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Review

Application of Membrane Technologies for Drinking Water Treatment in Florida

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1. Introduction

Membranes represent one of the newly applied, advanced water treatment processes that offer a versatile approach to meeting multiple drinking water quality objectives. Membranes have tremendous potential for the treatment of drinking water because of their universal treatment capabilities and competitive cost. Very few drinking water contaminants can not be removed economically by membrane processes. Membrane processes that have the greatest immediate application to potable water treatment are pressure-driven membrane processes, which are reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) [1].

Membranes provide distinct advantages over conventional water treatment (*i.e.* coagulation, sedimentation, and filtration). The most important superiority of membrane filtration is its ability to produce the best quality of product water, which complies with existing and future drinking water regulations. Other advantages can be summarized as:

- The amount of chemicals needed for water treatment is significantly reduced with membrane treatment (less coagulants and disinfectants).
- The spatial requirement for membrane plant is 5 to 10 times less than conventional treatment processes because of no need for clarification and sedimentation.
- The operation of membrane plant can be easily controlled and automated (less operators).
- Membrane plant does not generate sludge, reducing costs associated with sludge handling and disposal.

This paper presents the application of membrane processes for drinking water treatment in Florida. First, current and future drinking water regulations are summarized and the capability of membrane technologies to meet these regulatory challenges is discussed. Secondly, typical membrane treatment processes used in various membrane drinking water treatment plants in Florida are briefly explored. Lastly, some examples of the membrane filtration plants in Florida are introduced and their processes are documented in detail.

2. Membrane Treatment for Regulation Compliance

The growth of drinking water regulations for both chemical and biological species, improved water quality analysis, and advances in membrane technology, have created applications for

Table 1. Summary of Membrane Process Applications for Drinking Water Regulations

Rule	Membrane process			
	RO	NF	UF	MF
SWTR/ESWTR	Yes	Yes	Yes	Yes
CR	Yes	Yes	Yes	Yes
LCR	Yes	Yes	No	No
IOC	Yes	Yes	No	No
SOC	Yes	Yes	Yes(+PAC#)	Yes(+PAC)
Radionuclides	Yes	Yes	No	No
DBPR	Yes	Yes	Yes(+Coag*)	Yes(+Coag*)
GWDR	Yes	Yes	Yes	Yes
Arsenic	Yes	Yes	Yes(+Coag*)	Yes(+Coag*)
Sulfates	Yes	Yes	No	No

#PAC: Powdered Activated Carbon, *Coag: Coagulation,

Note: SWTR/ESWTR: Surface Water Treatment Rule/ Enhanced Surface Water Treatment Rule, CR: Coliform Rule, LCR: Lead and Copper Rule, IOC: Inorganic Compounds, SOC: Synthetic Organic Compounds, DBPR: Disinfection By Products Rule, GWDR: Ground Water Disinfection Rule.

membranes that will change accepted drinking water treatment technology forever. Membranes can be effectively used for removal of pathogens, inorganic and organic contaminates. There are very few instances where membranes can not be utilized to meet or exceed all drinking water regulations. Membrane technology is clearly among the leading technologies for meeting the current and impending drinking water regulations in the United States and the world today.

Existing regulations have and will be modified to include more stringent control of biological and chemical toxins [2]. The Safe Drinking Water Act (SDWA) amendments that were modified in 1996 still require the United States Environmental Protection Agency (USEPA) to create new drinking water regulations [3]. The regulatory changes will continue to create a need for new drinking water technology to meet these challenges. A summary of membrane process applications and drinking water regulations is shown in Table 1. Among these, the regulations that have driven technological change and had the greatest impact on drinking water treatment are the Surface Water Treatment Rule (SWTR) and the Disinfection By-Product Rule (DBPR).

SWTR: The SWTR has fundamentally changed the disinfection requirements for surface water treatment [4]. In the past, disinfection regulations required that water is maintained in plant for a specified time and residual, which was typically 1 mg/L Cl_2 for 15 minutes at peak flow. Presently, regulations are based on a multiple barrier approach requiring log reductions of given organisms and a residual in the distribution system. Specifically, the SWTR requires 3-log and 4-log removal and/or inactivation of *Giardia* cysts and viruses, respectively. Because of monitoring for particular microorganisms such as Giardia, the SWTR emphasizes treatment techniques for compliance, rather than establishing maximum contaminant levels. For examples, 2.5-log reduction of *Giardia* is given to a coagulation, sedimentation, and filtration (CSF) process operating with conventional engineering guidelines. The additional 0.5-log reduction for disinfection requires a specific CT (the product of disinfectant concentration and time) and varies by water quality and organism. Although there are several CT's for different organism, the largest CT is for Giardia, which controls design of the disinfection process.

