clarified effluent is discharged at the top of the unit. Solids are maintained in the unit at a set height by use of a solids overflow weir. Solids overflow into a hopper and can be removed at a set interval.

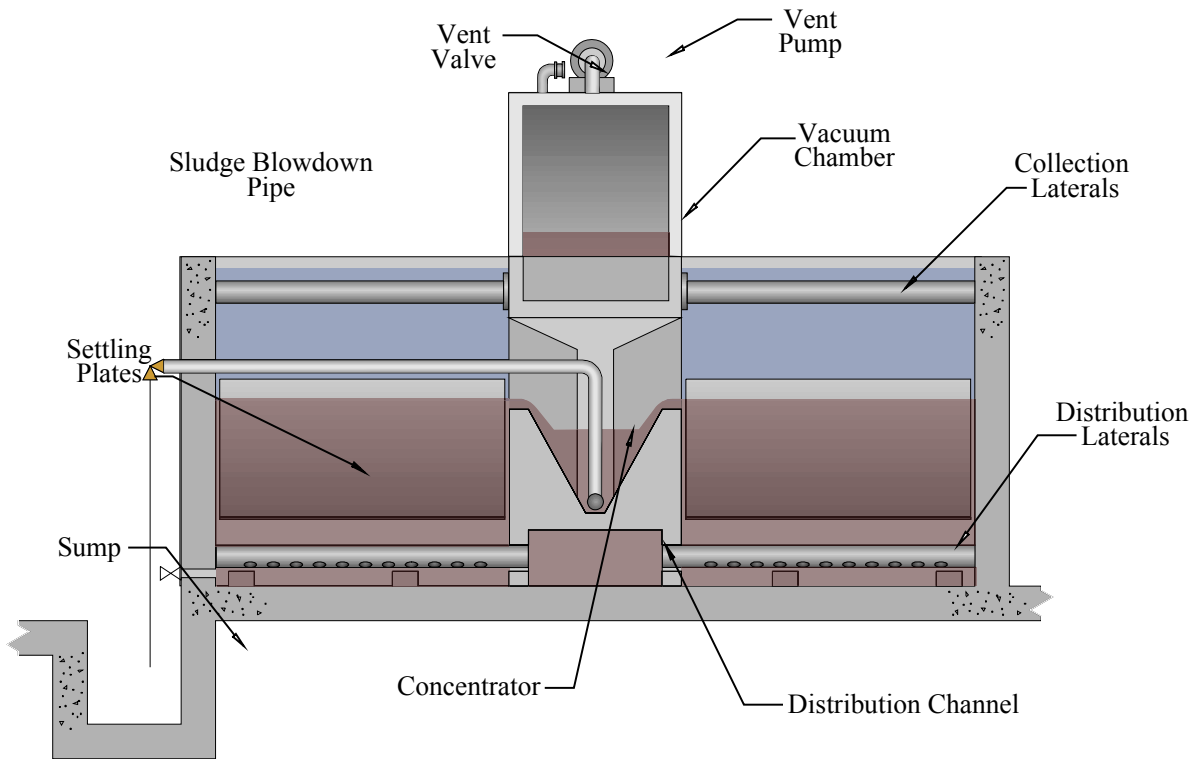


Figure 3. Superpulsator® Schematic

Typical solids concentrations range from 0.5 to 2 percent in the concentrated sludge.

These units have loading rates of up to 3 gpm/ft². At these loading rates the detention time is approximately 45 minutes, much less than conventional clarification. A polymer is required at doses between 0.1 to 0.4 mg/L for cohesion of the sludge blanket.

These units have no submerged moving parts or mechanisms, and the sludge blanket is self-leveling. At the high loading rate of 3 gpm/ft², much less surface area is required for equivalent treatment as compared to a conventional process. These units have been shown to be effective at removing turbidity and TOC. Since the sludge is partially recirculated increasing the sludge age, use of powered activated carbon (PAC) is particularly effective at removing taste and odor (T&O)-causing compounds in these units. Along with T&O-causing compounds, TOC can also be adsorbed in the solids blanket containing PAC.

In 1999, Alvarez et al. reported that for treatment of water from the St. Johns River at Lake Washington, the Superpulsator[®] was able to achieve turbidity levels below 0.5 nephelometric turbidity units (NTUs) with subsequent filter runs over 35 hours. In addition, it was reported that after effective coagulation, the Superpulsator[®] was able to achieve greater than 3-log removal of *Cryptosporidium*. Previous studies have found that the Superpulsator can retain a blanket of light organic floc up to TOC levels of 15 mg/L without the addition of PAC for weight. However, Alvarez reported that at TOC levels in excess of 25 mg/L, without PAC addition, the sludge blanket of the Superpulsator[®] was unstable in retaining the light organic floc.

There are more than 75 municipal water treatment plants in the U.S. that are successfully using this technology to meet water quality goals, and it has become an accepted standard clarification process in many states. Table 1 lists some of the major Superpulsator[®] installations in the U.S.

Microsand Ballasted Clarifier-Actiflo[®]

Actiflo[®] is a high rate clarification process that uses microsand-enhanced flocculation and lamellar settling to produce a clarified effluent. Figure 4 illustrates the Actiflo[®] process.

Table 1. Superpulsator® Installations in the U.S. on Surface Water

Plant	Location	Start Date	Capacity (MGD)	Source Water
Cornish Creek WTP	Covington, GA	1992	3.0	Surface
Pistapaug Pond WTP	Wallingford, CT	1993	12.0	Surface
Schriever WTP	Terrebonne, LA	2000	4.0	Reservoir
F.L. Ward WTP	High Point, NC	1999	16.1	Reservoir
Sweeney WTP	Wilmington, NC	1998	5.0	River
Forsyth County WTP	Cumming, GA	1999	5.0	Reservoir
Harwoods Mill WTP	Newport News, VA	1988	31	Reservoir
Portsmouth WTP	Portsmouth, VA	1995	15	Reservoir
Hyde Park Fire & Water District	Dutchess County, NY	1994	6.0	Reservoir
Hays Mine WTP	Pittsburgh, PA	1990	60.0	Surface
LaGrange WTP	LaGrange, GA	1992	6.8	Surface
Santee Cooper WTP	Moncks Corner, SC	1993	6.0	River

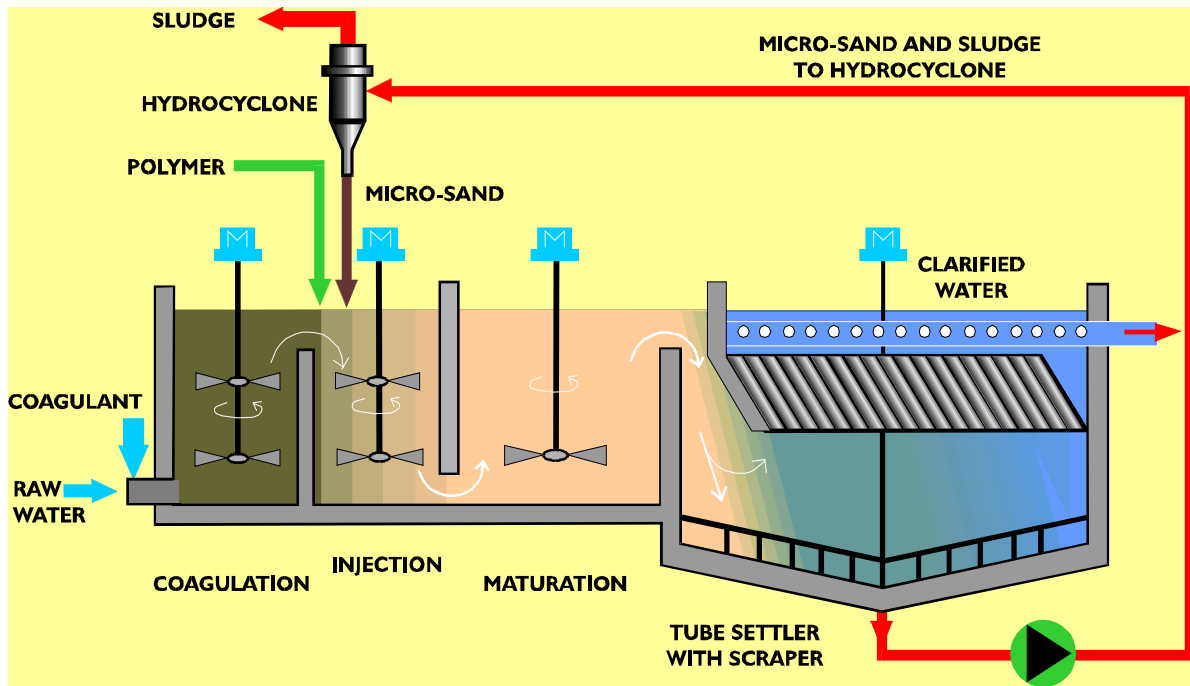


Figure 4. Actiflo® Schematic

The process consists of a rapid mix in which a coagulant is added, followed by an injection tank, where micro-sand and a polymer are added in a high energy mixing environment. Following this is a maturation zone, where a lower energy mixing takes place to build the floc. The detention time for all these steps is about 6 minutes. The water then enters the settling tank where the micro-sand flocs settle out quickly. Further clarification occurs with inclined tube settling as the water overflows into the effluent channels. Total retention time is between 10 and 15 minutes.

The micro-sand sludge at the bottom of the settling tank is pumped to a hydrocyclone, where the sand is separated from the sludge by centrifugal force. The sand is then returned to the head of the process for reintroduction in the injection tank. The separated sludge is removed at concentrations of 0.1 to 0.2 percent typically requiring further thickening.

Advantages of this process include very high loading rates (up to 30 gpm/ft²) that can significantly reduce surface area requirements. The use of microsand also allows the system to easily adjust to changing raw water quality or process flow rates. The system also requires a significant amount of energy beyond other conventional processes. The microsand must be replenished due to minor loss in the separation process.

In 1999, Alvarez et al. reported that for treatment of water from the St. Johns River at Lake Washington, the Actiflo[®] process was able to achieve turbidity levels below 0.3 NTU with subsequent filter runs over 50 hours. In addition, it was also reported that after effective coagulation, the Actiflo[®] was able to achieve greater than 4-log removal of *Cryptosporidium*. Alvarez also reported that with the microsand addition, the Actiflo[®] was able to achieve a more stable operation than the other three clarifiers evaluated.

Table 2 summarizes the current Actiflo installations in the U.S. Currently, there are nine installations in operation in the U.S., the largest of which is a 27 million gallons per day (MGD) installation in Wyoming. Three additional plants are slated for startup in 2001. These three plants, located in Florida, treat high TOC surface water. One plant is located on the St. Johns River at Lake Washington in Melbourne, Florida. Larger installations up to 150 MGD exist overseas. Table 2 summarizes the Actiflo[®] installations in the U.S.

Table 2. Actiflo® Installations in the U.S. on Surface Waters

Location	Start Date	Capacity (MGD)
Golden, CO	1998	11
Casper, WY	1999	27
Newport, KY	1999	15
Salt Lake City, UT	2000	20
Sharon, PA	2000	16
Spotsylvania, VA	2000	12
Statham, GA	2000	1
Lincolnton, NC	2000	9
Bardstown, KY	2000	8
Tampa, FL	2001	40
Tampa Bay, FL	2001	60
Melbourne, FL	2001	20

The high-rate Actiflo® process can be used in place of a conventional coagulation, flocculation, and clarification step for pretreatment for the membranes. Figure 5 illustrates an example of the Actiflo® process feeding the membrane desalting stream. In this arrangement, other high-rate clarifiers such as the Superpulsator® or dissolved air flotation (DAF) can be used in the step for the membrane pretreatment.