DBPR: The DBPR has also impacted the disinfection process, but in an opposite manner of the SWTR. Initial DBP regulation began in the late seventies with trihalomethanes (THMs). Present and pending DBP regulation includes Stage 1 maximum contamination limits (MCLs) of 80 μg/L THMs and 60 μg/L HAAs (haloacetic acids), which will be effective in 2001. Stage 2 MCLs for THMs and HAAs are 40 and 30 μg/L. The effective date of Stage 2 DBP regulation is uncertain. It should be noted that, under the Information Collection Rules, water utilities using source waters with high DBP formation potential are currently conducting bench or pilot studies on DBP precursor removal using either membranes or granular activated carbon (GAC), in order to collect treatment process data necessary to develop the second stage of the DBPR.

The control of DBPs and pathogens conflicts for traditional drinking water treatment technologies. Increasing disinfectant dose and contact time is desirable for pathogen inactivation, but increases DBP formation:

Regulatory Conflict :

Pathogens ⇓ versus DBPs ⇑ as Cl_2 ⇑

One means of reducing pathogens without increasing DBPs is to remove the organic precursors such as natural organic matter (NOM), prior to disinfectant addition. NOM are ubiquitous in all drinking water sources and form DBPs regardless of which disinfectant is used to maintain a residual in the distribution system. Consequently, drinking water technology has turned towards membrane processes because membranes can remove more DBP precursors and pathogens than existing processes such as coagulation and add no by-products to the finished water. The DBP (NOM) and pathogen (cysts) rejections are shown in Figure 1 for conventional treatment (*i.e.*, coagulation, sedimentation and filtration) and pressure driven membrane processes [5,6]. CSF can remove from 30 to 70%, UF/MF can remove 0 to 10% and RO/NF can remove from 85 to 95% of DBP precursors. In addition, UF/MF membranes reject six logs and RO/NF membranes reject five logs or more of cysts, more than 1000 times the rejection of conventional drinking water treatment. It is surprising that UF/MF membranes reject an order of magnitude more cysts than RO/NF membranes as UF/MF membranes have pores that are 10 to 100 times larger than the pores of RO/NF membranes. The difference in rejection is due to the difference in construction. Spiral wound RO/NF membranes may provide more opportunity for passage of contaminants, probably due to imperfections involving, glue lines, o-rings, and element interconnects.

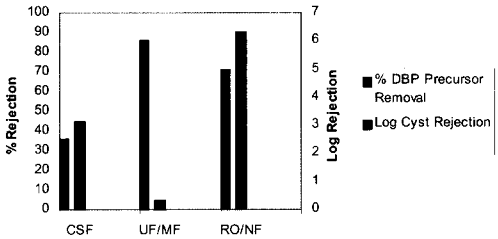

Fig. 1. Comparison of Contaminant Rejection.

3. Drinking Water Membrane Treatment

A typical RO/NF treatment system includes pretreatment, membrane filtration, and post treatment as shown in Figure 2 [7,8]. In the following subsections, source water, pretreatment, membrane array, post treatment, cost associated with membrane operating are discussed briefly.

3.1. Source Water

Drinking water supplies are generally classified as surface or ground waters. There are advantages and disadvantages associated with each source. Ground waters are typically harder (higher calcium and magnesium concentrations), subject to iron and manganese contamination, more difficult to access, and less productive than surface waters. However, ground waters have less organics, pathogens, taste and odors than surface waters. The advent of increasingly stringent regulations require consideration of finished water quality to accurately determine the most economical source for supply. Since high concentrations of pathogens or DBP precursors are not desirable, ground water supplies generally have been a choice of

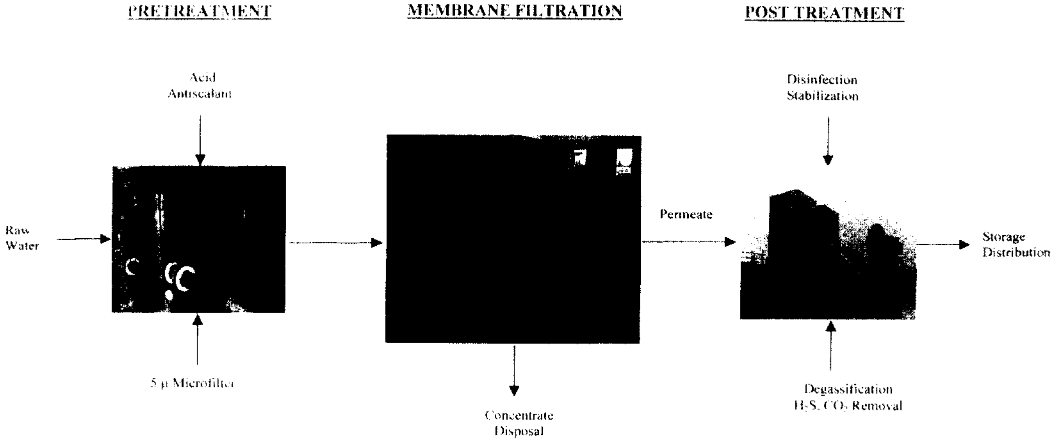

Fig. 2. Typical Membrane Plant Configurations for Drinking Water Treatment.

drinking source water for Florida (*i.e.* 92% of total drinking water source). However, with the depletion of pristine groundwater sources, the use of surface waters is expected to increase significantly in the future.

3.2. Pretreatment

Membrane fouling is an important factor affecting the operation of membrane plants. Wide spectrums of constituents in source waters are known to contribute to fouling. Membrane foulants can be classified roughly into four categories: (i) dissolved organic substances, (ii) colloidal or particulate matter, (iii) insoluble inorganic compounds, and (iv) biological matter such as bacteria [9]. Membrane operations require feed-water pretreatment for controlling membrane fouling. The pretreatment is feed-water-specific and differs from application to application and site to site. The minimum pretreatment processes for RO or NF consist of anti-scalent and/or acid addition and static microfiltration. These pretreatment processes are used to control scaling and to protect the membrane elements. Preceding scaling control and static microfiltration, advanced pretreatment may be required for raw waters with high fouling potentials. Examples of advanced pretreatment would be coagulation, oxidation followed by green sand filtration, continuous microfiltration, GAC filtration, and ground bank filtration.

3.3. Membrane Arrays

The exact type and configuration of the membrane system is dependent on a host of factors which include operating flux, recovery rate, pressure limitations, required solute rejection, source water supply, and source water quality. Although a multitude of membrane system configurations are possible, most full scale water treatment facilities are configured in a series of trains, each arranged in multiple stages, typically 2 to 3 stages in Florida. In general, these trains are similar in configuration and the number of membrane elements decreases in each succeeding stage.

3.4. Post-treatment

The primary post treatments for RO/NF processes are aeration, disinfection and stabilization. Additional post-treatments of concern are hydrogen sulfide removal, if present, and alkalinity recovery. Most solutes are removed by RO/NF membranes including carbonate alkalinity; however, all dissolved gases including carbon dioxide and hydrogen sulfide would pass through the membrane. As a result, the permeate stream leaving the membrane trains is very acidic with high concentrations of carbon dioxide, and possibly hydrogen sulfide, which results in a highly corrosive water. The pH of the permeate can be elevated through the addition of caustic soda. This increase in pH recovers a significant amount alkalinity that is destroyed in pretreatment by the addition of acid. Furthermore, the rise in pH resulting from caustic soda addition begins to stabilize the corrosive water. Degasification often follows the recovery of alkalinity. In this process, the water stream laden with undesirable gases (carbon dioxide and hydrogen sulfide if present) is transported to a packed tower with forced aeration. As the water passes through the tower, undesirable gases are stripped out of solution while oxygen is imparted. The benefits from this process are three-fold: the pH of the solution is increased, the taste of the water is improved, and the offensive odors are minimized. Disinfection of the permeate stream is most commonly achieved through the addition of chlorine. Typical chlorine doses following a RO or NF process range from 3 to 10 mg/L. Depending on the quality of the product water, additional stabilization may be required to prevent the deterioration of distribution pipes. Normally, finished waters with 1 to 3 meq/L of bicarbonate alkalinity are considered desirable for corrosion control. This can be accomplished through the addition of sodium hydroxide, corrosion inhibitor, or a combination of the two, which will reduce the corrosivity of the solution. Lastly, the finished water is placed into storage where it awaits distribution.