Dissolved Air Flotation (DAF)

DAF was first used for clarification in South Africa and Scandinavia in the 1960s and became more widely used worldwide in the 1980s and 1990s. DAF is becoming more common in the U.S. because it provides a cost-effective alternative to conventional sedimentation. DAF has also been successfully used to remove algae.

A typical DAF schematic is illustrated in Figure 6. In DAF clarification, the solids are separated out by floating the floc to the water surface, as opposed to settling to the bottom of the basin. The process introduces air bubbles at the bottom of the contactor to float the floc. The air bubbles are produced by reducing to ambient pressure a pressurized recycle water stream saturated with air. The “float” is scraped from the top of the reactor, and the clear water is removed from a location well beneath the surface.

DAF is particularly effective in removing solids, such as algae, which are close in density to that of water and, thus, are resistant to removal by sedimentation. DAF has been shown to be as effective as conventional processes at removing low levels of turbidity and TOC. It is also able to have an effect on some T&O compounds that can be readily stripped by the dissolved air in the water. DAF provides enhanced particle contact that can increase the removal of small particles and small diameter pathogens, such as *Giardia* and *Cryptosporidium*.

DAF applications can have loading rates up to 8 gpm/ft². Detention times required for both flocculation and clarification are less than in conventional treatment. These higher loading rates result in a smaller facility footprint than conventional clarification. DAF also produces a more concentrated sludge than conventional treatment. DAF also requires much more energy input than conventional treatment, and requires considerably more mechanical equipment to run the system.

In 1999, Alvarez et al. reported that for treatment of similar water for the St. Johns River at Lake Washington, DAF was able to achieve turbidity levels below 1 NTU with subsequent filter runs of 30 hours.

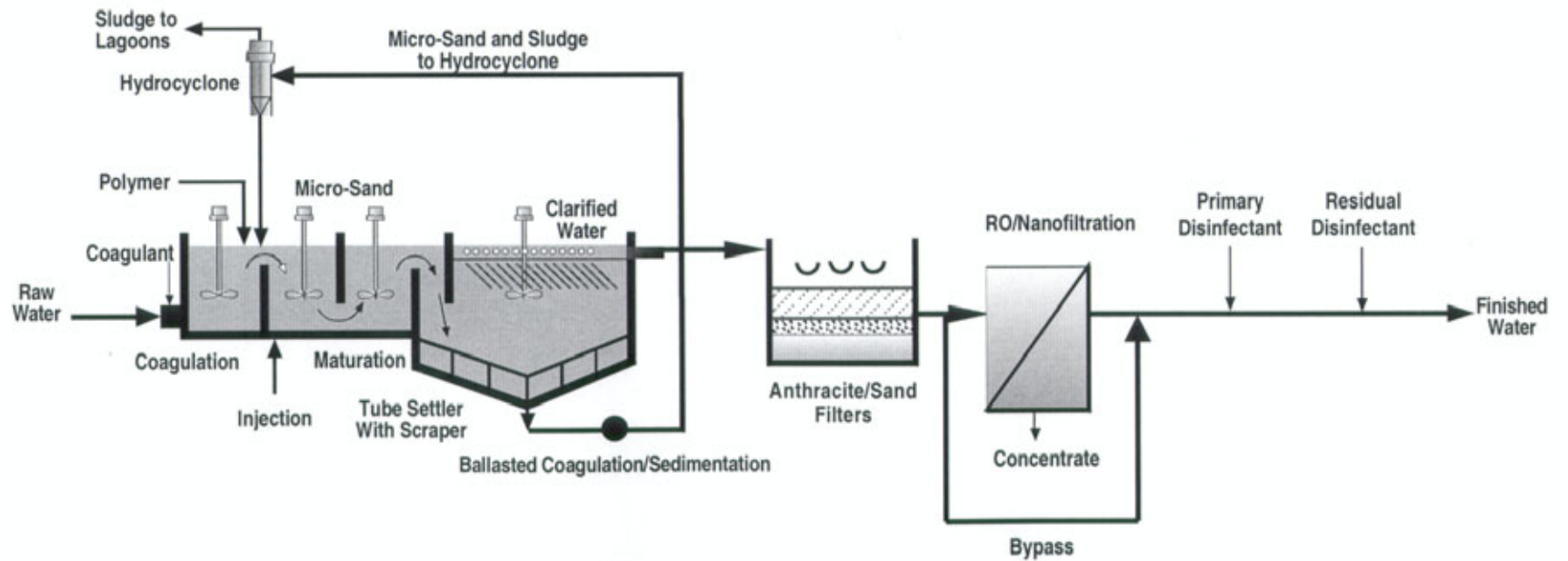


Figure 5. High-Rate Conventional Treatment, Partial Desalting

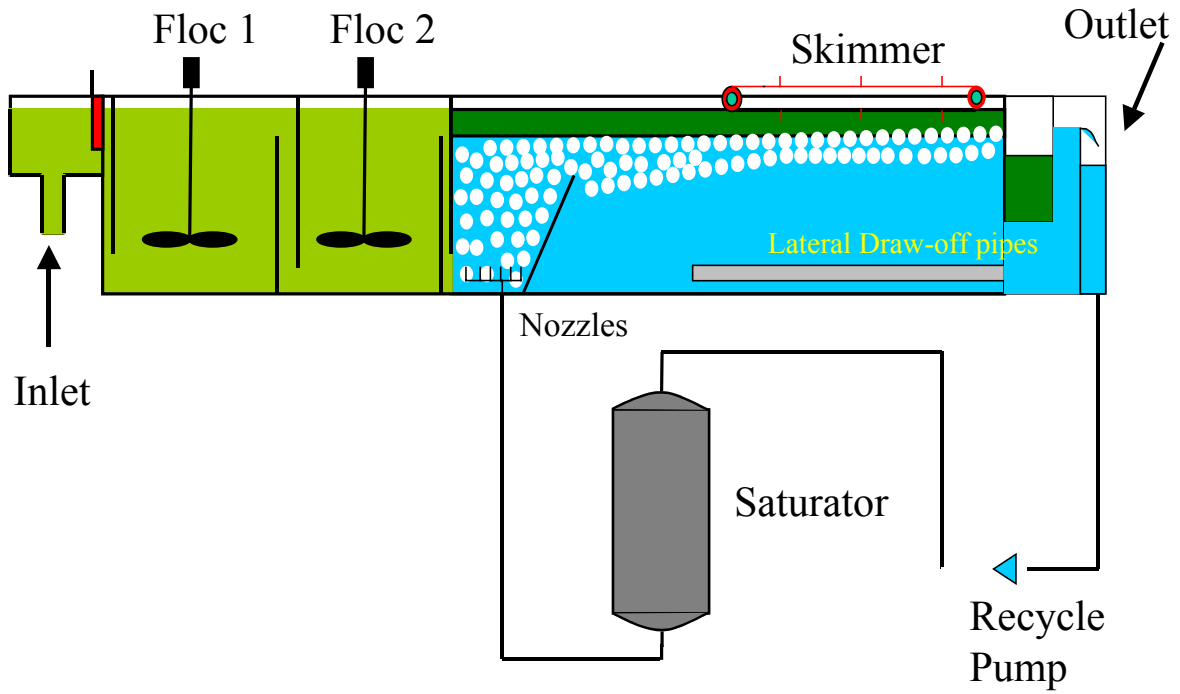


Figure 6. DAF Schematic

In addition, it was reported that after effective coagulation, DAF was able to achieve greater than 2.5-log removal of *Cryptosporidium*. Alvarez also reported that with the high doses of iron coagulant required to remove the TOC and color, the DAF system was unable to float all of the solids produced, especially at the high temperatures during the summer when the saturation of oxygen is at a minimum. These conditions for raw water TOC levels in excess of 25 mg/L resulted in a very unstable performance from the DAF clarifier.

DAF is currently installed at roughly 15 plants in the U.S. for drinking water treatment. Table 3 lists the plants in the U.S. with capacity greater than 0.5 MGD.

Note that many of the applications listed in Table 3 are in the northeastern United States. These source waters are typically much lower in TOC and turbidity than Florida surface waters.

FILTRATION TECHNOLOGIES

In the multibarrier approach to water treatment, the process after coagulation/flocculation/clarification is the filtration step. The filtration step can be conducted by using granular media filters or membranes. The most common filtration process is media filtration with membrane filtration a more recent application. The purpose of the filtration process is to remove the small particles and pathogens not removed by the coagulation/flocculation/clarification step.

Granular Media Filters

The most common filtration step is granular media filtration. Most granular media designs are monomedia or dual media designs using sand, anthracite, granular activated carbon (GAC), or combinations of two of the media types. Figure 7 illustrates a typical schematic for a granular media filter.

Dual media filters are the most common filters found at water treatment plants today. Most designs are anthracite/sand or GAC/sand. The dual media design is typically a shallow bed with 18 to 24 inches of anthracite or GAC followed by 12 inches of sand. Media sizes can vary to balance the particle removal and headloss, but the most common media size for the sand in the filter is 0.5 millimeters (mm) (effective size), while the anthracite and GAC can range from 0.8

to 1.2 mm (effective size). Dual media filters exhibit additional headloss as compared to deep bed monomedia designs, but provide

Table 3. DAF Installations in the U.S. on Surface Waters

Plant	Location	Start Date	Capacity (MGD)
Millwood WTP	New York	1993	7.5
Beaver Run WTP	Westmoreland, PA	1995	3.5
Danbury WTP	Danbury, CT	1998	5.5
Rockport WTP	Massachusetts	1998	1.2
Tazewell RWA	Virginia	1999	2.0
Lee Hall WTP	Newport News, VA	2000	52.0
Penn Hill WTP	West Chester, PA	1998	3.0
Table Rock WTP	Greenville, SC	1999	75.0
Fresh Pond WTP	Cambridge, MA	2000	24.0
Wangum WTP	Norfolk, CT	1996	0.5
Lakeville WTP	Lakeville, CT	1996	0.5
Hemlocks WTP	Fairfield, CT	1997	50.0

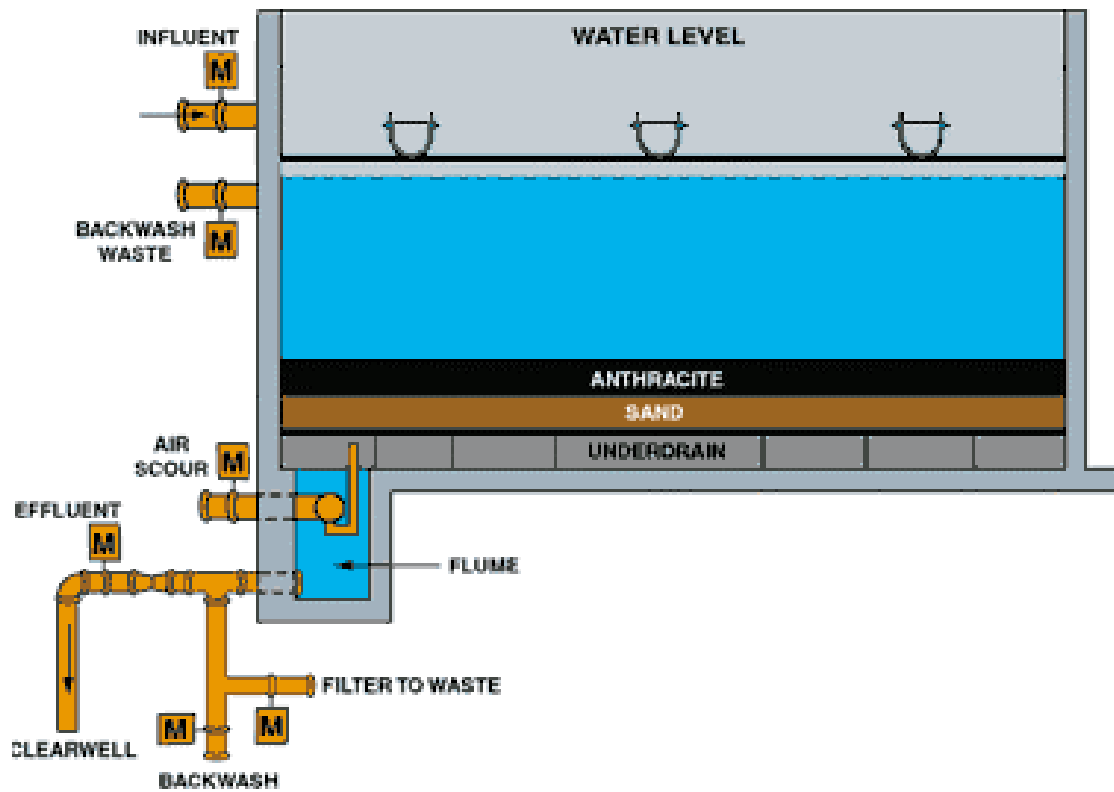


Figure 7. Granular Media Filter Schematic

equal finished water quality. The smaller sand media provides a barrier to particle breakthrough at higher loading rates or long filter run times. The finer the media, the greater the protection; however headloss increases with the finer media, thereby reducing filter productivity.

Monomedia filters are usually deep bed GAC or anthracite filters that are run at high loading rates with coarse media (1.2 to 1.5 mm effective size). Typical depths range from 5 to 8 feet. The high loading rates and increased media depth over conventional dual media filters increases the headloss through the filter. However, this increase in headloss is offset by increased media size. Advantages to this type of filter design include reduced headloss and production of more water per unit area versus dual media designs. Deep bed filters also provide flexibility to use different media designs as future regulations become more stringent for finished water. Deep bed monomedia filters can produce similar finished water quality as dual media designs. Disadvantages to this type of filter include the increased possibility of particle and turbidity breakthrough in long filter runs, and the additional capital costs for deep filter boxes.

Biologically Active GAC Filters (BAC)

Biologically active GAC filter (BAC) is another necessary filtration step that is generally required after ozonation. BAC filters are used following ozonation to provide DBP control and produce a biologically stable filter effluent. Either a deep bed monomedia GAC or dual media sand/GAC filter is used. Biological growth can be supported on GAC, sand, and anthracite because of the surface area available to the bacteria.

Advantages of BAC include:

- Production of a biologically stable filter effluent after ozonation that reduces regrowth in the distribution system
- Reduction in the quantity of organic precursors to DBPs
- Reduction in the disinfectant demand of the filter effluent, thereby reducing the amount of disinfectant required in the finished water and possibly reducing DBPs
- Removal of many ozone byproducts

Membrane Filtration

Membrane filtration (using MF or UF membranes) can be used in place of granular media filtration. UF and MF membranes are limited to the rejection of particles and pathogens and do not have small enough pores to remove TDS or salts such as chloride as illustrated in Figure 8.

UF membranes have a nominal pore size of between 0.003 and 0.03 micrometers (μm) and can reject dissolved organics. MF membranes have a nominal pore size of between 0.05 and 0.5 μm and are unable to remove organics unless supplemented with coagulation and flocculation.

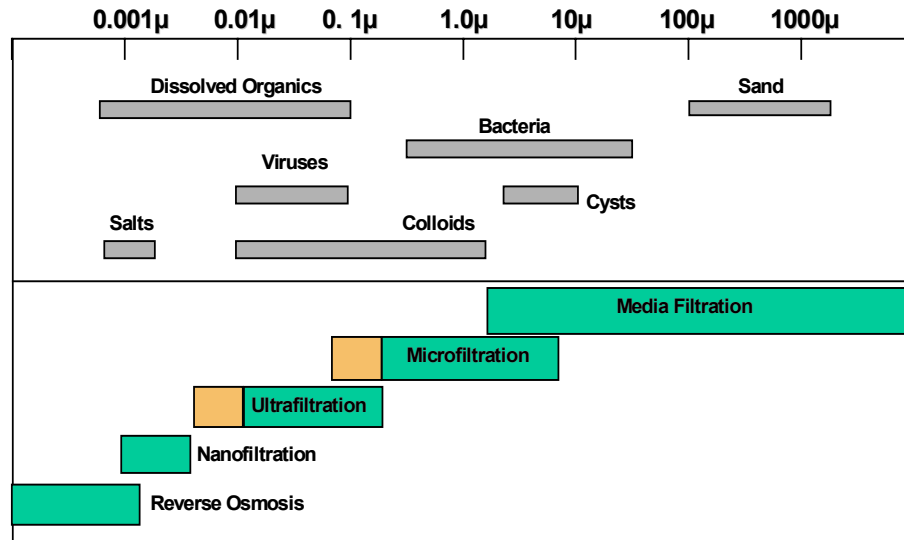
MF membranes, because of the pore size, are limited to rejection of *Giardia* and *Cryptosporidium*, while UF membranes have the added feature of rejecting not only *Giardia* and *Cryptosporidium* but also viruses.

The earliest commercially available UF and MF membrane systems designed to filter clarified water are known as pressure-driven, hollow-fiber membranes. The liquid is passed either from the outside to the inside (lumen) of the hollow fiber (outside-in) or from the lumen to the outside of the fiber (inside-out). The hollow fibers are installed in vessels, which provide support for the pressure necessary to drive the liquid through the membrane pores. This type of filter is commercially available from Aquasource (UF) and Memcor (MF). Other suppliers active in the U.S. include Pall (UF or MF), Hydranautics (UF), PCI (UF), and Smith and Loveless (UF). These units use water, air, or air/water backwash systems.

Immersed membranes are a relatively recent development in membrane process configuration. In this process, hollow fiber membranes are installed (immersed) in a vessel and a small vacuum is applied to their downstream side. Immersed membranes are available from Zenon (UF) and Memcor (MF). With the Zenon ZeeWeed[®] Process, air is introduced at the bottom of the membrane feed vessel, which creates turbulence in the tank effectively scrubbing the solids from the membrane surface. Memcor uses air only in the backwash of its immersed membranes. An example schematic of an immersed membrane is illustrated in Figure 9a. An example of an immersed membrane installation is illustrated in Figure 9b.

As mentioned previously, MF or UF technology can be used in place of granular media filtration. Figure 10 illustrates an example of

an



μ = micro (micrometer)

Figure 8. Pressure-Driven Membrane Process Application Guide

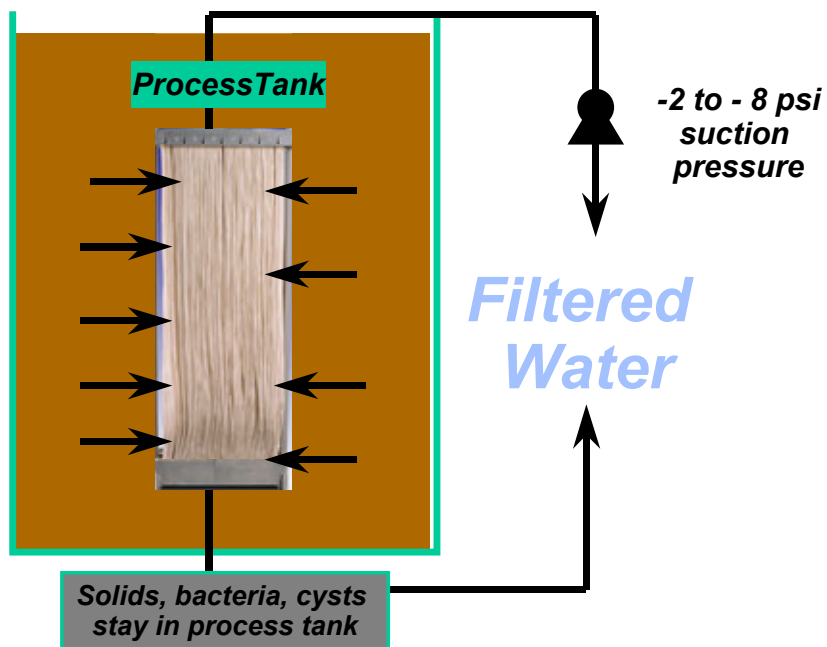


Figure 9a. Immersed Microfiltration Membrane Schematic



Figure 9b. Immersed Microfiltration Membrane Installation

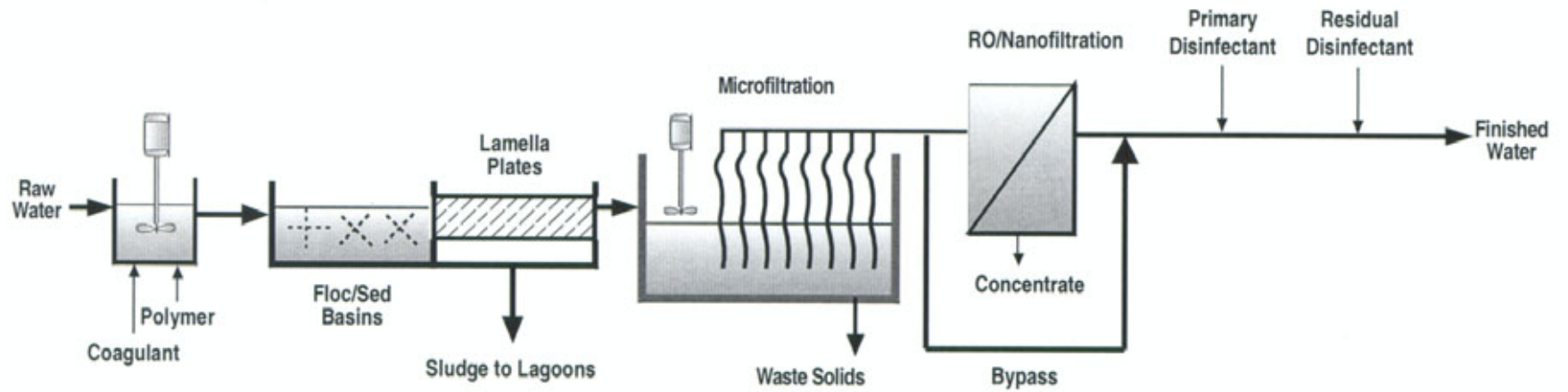


Figure 10. Conventional with MF, Partial Desalting

MF unit for membrane pretreatment. Other potential arrangements include coagulation/high-rate clarification supplying an MF or UF process for membrane pretreatment. In some cases, coagulation can be applied with an immersed MF technology to be used as a one step pretreatment for NF or RO. In this application, the immersed MF unit serves as both the clarifier and gravity filter. This potential coagulation/MF/RO schematic is illustrated in Figure 11.