3.5. Waste Disposal

Concentrates from RO/NF plants are highly regulated by governments, posing more serious disposal problem to water utilities. The techniques used for concentrate disposal in the United States are surface water discharge, land application, sewer discharge, and deep well injection. Surface water discharge involves disposal of membrane concentrate to surface water body such as tidal lake, brackish canal, or sea, and is probably the most common technique of concentrate disposal in the United State. Land application of NF concentrates is possible in some locations because of the low TDS concentration, typically 1000 to 2000 mg/L, relative to RO concentrates. Sewer discharge is usually an option for small plants. Deep well injection (discharge to groundwater) is more common in Florida than any other state because of the regulatory environment in Florida. Finally, evaporation pond is an alternative option for locations with high evaporation rates, low precipitation rates, and inexpensive land area.

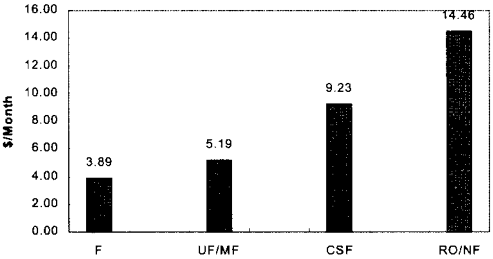

Fig. 3. Monthly Consumer Cost Comparison of Water Treatment Processes.

3.6. Membrane Treatment Cost

The approximate cost of conventional and membrane technology to the consumer is shown in Figure 3 for a community of 100,000 consuming 10 millions gallons per day (mgd). Filtration is included as a separate process since many communities in the northeast United States only filter the water. This cost assumes 30,000 households which accounts for the consumption of 10,000 gallons per month. The costs were estimated assuming 8% interest and a 20-year plant life. UF/MF costs should be compared with Filtration (F) consumer costs, and RO/NF costs should be compared with CSF costs since these treat similar sources. In each case, the cost of water for the consumer increases for higher quality. Changing from Filtration to a UF/MF process would increase consumer cost by 33% or $1.30/month. For that cost, consumers would receive water treated by a process that would reject 1000 fold more microorganisms. Changing from a CSF to RO/NF process would increase consumer cost by 56% or $5.23/month. For that, consumers would receive water treated by a process that would reject 100 fold more microorganisms than CSF and 90% of the DBP precursors. There is no doubt that higher quality treatment processes cost more and reduce adverse consumer health effects ranging from sickness to death for the consuming public.

4. Exmaples of Membrane Applications in Florida

The number of membrane drinking water treatment plants in the United States has increased dramatically since 1990. In particular, Florida has been a leading state that actively adopts membrane technologies for drinking water treatment. Rapid population growth (2.7 to 12.9 million from 1950 to 1990) and depletion of pristine groundwater in Florida have accelerated the use of alternative low quality and/or saline source waters. Membrane process is a choice of treatment technology for Floridian to augment their water supplies, while complying with stringent current and future regulations. Installed RO/NF capacity in the state of Florida is currently well in excess of 100 mgd with a build out capacity exceeding 200 mgd. Primary examples of RO/NF membrane plants in Florida are briefly summarized in Table 2. The operation of three membrane facilities among those listed in Table 2 are presented in detail in the following subsections.

4.1. Jupiter-Town of Jupiter Water System

The City of Jupiter currently houses the Town of Jupiter Water System, a 9-MGD low pressure RO water treatment facility. The source water for this facility is provided by the Floridan aquifer, 1200 to 1600 feet below the ground surface. This source water contains high TDS, but low turbidity (0.2 NTU) and TOC (1 mg/L). Ten wells, with a full capacity of 21.1 mgd, supply this facility with a consistent source water quality throughout the year. During operation, all wells flow into a common raw water pipe that transports the water to the treatment facility.