MF and UF units are now in use or in planning at many locations for potable water treatment. Some of the recent large installations in North America are shown in Table 4. MF and UF costs have significantly decreased in the past few years with the development of the technology. The advantage of a solids separation barrier with a known diameter makes MF or UF a feasible technology for control of microbes and provides effective filtration after clarification. Product water recovery for MF and UF membranes ranges from 85 to 95 percent and can be even higher in some cases.

Table 5 lists the advantages and disadvantages of MF/UF filtration compared to granular media filtration.

MEMBRANE DESALTING TECHNOLOGIES

As discussed earlier, the typical multibarrier approach would include the coagulation/clarification/filtration steps. However, since the St. Johns River is also brackish with high levels of TDS and chloride, a membrane desalting step must be used in addition to the typical multibarrier processes.

Desalting membranes primarily include RO membranes and some NF membranes.

As illustrated in Figure 8, NF membranes remove particles but also can remove TOC and some dissolved salts. RO membranes remove everything the other membranes do, including most dissolved salts. A schematic of a desalting spiral wound membrane pressure vessel is illustrated in Figure 12.

Due to the high levels of particles and TOC in the raw water, in order to operate NF or RO on a surface water, the feed water must be pretreated with conventional treatment or an equivalent. As shown earlier, Figure 1 illustrates the RO desalting step following the CSF pretreatment.

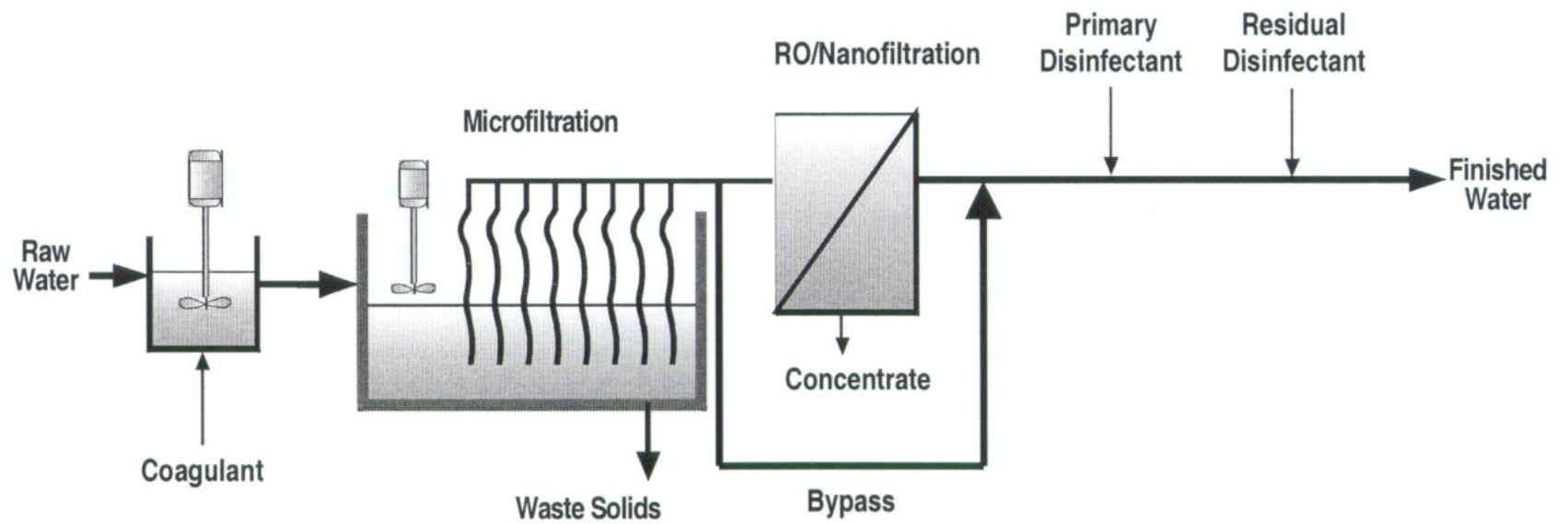


Figure 11. Coagulation/MF, Partial Desalting

Table 4. Large MF/UF Installations in North America

Location	Type	Startup Date	Capacity (mgd)
Kenosha, WI	MF	December 1998	14
Manitowoc, WI	MF/UF	May 1999	11
Thunder Bay, Ontario	MF	September 1998	9
San Antonio, TX	UF	1999	9
San Patricio, TX	MF	September 1999	7.8
Collingswood, Ontario	Immersed UF	December 1998	7.4
Maui, HI	MF	May 1998	7.2
Marquette, MI	MF	October 1997	7
Scottsdale, AZ	MF/UF	February 1999	6
Saratoga, CA	MF	March 1994	5
Cucamonga County, FL	MF/UF	May 1997	4
Brooklyn, NY	MF/UF	February 1999	3.5
Ft. Lupton, CO	MF/UF	December 1996	3
Millersburg, OR	MF	2001	3
Warranton, OR	MF	2001	6
Youngs River, OR	UF	2001	3

Table 5. Advantages and Disadvantages of Using MF/UF Filtration as Compared to Granular Media Filtration

Advantages	Disadvantages
Increased particle and turbidity removal	Issues of membrane integrity
Reliability of consistent effluent quality	Need to clean membranes using acids or surfactants (new waste stream)
Removal of pathogens (protozoa and bacteria [MF], protozoa, bacteria, viruses [UF])	Production of a more concentrated backwash stream (particles and pathogens)
Ease of automation of the treatment system	Capital costs still high as compared to granular media filtration
More flexibility in being able to meet future finished water quality goals	

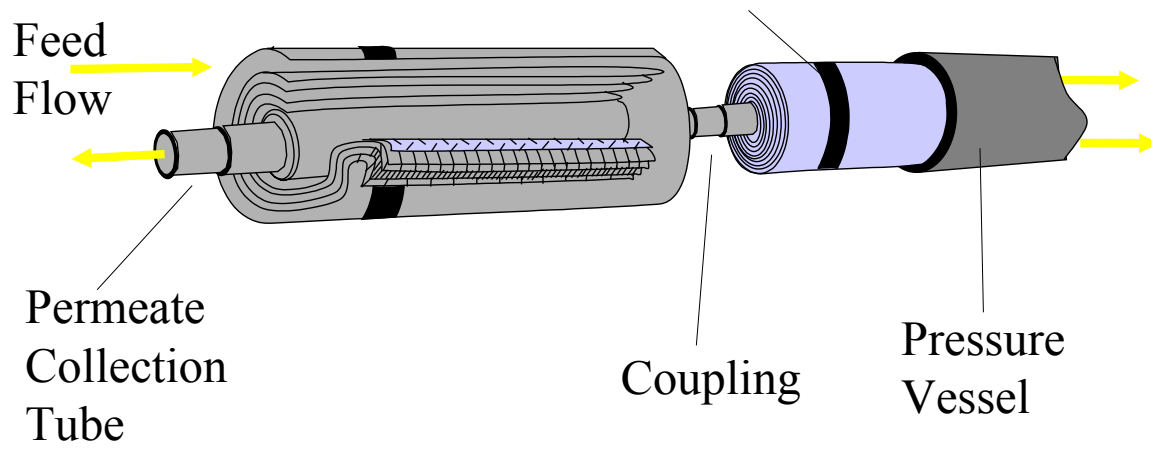


Figure 12. RO/NF Membrane Pressure Vessel Schematic

One result of using an RO or NF system is the concentrated waste stream produced by the process. The high concentration of ions in the waste stream usually requires some type of disposal and is not able to be recycled into the head of the process. The recovery of the feed water on the RO or NF units is less than in MF or UF units. Typical product water recovery is between 80 and 90 percent.

There are numerous NF and RO installations across the U.S. Table 6 summarizes some current NF and RO installations on similar high TDS and/or high TOC water.

Membrane Treatment Waste Streams

As mentioned previously, membrane treatment produces a concentrated waste of rejected constituents from the raw water. Treatment of the membrane concentrate from MF or UF systems is usually much easier than that from an NF system. This is because of the smaller pore size of the NF membrane and removal of some molecular size compounds that can significantly affect the pH of the concentrate. MF/UF membranes are also periodically backwashed, which produces washwater that must also be treated.

Typical concentrate from an MF or UF system can be treated by the same treatment methods as those used for backwash recycle, or another membrane can be used with a high recovery rate to produce high quality filtrate that can be recycled or disposed of. The small volume of remaining concentrate can be combined with other solids residuals (if present) for further processing or possibly disposed in a sanitary sewer.

The concentrate from an NF or RO system can contain high levels of ions, organics, and salts. Concentrate from NF or RO can be treated again by another membrane to further concentrate the waste stream prior to discharge to reduce the volume of the discharge. Disposal options for the NF concentrate include softening and thickening, evaporation ponds, or discharge to surface waters.

In addition, a secondary waste stream that must be dealt with is that produced during cleaning of the membranes. Membranes are typically cleaned with low or high pH solutions on a periodic basis to maintain adequate production through the membrane. Treatment of this wastestream is usually done by using a tank for pH neutralization of the spent cleaning solution followed by a sanitary sewer discharge.

Table 6. NF/RO Installations in North America

Location	Type	Startup Date	Capacity (mgd)
Barrow Utilities , AK	MF/NF (SW)	1996	1
Hollywood, FL	NF	1991	14
Tampa, FL	NF	1988	12.5
Plantation Central, FL	NF	1991	12
Fort Myers, FL	NF	1992	12
Collier County, FL	NF	1993	12
Boynton Beach, FL	NF	1994	8
Chesapeake, VA	(BW/SW) RO	1997	10
Florida Keys, FL	(BW) RO	1997	3
Clifton, CO	NF	1997	2.4
Borough, AK	MF/NF, (BW/SW) RO	1996	1

BW indicates brackish water.
SW indicates surface water.

INTEGRATED MEMBRANE SYSTEMS (IMS) APPLICATIONS

As discussed previously, membranes employed within a multiprocess water treatment system for surface water treatment are referred to as integrated membranes systems. Typical IMS applications, as illustrated previously in Figure 1, include a pretreatment step such as conventional CSF or high-rate clarification followed by a membrane step (nanofiltration or reverse osmosis) for desalting. In some cases, pretreatment for the membranes can also take place using MF or UF technologies. The purpose of the IMS applications is to remove the particles and some of the organics before the NF or RO desalting step. The following will discuss some recent IMS applications for surface water treatment that are applicable to this study of the St. Johns River.

The following IMS applications/studies will be discussed:

- CSF pretreatment followed by RO
- High-rate pretreatment followed by NF
- MF/UF pretreatment followed by RO or NF
- Riverbank infiltration followed by NF
- Multiple pretreatment evaluations
- Fouling/flux considerations for IMS applications

CSF Pretreatment Followed by RO

The IMS project for Chesapeake, Virginia, is a very applicable example due to the similarity in water quality between the St. Johns River, Florida, and the Northwest River, Virginia. Both rivers are influenced by brackish groundwater (TDS ranges from 30 to 3,000 mg/L in the Northwest River) and fluctuating concentrations of TOC that are dependent on the season. The Northwest River is characterized as a highly colored, low-pH, and low-alkalinity source. An RO plant was constructed to reduce TDS and chlorides and reduce DBP formation after conventional pretreatment. (Bergman et al., 1999).

The pretreatment consists of conventional rapid mix, flocculation and sedimentation, and granular media filters (CSF) (Bergman et al., 2000). After conventional treatment, high levels of TOC (7-12 mg/L) remain in the water making adequate control of DBPs in the finished water difficult (Sanders et al., 1995).

The membrane treatment facilities target removal of organics (color, TOC, and DBP precursors), iron, manganese, and seasonally, chloride and TDS. The RO membrane system was designed with multiple parallel process trains with relatively constant feed flow and the highest allowable recovery to maximize the feed water supply sources and finished water output. When in operation, plant staff monitors feed, concentrate, and permeate water quality and operating pressures, and vary the recovery as needed (Bergman et al., 2000).

Cellulose acetate (CA) membranes demonstrated lower levels of fouling; however, thin film composite (TFC) membranes provided greater organics removal (Sanders et al., 1995). Based on pilot flux decline data, it was estimated that for surface water treatment, CA membranes would need to be cleaned about 6 times per year versus 13 times per year for TFC membranes. Power costs associated with the greater required feed pressure of the CA membranes relative to the composite membranes were more than offset with the lower purchase price of the elements and lower costs for cleaning and disposal of spent cleaning solution (Bergman et al., 2000).

Post-treatment includes primary disinfection with sodium hypochlorite (free chlorine) and secondary disinfection with chloramines in order to remain below the DBP standards (Bergman et al., 2000).

High-rate Clarification Pretreatment Followed by NF

An IMS plant in Mery-sur-Oise, France, utilizes coagulation, high-rate sedimentation (using Actiflo[®]), ozonation, and granular media filtration before NF. This treatment scheme provided adequate removal of nutrients, pesticides, and TOC to meet drinking water standards in France (Ventresque et al., 1997). The membrane pretreatment with Actiflo[®] achieved all of the pretreatment goals including a fouling index of approximately 3, less than 200 particles in the clarified water, and an iron content of less than 0.050 mg/L.

MF Pretreatment Followed by NF

An IMS system was constructed in Alaska to address treatment of highly colored source water with moderate levels of TDS and significant levels of *giardia* and *cryptosporidium*. The system consists of MF followed by NF. The raw water TOC ranged between 7.6 and 21.4 mg/L, and TDS ranges between 150 and 319 mg/L (Lozier et al., 1997).

The MF stage was effective for the removal of particles, turbidity, and protozoan cysts and oocysts regulated by the SWTR. Challenge studies have demonstrated complete removal of *giardia* and *cryptosporidium* (Lozier et al., 1997).

This system did not require chemical treatment (other than that associated with scale control) or the associated operator attention necessary to adjust the chemical conditioning program to match changes in feedwater quality. Spikes in turbidity and seasonal changes in alkalinity and organics required no changes in the routine operation of the equipment (Lozier et al., 1997). The combination of low raw water temperature, high concentration of organics, and elevated flux rate produced relatively short runs for the MF unit. Chemical cleaning frequency can be reduced dramatically (from 1 to 2 weeks to several months) by reducing flux (Lozier et al., 1997).

MF pretreatment did not remove all foulants that were present in the raw water supply. Fouling occurred predominantly in the first stage of the NF units, requiring that chemical cleaning be performed every 6 to 8 weeks on the basis of a 15 to 20 percent flux loss. The major foulant was believed to be dissolved organics, although bacterial growth may have played a part (Lozier et al., 1997).

In addition, a series of bench-scale experiments were conducted by Ngo et al., (2000). These tests were conducted with a Millipore flat sheet MF module modified to incorporate in-line PAC addition. This system was found to remove a significant portion of organics prior to entering the MF unit. The PAC-MF was an effective treatment method for removing NOM from water. The PAC addition also led to the improvement in the permeate flux of the MF unit (Ngo et al., 2000). MF can readily achieve 90 to 99 percent organic and color removal, but MF alone cannot remove organics (<20 to 30 percent); however, if it is combined with PAC, it may be able to remove a significant amount of organic contaminants and DOC.

Riverbank Filtration Pretreatment Followed by NF

In Vechterweerd, Netherlands, riverbank filtration and conventional ground water treatment as a pretreatment for membranes lengthened the duration between membrane cleanings. However, fouling was mainly due to biogrowth and partly to colloidal fouling (iron). Biofouling on the membranes seems to promote iron deposition (van Paassen et al., 1999). This form of pretreatment did not provide

adequate enough pre-treatment, when compared to CSF pretreatment, thus requiring more frequent membrane cleaning. Biogrowth must be controlled on the membranes to allow for slower decline in MTC (van Paassen et al., 1999).

Pretreatment Comparison Studies

In Hillsborough County, Florida, several IMS technologies were pilot tested for treatment of high TOC river water and removal of *bacillus subtilis* for different IMS combinations. The pretreatments included MF, coagulation with MF, and CSF. Pretreatment coagulation was accomplished using an iron coagulant. The water had an average TOC of 16.4 mg/L and an average TDS of 169 mg/L (Reiss et al., 1999; Owen et al., 1999). Microfiltration did not remove significant amounts of color, DBP precursors, or DOC unless it was previously coagulated. However, microfiltration did remove significant amounts of particles, turbidity, and pathogens (Reiss et al., 1999). Absolute rejection of spores was not achieved; however, IMS spore rejection exceeded credited regulatory rejection of similar sized microorganisms by conventional treatment by several logs (Owen et al., 2000). Both microfiltration systems outperformed CSF as a pretreatment for removal of *bacillus subtilis* (Reiss et al., 1999). The least capable IMS (conventional followed by CA membrane) averaged 5.4 log removal compared to 10.7 log removal for the most capable system, MF followed by a low molecular weight cut-off TFC nanofilter (Reiss et al., 1999).

An IMS pilot study compared MF, UF, and CSF as pretreatment strategies for surface water NF for the Occoquan Reservoir, Virginia. The source water had a TOC ranging from 3.1 to 6.6 mg/L and low TDS. (Chellam et al., 1997). MF and UF pretreatment resulted in lower NF fouling rates and longer cleaning intervals compared with those measured after conventional treatment. NF fouling was more influenced by colloidal materials than by organic matter. MF and UF pretreatment resulted in longer NF cleaning intervals when compared to conventional treatment. Conventional treatment, pH, and inorganic scale control, as well as treatment using GAC, were reported to be unsuccessful in controlling NF fouling (Chellam et al., 1997). Fouling of the hydrophilic NF membrane was attributed to the hydrophobic fraction of NOM (Chellam et al., 1997).

In East St. Louis, a pilot-scale test was conducted to compare CSF, coagulation-sedimentation-UF, coagulation-UF, and UF as pretreatment strategies for NF. All successful IMS systems required coagulation-sedimentation pretreatment. UF of the raw water without coagulation was not successful. Membrane film chemistry significantly affected productivity decline. CA did not foul as readily as TFC membranes (Lovins et al., 1999).

Fouling/Flux Considerations for IMS Applications

Flux decline influences the operating and capital cost of membranes in two ways; first, it determines the frequency with which membranes must be rinsed, cleaned, or both to remove accumulated materials, and second, it quite possibly determines the frequency of membrane replacement if irreversible fouling is significant (Nilson and DiGiano, 1996). Foulants include inorganic and organic particulate matter, large molecular weight dissolved organic matter, and microorganisms (particularly aerobic bacteria) (Sanders and Lozier, 1995).

CA nanofilters are susceptible to biodegradation and/or hydrolysis, whereas TFC membranes are not. Biodegradation occurs due to the accumulation of microbiological organisms on the membrane surface (Reiss et al., 1999). Generally, biological fouling can be reduced with the addition of monochloramine (van Houtte et al., 1999) or by removal of dissolved oxygen before membrane treatment. Often, the addition of monochloramine is only possible for the CA membrane, whereas TFC membranes are sensitive to oxidation by monochloramine (Reiss et al., 1999).

The hydrophobic fraction of NOM is often responsible for flux decline with respect to organic fouling. The hydrophilic fraction, being more soluble in water, is rejected poorly compared to the hydrophobic NOM (Nilson et al., 1996). Also, lower flux and lower recovery for a membrane will reduce the fouling (Reiss et al., 1999).

OXIDATION AND DISINFECTION

After the desalting step, the final step in treatment is the oxidation/disinfection step. In this step, oxidation can take place for taste and odor removal and primary disinfection. Primary disinfection is when inactivation of viruses, *Giardia*, and *Cryptosporidium* is conducted. After primary disinfection, a residual disinfectant must be added before the water enters the distribution system.

In some cases, a primary disinfectant can also be used as an oxidant. Table 7 lists all the oxidants/disinfectants that should be considered, and their application in water treatment processes. Each following section goes into greater detail about each process.

CHLORINE

Chlorination has been practiced in water treatment since the early 1900s as an effective disinfectant for the protection of public health against waterborne diseases. It is relatively inexpensive and provides a residual concentration in a distribution system. Today it is the most commonly used disinfectant in water treatment. For many plants, the source of chlorine is liquefied chlorine gas or a sodium hypochlorite solution. When chlorine gas is applied to water it forms hypochlorous acid (HOCl) and hydrochloric acid (HCl). When sodium hypochlorite is added to water it forms HOCl and a hydroxyl ion (OH⁻). Therefore, when chlorine gas is added to water the pH decreases, and when sodium hypochlorite is added to water the pH increases.

Hypochlorous acid can be deprotonated to form hypochlorite ions (OCl⁻) depending upon the pH of the solution. At lower pH values (less than 7.6) HOCl dominates, while above 7.6 OCl⁻ dominates. HOCl is a much more effective disinfectant than hypochlorite ion; therefore optimum disinfection occurs at lower pH values (below 7). Temperature also is a factor in the disinfection efficacy of chlorine. As the temperature of the water increases, so does the inactivation efficacy for all microorganisms.

Chlorine is highly effective as a disinfectant for bacteria and viruses, with limited effectiveness on *giardia* and virtually no effect on *cryptosporidium* at the doses typically used in water treatment (less than 5 mg/L). Contact time (CT) requirements for surface waters were promulgated under the Safe Water Treatment Rule (SWTR) (1989) to ensure inactivation of at least 0.5-log of *giardia* and 2-log for viruses for

conventional treatment plants, and increased log inactivation for other types of plants (i.e., direct filtration).

Table 7. Applicability of Oxidants/Disinfectants in Water Treatment

Oxidants/Disinfectants	Oxidant	Primary Disinfectant	Residual Disinfectant
Chlorine	Yes	Yes	Yes
Chloramines	No	No	Yes
Chlorine Dioxide	Yes	Yes	Yes
Ozone	Yes	Yes	No
Ultraviolet Light (UV)	No	Yes	No
Potassium Permanganate	Yes	No	No

Chlorine is also highly effective as an oxidant in water treatment for use in iron and manganese oxidation, hydrogen sulfide reduction, color removal, and T&O control. Chlorine can also increase particle removal and decrease turbidity through filtration by its oxidation power. In addition, it is employed to control algal and biofilm growth in treatment plant basins. Depending upon its intended use, chlorine can be applied at multiple locations in a treatment train. Most commonly, chlorine is applied upstream of the coagulation process, prior to the filters, and as a final disinfectant for the distribution system.

There are disadvantages to using chlorine as a disinfectant/oxidant in water treatment. Its oxidation power also acts upon natural organic matter (NOM) to form DBPs in the plant and the distribution system. The most common DBPs formed are trihalomethanes (THMs) and haloacetic acids (HAAs). These are currently regulated under the Stage 1 D/DBPR and will be further regulated under the Stage 2 rule. In most cases, the higher the dose of chlorine used, and the further upstream in the process it is used, the greater the formation of DBPs. DBPs can also be influenced by the pH of the water.

High doses of chlorine can cause new taste and odor concerns from the chlorine itself. Chlorine is also a dangerous chemical to handle as both sodium hypochlorite and gaseous chlorine. Gaseous chlorine is also a poisonous gas that is highly regulated by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Transportation (DOT), as well as local fire and building codes. Many gaseous chlorine facilities require a scrubber system in addition to the process components. Sodium hypochlorite is a corrosive liquid that requires handling similar to other types of corrosive liquids, as well as spill containment and corrosion resistant materials of construction.

Table 8 lists some of the advantages and disadvantages associated with the use of chlorine.

CHLORAMINES

Chloramines are formed by the reaction between hypochlorous acid and ammonia to form a more stable disinfectant than free chlorine. Three different species can be formed from the reaction, i.e., monochloramine (NH_2Cl), dichloramine (NHCl_2), and trichloramine

(NCl_3). The speciation is competitive between the reactions and depends upon two factors: the pH of the water, and the chlorine to

Table 8. Advantages and Disadvantages of Using Chlorine

Advantages	Disadvantages
Best known and most widely used method of disinfection	Chlorine gas or hypochlorite are hazardous substances and corrosive
Least expensive method of disinfection	Produces halogenated DBPs (TTHMs and HAAs), controlled by the dose and application points.
Provides a stable residual for the distribution system	Special materials and containment needed for storage and handling
Effective in inactivation of bacteria and viruses	Taste and odor problems at high concentrations
Can enhance coagulation and filtration processes	Cannot be used as a prefilter oxidant or disinfectant with GAC filter media
Effective oxidant for iron, manganese, color, and taste and odors	
Effective to control biological fouling in the treatment plant	

nitrogen ($\text{Cl}_2:\text{N}$) ratio. As the $\text{Cl}_2:\text{N}$ ratio increases, the reaction is driven more towards trichloramines. As the pH decreases below 6, dichloramine is favored over monochloramine. Above pH 6, monochloramine is dominant. Monochloramine is the desired form because the other two forms are sometimes associated with T&O issues. Therefore, chloramine formation conditions are best when the pH is at or above neutral with a 3:1 $\text{Cl}_2:\text{N}$ ratio.

Chloramines are effective as a residual disinfectant for establishing and maintaining a distribution system residual. The dose requirements for maintaining a measurable residual in the distribution system are fewer since chloramines are much more stable than free chlorine. Monochloramine has also been found to be effective in controlling biofilms in distribution systems. Chloramines have been found to be adequate disinfectants for bacteria; however, they are not effective for inactivation of viruses and protozoa.

Chloramines are much less reactive than free chlorine, thereby reducing the formation of halogenated disinfection byproducts as well as taste and odor compounds in the distribution system. Normal dosages are in the range of 1.0 to 4.0 mg/L. High CTs are required when using chloramines if any inactivation credit is desired from the process.

Chloramines can also be used upstream of non-biological filters to reduce biological growth in the treatment plant basins. Chloramines are not effective as oxidants for iron and manganese, color, or primary taste and odor control. Problems can also occur in the distribution system due to excess nitrogen in the finished water that can cause nitrification. Nitrification can cause a loss of chlorine residual and an increase in bacterial counts in the distribution system. This can be controlled via ammonia addition controls and seasonal free chlorine flushing of the distribution system.

The ammonia added for chloramine formation can be either from aqueous ammonia or anhydrous ammonia. This requires capital costs associated with storage and process equipment to use chloramines in the process. However, the production of chloramines is relatively inexpensive as compared to other disinfectants.

Chloramines have been used successfully at large surface water utilities in Florida for many years, including City of Tampa, City of Melbourne, Manatee County, and others.

Table 9 lists some of the advantages and disadvantages associated with the use of chloramines.

Table 9. Advantages and Disadvantages of Using Chloramines

Advantages	Disadvantages
Little reaction with NOM to form DBPs, easier to meet D/DBPR	Less efficacy against microorganisms than other disinfectants (need a primary disinfectant)
Maintain a stable residual for a longer period of time than other disinfectants in the distribution system	No oxidation power
Less taste and odor formation in distribution system with monochloramines	Nitrification problems and potential regrowth in distribution system
Inexpensive disinfectant	Taste and odors associated with di- and trichloramine
Effective for reducing biological growth in the treatment plant	High CT required for any disinfection credit
	Must be produced onsite (operational and maintenance concerns)

CHLORINE DIOXIDE

Chlorine dioxide has uses as both an oxidant and a primary disinfectant in water treatment. Currently 700 to 900 public water systems world-wide use chlorine dioxide to treat potable water. It is generated by the reaction of sodium chlorite with gaseous chlorine or sodium hypochlorite in a generator located onsite at the treatment plant.

Chlorine dioxide generation and addition to water produces byproducts of chlorite and chlorate, both of which can be harmful to human health. The new Stage 1 D/DBPR regulates both chlorine dioxide and chlorite. The maximum residual disinfectant level (MRDL) for chlorine dioxide is 1.0 mg/L, and the MCL for chlorite is 0.8 mg/L. The formation of chlorite greatly limits the dose that can be applied to surface water. If the oxidant demand of the water to be treated with chlorine dioxide is greater than 1.4 mg/L, the formation of chlorite in the water may exceed the MCL. Chlorine dioxide can also produce taste and odor concerns at residual levels above 0.4 mg/L. Typical doses used in water treatment vary between 0.07 to 2.0 mg/L (EPA, 1999).

Chlorine dioxide is usually applied at the head of the plant prior to coagulation in a liquid solution. However, it can also be applied in the clarifiers or at an intermediate point following clarification. As with all oxidants and disinfectants, the oxidant demand of the water plays an important role in the application point and potential use of the chemical.

Chlorine dioxide produces chlorite and chlorate as byproducts in water that are regulated by the Stage 1 D/DBPR. Chlorine dioxide does not produce halogenated DBPs, and can be used as one mechanism for the reduction of DBP precursors (by oxidation of organic material) in water. However, the possibility does exist for the production of nonhalogenated DBPs that are not currently regulated but may be regulated in the future.

In disinfection, credit based on the "CT" for chlorine dioxide is currently given for *Giardia* and viruses. Chlorine dioxide has been found in many studies to be more effective than chlorine in disinfection of bacteria, *Giardia*, and *Cryptosporidium* over a wide range of pH. For viruses, chlorine dioxide has been found to be equally effective as chlorine in inactivation. With a CT of approximately 4

mg/min/L at 15 degrees Celsius (°C), 1-log *Giardia* inactivation can be achieved (AWWA, 1991). Studies that have been completed have shown that chlorine dioxide inactivation of *Cryptosporidium* is possible at reasonable doses, but the dose and residual needed to achieve the CT required for 0.5 to 1-log inactivation may not be possible due to the Stage 1 D/DBPR limits.

As an oxidant, chlorine dioxide can be used to treat taste and odors, and oxidize dissolved iron and manganese. Chlorine dioxide can destroy phenolic compounds that cause taste and odors, as well as compounds associated with decaying vegetation and algae. Chlorine dioxide reacts with soluble forms of iron and manganese to form precipitates that can be removed through coagulation. The dose of chlorine dioxide may be limited by the new Stage 1 D/DBPR limit of 1 mg/L chlorite. Chlorite is the decay product of chlorine dioxide. In some locations, chlorine dioxide can be used ahead of the clarification process to replace chlorine as a chemical for the control of algae growth in the water treatment plant.

Major equipment that would be required for a chlorine dioxide system includes stock chemical storage and feed systems, chlorine dioxide generators, and feed piping and injection equipment. If a plant uses sodium hypochlorite or gaseous chlorine for chlorine or chloramine disinfection of the finished water, the storage from this system can be used to feed the chlorine dioxide system. A separate storage and feed system must be provided for the sodium chlorite stock solution. Chlorine dioxide generators require careful monitoring of the chemical feed rates and mixture to ensure the most efficient production of chlorine dioxide. If not carefully monitored, chlorine dioxide generation can produce excess chlorine, as well as excessive concentrations of chlorites that cannot be easily removed from the process stream.

Table 10 lists some of the advantages and disadvantages associated with the use of chlorine dioxide.

OZONE

Ozone is one of the most powerful disinfectants and oxidants available for use in water treatment and has been used in Europe since the early 1900s. It has more recently found acceptance in the U.S. The number of water treatment plants utilizing ozone has increased from about 15 in 1985 to more than 300 in the year 2000. With new and anticipated

future regulations, ozone has become widely accepted as a disinfectant for the inactivation of *Cryptosporidium*.

Table 10. Advantages and Disadvantages of Using Chlorine Dioxide

Advantages	Disadvantages
More effective inactivation of most pathogens than chlorine or chloramines	Formation of chlorite and chlorate as byproducts
Control of taste and odors in water	High doses cannot be used based on Stage 1 D/DBPR for chlorite MCL and chlorine dioxide MRDL
Provides a residual under most conditions	Higher residuals (above 0.4 mg/L) can cause taste and odor concerns
Oxidation of iron and manganese	Chemical costs for sodium chlorite are high
Provides plant control over algae growth	Training, laboratory equipment, and sampling is expensive
Does not produce halogenated DBPs	Must be produced on-site (more maintenance and operational concerns)
Oxidation of DBP precursor material	Usually has higher operational costs than other disinfectants

Ozone is produced by the passing of dry air or oxygen between two electrodes. A high potential (10,000 to 30,000 volts) is applied across the electrodes, which converts some of the oxygen to ozone. Ozone must be generated onsite and used immediately. It has a very short half-life (less than 30 minutes) under normal conditions encountered in water treatment.

Ozone generators can be fed either from dried air from the atmosphere or from a liquid oxygen (LOX) system. Ozone can be generated at a higher percent weight concentration with LOX systems versus dry air systems. Most manufacturers of ozone equipment prefer the use of LOX system for feed gas. With a dry air feed system, more equipment including air dryers and compressors are required to supply the air feed to the ozone generator. Dry air feed systems can be more maintenance-intensive than LOX fed systems.

Ozone is used as a disinfectant because of its efficacy against bacteria, viruses, and protozoa at low doses. Typical doses for inactivation range from 1.0 to 4.0 mg/L. Ozone can be applied at various points in the treatment train, although it is usually applied prior to coagulation or filtration. Disinfection is not significantly affected by temperatures or pH found in water treatment. Hulsey et al. (1999) notes that the values for CT recommended by the EPA to obtain 1-log of *Giardia* inactivation or 2-log virus inactivation can be met by obtaining an initial ozone residual above 0.3 mg/L and allowing it to decay over several minutes prior to exiting the contactor. However, the ozone residual needs to be much higher for *Cryptosporidium*. Oppenheimer et al. (2000) determined that CT values for ozone used on *Cryptosporidium* are 5 to 20 times greater than for *Giardia*.

As a comparison of different disinfectants for *Giardia* inactivation, a CT of 1.43 milligrams per minute per liter (mg-min/L) is required for ozone. The respective CT for chlorine is 112 mg-min/L and is 1,850 mg-min/L for chloramines (AWWA Disinfectants Teleconference, 2001). This illustrates the reduced contact time and/or dose required by ozone when compared to chlorine and chloramines.

Since ozone is such a powerful oxidant, it has been found to have many other uses than just for disinfection, such as iron and manganese reduction, taste and odor removal, removal of color, improvement of downstream processes (coagulation and filtration), and reduction of

DBP precursors. Ozone also does not lead to the formation chlorinated DBPs when applied.

Ozonation is also effective in reducing the algal taste and odor compounds geosmin and 2-methylisoborneol (MIB). Ozonation alone can bring about partial destruction of these taste and odor compounds. Ozonation also makes nonbiodegradable NOM into smaller more oxidized compounds that are substrates for bacteria and more biodegradable. Therefore, biofiltration, with BAC filters, following ozonation stabilizes the water by significantly reducing the concentration of biodegradable organic matter as well as removing residual MIB and geosmin. In addition, ozonating the water can enhance the ability of a BAC filters to degrade and remove MIB (Nerenberg et al., 2000).

Although ozone does not form any THMs or HAAs, ozone still forms its own DBPs that must be controlled. Ozone-related byproducts include aldehydes, ketones, carbonxy acids, epoxides, peroxides, quinone phenols, and brominated organics as well as an increase in assimilable organic carbon (AOC) (Hu et al., 1999). These byproducts are not regulated in drinking water.

Ozonation of waters containing bromide (Br^-) leads to the formation of bromate (BrO_3^-) which is regulated in the U.S. to $10 \mu\text{g}/\text{L}$. Researchers have demonstrated that under laboratory conditions, since bromate is 63 percent bromide by weight, complete conversion of only $6.3 \mu\text{g}/\text{L}$ of Br^- to BrO_3^- is required to exceed the $10 \mu\text{g}/\text{L}$ standard. However, pilot studies (City of Melbourne, 1999) have demonstrated that ozonation of clarified water with bromide levels up to $0.30 \text{ mg}/\text{L}$ produce bromate levels still below the $10 \mu\text{g}/\text{L}$ limit. These results suggest that ozonation of water with residual organics and color increase the ozone demand and leave less ozone available for the oxidation of bromide.

Bromate formation is affected by water quality conditions (bromide concentration, pH, temperature, carbonate alkalinity, ammonia concentration, and NOM character (Amy et al., 2000).

During ozonation, minimization of bromate formation and disinfection are two opposing goals. This is even more problematic when high ozone exposures are required for inactivation of *Cryptosporidium parvum*, which results in a high bromate formation. To overcome the problem of bromate formation, pH depression or ammonia addition could be employed as control options to minimize bromate formation

(von Gunten and Pinkernell, 2000). Also, tapered application versus single-stage ozone application can help to reduce the bromate formation potential (Amy et al., 2000).

In a recent study comparing ozone and chlorine as a primary disinfectant, ozonation followed by chlorination proved to be better in terms of THMs and HAAs control when compared to chlorination alone. The combined system produced 28.3 percent less DBPs (Hu et al., 1999).

Due to its short half-life, ozone decays quickly and does not maintain a residual for downstream processes. Therefore, ozonation can be used as a primary disinfectant but must be followed by a residual disinfectant (chlorine or chloramines) for the distribution system.

Table 11 lists the advantages and disadvantages associated with the use of ozone.

ULTRAVIOLET LIGHT (UV)

UV disinfection is a physical disinfection process, as opposed to a chemical disinfection process. It uses electromagnetic energy in the 200 to 300 nanometers (nm) wavelength range to inactivate microorganisms. For many years, UV has been used in wastewater treatment for final disinfection in place of chlorine. Recently, changes in technologies and studies on the effects of UV on protozoa and other emerging pathogens have made UV a feasible option for primary disinfection of drinking water.

The inactivation of microorganisms is based on the UV dose (mWs/cm^2), which is a product of the light intensity (mW/cm^2) and the exposure time (seconds). The UV dose is analogous to the CT term used for inactivation credit for chemical oxidants. Since the UV dose is primarily based on the light intensity, water quality parameters that have the most effect on UV dose are turbidity and suspended solids that can shield microorganisms from the UV light, and some organic and inorganic compounds that can absorb UV light.

UV light is generated by a flow of electrons from an electrical source through ionized mercury vapor. UV lamps are classified as low-pressure and medium-pressure lamps. Low-pressure lamps are more efficient than medium-pressure lamps, but the total UV radiation is weaker. Medium-pressure lamps produce 10 to 20 times more UV radiation output than low-pressure lamps. Some low-pressure lamps

are classified as low-pressure, high-intensity and have special design features that allow for a higher transmittance of UV radiation at a low pressure in the lamp. The systems currently being tested for use in water treatment are the low-pressure, high-intensity lamps and the medium-pressure, high-intensity lamps.

Table 11. Advantages and Disadvantages of Using Ozone

Advantages	Disadvantages
Effective inactivation of <i>Cryptosporidium</i> at low ozone dosages	Formation of brominated DBPs in waters with bromide
Control of taste and odors	Initial capital costs for equipment are high
Oxidation of iron, manganese, color	Expensive to generate, and must be produced on-site
Very short contact time required for disinfection, thereby reducing capital costs associated with contactors	Provides no residual (need a residual disinfectant)
No chlorinated byproducts	Need BAC filters to remove BDOC or can cause regrowth problems in distribution system
Disinfection efficacy is not significantly affected by temperature or pH	
Enhancement of treatment processes to increase particle removal and decrease turbidity	Ozone systems require a high amount of training and skill to operate
Reduction of DBP precursors (more reduction when used with BAC filters)	
Production of a stable effluent (when used with BAC filters)	

Figure 13 illustrates a UV lamp used in water treatment applications.

A 10-mgd UV disinfection system is being installed in Henderson, Nevada, and has state approval as a disinfection process.

Extremely low dosages of UV can be highly effective for inactivating oocysts (Clancy et al., 2000). Recent research has shown that at reasonable doses of UV (less than 30 mWs/cm²), 3-log inactivation of *Cryptosporidium* and 2-log inactivation of *Giardia* can be achieved.

There are several types of UV lamps. The most notable are low and medium pressure lamps. Low pressure lamps emit UV at a monochromatic output at 254 nm. Medium pressure lamps have a polychromatic in which multiple wavelength outputs are utilized for inactivation of microorganisms (Giese and Darby, 2000). A comparison of medium- and low-pressure lamps demonstrated no significant differences (Clancy et al., 2000) in germicidal efficiency.

For comparison, the required CT values for ozonation were about 3 and 8 mg*min/l for the 2-log and 3-log reduction in infectivity of *C. parvum* oocysts at room temperature, respectively. At 5 °C, CT values were 10 and 17 mg*min/l for the 2 and 3 log reductions respectively.

More than 1-log reduction in infectivity was obtained with 15 second of UV irradiation (Kanjō et al., 2000).

UV disinfection has a major advantage of little or no production of DBPs. Studies have shown that there is no appreciable increase in TTHM or HAA concentrations as a result of UV disinfection at doses that would be applicable in water treatment. However, low levels of formaldehydes and assimilable organic carbon were produced from UV treatment of finished water.

Table 12 lists the advantages and disadvantages associated with UV disinfection.

POTASSIUM PERMANGANATE

Potassium permanganate is used primarily as an oxidant and is a very poor disinfectant. It can be used in place of chlorine as a means to control some problems such as taste, odor, iron, manganese, algae, color, and regrowth in the treatment plant. Potassium permanganate is a very strong oxidizer and is effective in this role as opposed to other oxidants.

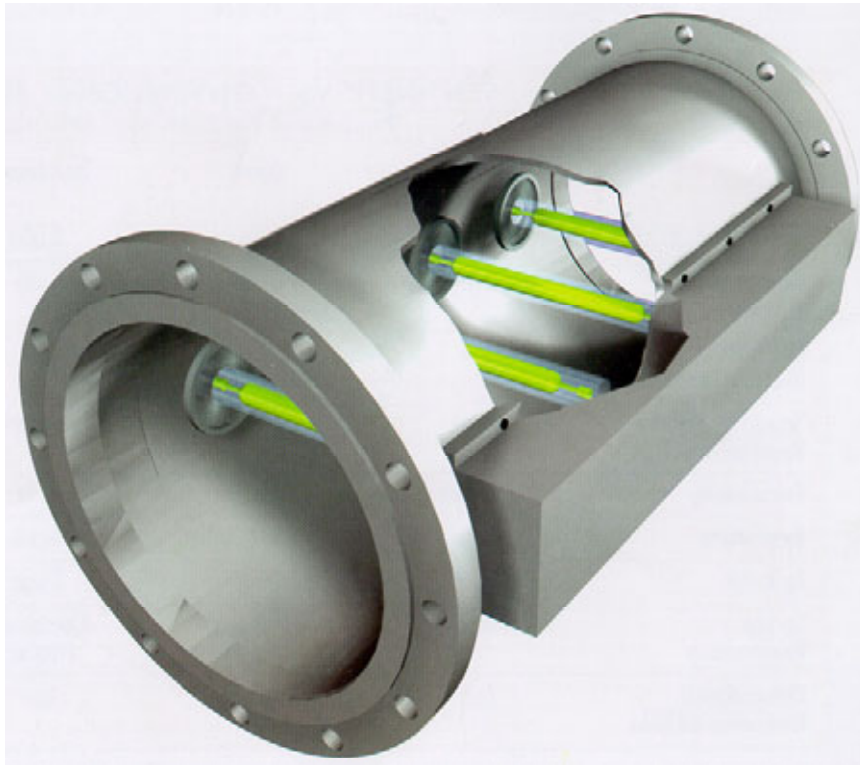


Figure 13. UV Disinfection Unit

Table 12. Advantages and Disadvantages of Using UV Disinfection

Advantages	Disadvantages
Effective disinfectant against <i>Giardia</i> and <i>Cryptosporidium</i>	Little full-scale experience in surface water treatment
Little to no production of DBPs	Does not hold a residual, must be followed by a residual disinfectant for the distribution system (i.e. chlorine, chloramines)
Efficacy not as dependent upon typical water quality parameters (pH, temperature) as chemical disinfectants	Effectiveness can be compromised by particle clumping
Identified by EPA as a viable mechanism for primary disinfection	Technology is still evolving
Relatively low cost	Measurement of transmitted dose (analogous to chemical residual) to measure effectiveness is difficult
	Not yet acceptable to most state regulatory agencies for surface water

Potassium permanganate is made up in a batch or continuous feed using a dry crystalline solid from which a 1 to 4 percent solution is made. The stock solution is usually applied at the head of the treatment train or in the clarifiers to achieve oxidation. No residual is maintained from the application of potassium permanganate. Any residual can affect downstream processes, especially ozonation, so care should be taken in choosing the appropriate application point.

In addition to its oxidizing capabilities, potassium permanganate can effectively reduce DBP formation by eliminating the use of chlorine for oxidation and plant maintenance needs.

Potassium permanganate should not be added concurrently with PAC in the front of the plant, because PAC will consume permanganate and make it unavailable for adsorption of organics and for taste and odor control. Potassium permanganate may also increase finished water manganese levels, which may be a concern in some waters. It is a very toxic chemical that is dangerous to handle, and therefore requires special storage and handling procedures.

Table 13 lists the advantages and disadvantages associated with the use of potassium permanganate.

Table 13. Advantages and Disadvantages of Using Potassium Permanganate

Advantages	Disadvantages
Effective oxidation of iron, manganese, color, taste and odor	Not an effective disinfectant
Control of treatment plant regrowth	Can be toxic and dangerous to handle
Can reduce some DBP precursors	Requires tight control over dosing to prevent downstream problems
Allows for the removal of chlorination as a preoxidant, thereby reducing the DBP formation potential	Overdosing results in pink water
No negative effects on downstream processes if no residual is maintained	

TOC REMOVAL NEEDED FOR FREE CHLORINE AS A RESIDUAL DISINFECTANT

For free chlorine to be used as a residual disinfectant in the distribution system, low TOC levels in the finished water must be obtained. Based on previous experience with other facilities, a TOC concentration of less than 1.5 mg/L is required to use free chlorine as the primary and residual disinfectant and avoid excessive DBP formation. At TOC levels above 1.5 mg/L, use of chloramines as the residual disinfectant would likely be required to meet DBP regulations.

The source water for the St Johns River can have TOC levels in excess of 25 mg/L. After CSF treatment, TOC levels would still likely be in excess of 5 mg/L. To reduce TOC levels below 1.5 mg/L, a TOC removal process is required. Effective TOC removal processes include NF/RO membranes, GAC contactors, and anionic resins. These processes have been demonstrated to achieve greater than 90 percent TOC removal.

MEMBRANES

As discussed previously, NF/RO membranes are effective processes for TOC removal. Figure 8 illustrated that dissolved organics size range from 0.1 μm to 0.001 μm , indicating that NF and RO membranes are most appropriate for dissolved organics removal. However, the potential treatment schematics discussed earlier include an RO/NF bypass that would be used during the less brackish seasons of the year. For TOC removal to below 1.5 mg/L, nearly 100 percent RO/NF treatment would be required for use of free chlorine as a residual disinfectant.

GAC CONTACTORS

GAC is another treatment process for high TOC removal. GAC is used in packed bed columns downstream of non-GAC filtration or membrane processes to adsorb TOC to low levels. It is also used in other installations without upstream filtration as an adsorptive media for organics. GAC packed bed columns can provide adsorptive capacity for T&O-causing compounds. Since these types of GAC columns are used in an adsorptive mode, the GAC must be

periodically regenerated or replaced (perhaps every 3 months) to retain the adsorptive capacity of the process.

Many factors influence the performance of GAC contactors to adsorb both DBP precursors and T&O-causing compounds. These include:

- **GAC Particle Size** – The smaller the particle size, the greater the surface area and therefore the greater the adsorptive capacity. Smaller particle size means more headloss.
- **Empty Bed Contact Time (EBCT)** – The amount of contact time and bed depth must be big enough to ensure a given level of treatment, and is usually based on bench-scale testing. The typical required EBCT is 10 minutes.
- **GAC Hardness** – The hardness of the carbon media can minimize the losses of GAC during handling and regeneration, as well as during the minimal backwashing that may be required.

Historically, GAC contactors are expensive in terms of both capital costs and operational costs to regenerate or replace the GAC. The headlosses associated with the contactors can have a significant effect on treatment plant hydraulics. The use of GAC contactors precludes the use of chlorine or chloramines upstream of the process for oxidation or disinfection credit.

ANIONIC RESINS

Anionic resins have been successfully demonstrated to remove TOC from source waters. Resin can be used in a contactor like GAC or as part of the chemical coagulation/flocculation process using a new resin called MIEX resin. These resins are not as widely used as GAC, but can be less expensive than membranes. These resins do not reduce salinity.

OCCURRENCE AND TREATMENT OF ALGAL TOXINS

BACKGROUND AND OCCURRENCE

The occurrence of cyanobacteria (blue-green algae) blooms and the subsequent production of cyanotoxins (algal toxins) have been identified along the reach of the St. Johns River being considered in this study. The term blue-green algal is used synonymously with cyanobacteria throughout the industry, however, blue-green algae are not actually algae and are classified as a bacteria (Howard et al., 1996).

Cyanobacteria have been thought to potentially cause human health problems as well as death in animals that drink water containing cyanotoxins, reducing the aesthetic quality (increasing color) of source water, emitting unpleasant odors, and blocking water-filtration systems due to high filter clogging indexes (Howard et al., 1996; Boisdon et al., 1994). Currently, algal toxins are not regulated in drinking water by EPA. However, the World Health Organization guideline value for total microcystin-LR is 1 µg/liter in drinking water. The World Health Organization does not have guidelines for anatoxin-a.

Several mechanisms exist by which toxins could enter the domestic water supply. One mechanism is cell lysis during which the bacterial cell is damaged and dissolved toxins are released into the water supply. This may occur due to the physical or chemical processes associated with water treatment, with toxins passing through to the consumer. Another possible mechanism is that healthy algal cells containing the toxin(s) may enter a treatment works from the source water and pass through the treatment works and distribution system to the customer. (Boisdon et al., 1994).

Light, temperature, and the chemical composition of the surrounding water are the major factors affecting the concentration of cyanobacteria. Cyanobacteria are often associated with eutrophic or nutrient-enriched water that contains sufficient concentrations of nitrogen, phosphorus, carbon and silica, thus enhancing cyanobacterial growth (Boisdon et al., 1994). The optimum temperature for algal blooms is approximately 25 to 35 °C and generally occurs in hard water within a pH range of 7.5 to 9.0. Diurnal changes in cyanobacterial density vary above and below water density resulting

in oscillatory vertical movement within the source water (Howard et al., 1996).

It is estimated that 50 to 70 percent of algal blooms are producers of algal toxins (Rositano et al., 2000). There are 40 different toxin-producing species of cyanobacteria with the most commonly implicated genera of *microcystis*, *anabaena*, *aphanizomenon*, *oscillatoria* with *gloeotrichia* (Repavich et al., 1990) and *nodularia* implicated less often (Howard et al., 1996).

TREATMENT

Several studies have shown the successful removal of cyanobacteria as well as the related toxin using some of the typical water treatment processes discussed earlier. Most of the research presented focuses on removal of microcystins and anatoxins.

Coagulation/Activated Carbon

Hart et al. (1998) demonstrated that PAC and GAC can effectively remove microcystin-LR and anatoxin-a by adsorption; a GAC bed that is biologically active will be able to provide complete removal of the toxins via adsorption and biodegradation, provided the contact time is long enough to encourage biological activity. Dissolved toxins can be removed effectively to less than 1 µg/L under conditions which are normally used in water treatment by biologically active GAC (Hall et al., 2000).

Ferric sulfate produced satisfactory algae removal over a broader range of coagulant doses and pH values, suggesting that it may provide greater stability in plant operations as compared to alum (Rastogi et al., 1999).

Oxidation

Recent research suggests that ozone is the best oxidant for the destruction of algal toxins, both dissolved and intra-cellular. Its action on the algae cells is decolorization of the cell due to the reduction of chlorophyll A, degradation of the external cell wall, reduction of cell counts, and decrease of fluorescence. Ozone also has coagulating effects, especially in the presence of phytoplankton in the raw water. Algae oxidation with ozone leads to suspended solids, which are easily separated by flotation (Boisdon et al., 1994). The main parameters

influencing ozonation reactions are NOM character, pH, and alkalinity as well as the inorganic matrix of the water (Rositano et al., 2000).

The cyanotoxins microcystin LR and LA were destroyed at low ozone doses, approximately the dose required to produce an ozone residual for each water. Lower ozone doses were required for the destruction of microcystin in treated water compared with raw water likely due to the reduced concentration of oxidizable material. Anatoxin-a was destroyed at an ozone dose required to obtain a residual of approximately 0.06 mg/L after 5 minutes. Another study showed ozone to be highly effective at removing both microcystin-LR and anatoxin-a with a dose of 2 mg/L sufficient to enable complete removal of the toxins from treated water (Hart et al., 1998). The saxitoxin class of compounds was very resistant to oxidation by ozone and would require further treatment such as GAC filtration. However, the mouse bioassay toxicity of the saxitoxin group of compounds decreases with increasing dose of ozone (Rositano et al., 2000).

Chlorination, under conditions similar to those used in disinfection of potable water, was shown effective at removing microcystin-LR at pH values below 7. At higher pH values, a longer contact time was required to remove microcystin-LR. No removal of anatoxin-a was possible using chlorine as the oxidizing agent (Hart et al., 1998).

For both microcystin-LR and anatoxin-a removal, potassium permanganate has been shown to be highly effective. A dose of 2 mg/L is sufficient to enable complete removal of the toxins from treated water (Hart et al., 1998).

Hydrogen peroxide, chlorine dioxide, and chloramine were ineffective for removing microcystins. When the oxidants were applied to water samples containing the toxic strain of *Microcystis* there was evidence that they were causing cell lysis and toxin release. Provided sufficient oxidant was added both the intra and extracellular toxins could be destroyed by all oxidants except chloramine.

UV

UV was capable of degrading both microcystin-LR and anatoxin-a at a dose of 20000 mWs/cm² compared to a typical water disinfection dose of 30 mWs/cm² (Hall et al., 2000). This would suggest that UV would not be feasible for use in treating algal toxins.

Membranes

The structure of anatoxin-a is different from that of the microcystins. It is a much smaller compound with a molecular weight of 165 compared to approximately 1,000 for the microcystins (Boisdon et al., 1994). NF-70 nanofiltration membrane with a molecular weight cutoff of 200 to 400 was able to remove microcystin-LR to below detectable concentrations. The removal of anatoxin-a was not tested, but having a smaller molecular weight, removal is expected to be less efficient (Hall et al., 2000).

Combined Treatment Techniques

Conventional treatment, termed earlier as CSF treatment, was ineffective at removing dissolved toxins; however, under suitable treatment conditions it is possible to remove toxins contained within the algal cells. There was no evidence to suggest that normal treatment would cause cell lysis and toxin release (Hart et al., 1998), but sufficient cells could penetrate particulate removal processes (except membranes) to be of toxicological concern (Hall et al., 2000). Algae can rapidly clog filters, even when the coagulation and sedimentation processes remove more than 90 percent of the algae in the influent (Rastogi et al., 1999).

In comparison to conventional treatment, microsand ballasted clarification (Actiflo®) consistently produced lower settled water algae counts. While optimal coagulation conditions with conventional treatment yielded settled water algae counts of about 2,000 cells per milliliter, settled water algae counts following microsand clarification could be reduced to about 400 cells per milliliter (Rastogi et al., 1999).

The ozone combined with flotation followed by a dual layer filtration when operating conditions are optimized, proved to be adequate for algae removal (Boisdon et al., 1994).

Source Water Management Strategies

Several management strategies exist to control algal blooms in the surface water. One such strategy is to sink the cyanobacteria by adding some form of coagulant or PAC to the surface water. Another strategy is to kill the resident population before/after blooming by adding copper sulfate to the surface water. However, by adding copper sulfate to kill the population, cell lysis occurs and a large release of toxin results and should be avoided once a bloom has

occurred. The final strategy is to prevent large growth from occurring by practicing nutrient control and/or light control (Howard et al., 1996).

SUMMARY

Performance in cyanobacteria removal depends on the type and concentration of bacteria as well as on raw WQ. Research indicates that algal toxin removal should be efficient at plants, which comprise both an ozonation and an activated carbon adsorption process. Further, biological activity in the different reactors should enhance the removal performance of the treatment plant. Dissolved microcystin-LR can be removed effectively to less than 1 µg/L under conditions that are normally used in water treatment by ozone, potassium permanganate, and chlorine. The results of the oxidation tests with dissolved toxins have shown that it is more effective to apply the oxidants to treated waters. Membranes should provide excellent removal assuming the molecular weight cutoff of the membrane is small enough to exclude the cyanotoxin.

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