Upon arrival, the water is split between two independent membrane systems, Bank 1 at 6.0 mgd and Bank 2 at 3.0 mgd. Both banks provide similar physical and chemical pre-treatment to the raw water prior to membrane filtration. The chemical pretreatment for the Town of Jupiter Water System consists of the continuous dosing of 3.0 mg/L Flocon 100, a commercially available polyacrylic antiscalent. Following antiscalent addition, the water is passed through ten banks of prefilters, five for Bank 1 and five for Bank 2. Each prefilter bank houses a total of 425 commercial polypropylene wound polycore microfilters, with a nominal pore size of 5.0 μm. To avoid excessive head loss and to ensure proper pretreatment, these microfilters are replaced every three months.

After the source water has been pretreated, it is pressurized by a total of six (four for Bank 1 and two for Bank 2) vertical turbine pumps. The pressurized water is then transported to the membrane systems of Bank 1 and Bank 2. Bank 1 consists of four identical two-stage trains, each producing 1.5 mgd. Each train contains 37 pressure vessels in the first stage, 14 pressure vessels in the second stage, and six Hydranautics CPA2 membrane elements per pressure vessel. Bank 2 consists of two identical two-stage trains, also producing 1.5 mgd each. These trains each contain 31 pressure vessels in stage one, 13 pressure vessels in the second stage, and six Hydranautics ESPA1 membrane elements per pressure vessel. In addition to the feed water pumps, the second stage feed pressure is increased by an inter-stage turbine booster pump, which is powered by the concentrate flow of the second stage. The Town of Jupiter Water System operates both Bank 1 and Bank 2 at a recovery of 75%, a flux of approximately 12.6 gsfd, and a feed pressure ranging from 220 psi to 250 psi.

Following membrane filtration, the permeate from each Bank is dosed with approximately 25 mg/L sulfuric acid and mixed in-line. Following the static mixing of the solution, the two permeate streams are joined and degassed in three towers where the removal of hydrogen sulfide and trace amounts of carbon dioxide takes place.

Table 2. Examples of Drinking Water Applications of Membrane Filtration in Florida
(Source: Survey by University of Central Florida and Web site, http:// www2.hawaii.edu/~nabil)

Name	Year	Capacity (mgd)	Process	Mem-brane	Recovery (%)	Pretreatment	Post-treatment	Concentrate Disposal
Cape Coral	1992	16.8	RO	Fluid	80	pH Adjustment Cartridge Filtration	Degasification Disinfection	Discharge to Waste Water Plant
Dunedin	1991	9.5	NF/RO	Hydra	83	Greensand Filter Sulfuric Acid Antiscalent Addition Cartridge Filtration	Degasification pH Adjustment Chlorination	Discharge to Waste Water Plant to Reclaim for Irrigation
Fort Myers	1992	12.0	NF	Hydra	88	Sulfuric Acid Cartridge Filtration Bank Filtration	Degasification pH Adjustment	Aeration and Discharge for Irrigation
Hollywood	1995	18.0	NF/RO	Hydra	85/75	Sulfuric Acid Antiscalent Addition Cartridge Filtration	Degasification Chlorination	Discharge to Waste Water Plant
Jupiter	1997	9.0	RO	Hydra	75	Antiscalent Addition Cartridge Filtration	Degasification Disinfection Blending	Canal Discharge Well Injection
Marco Island	1997	5.0	RO	Fluid	75	Lime Softening	Chlorination	Discharge to Ocean Outfall
Melbourne	1995	6.5	RO	Hydra	85	pH adjustment Antiscalent Addition Cartridge Filtration	Disinfection Blending	Discharge to Saltwater Lagoon
Naples	1993	12.0	NF/RO	Hydra	90	Sulfuric Acid Antiscalent Addition Cartridge Filtration	Degasification	Well Injection
Palm Coast	1991	2.0	NF	Dow	80	pH adjustment Antiscalent Addition Cartridge Filtration	Degasification pH Adjustment Disinfection	Discharge to Waste Water Plant Canal Injection
Pine Island	1993	1.6	RO	MSC	85	pH adjustment Antiscalent Addition	Disinfection Blending pH Adjustment Chlorination	Discharge to Percolation Pond
Plantation	1998	16.0	NF	Hydra	85	Acid Addition Antiscalent Addition Cartridge Filtration	Degasification pH Adjustment Disinfection	Groundwater Injection
Sanibel	1994	4.7	RO	Dow	80	Antiscalent Addition Cartridge Filtration	Degasification Blending	Discharge to Ocean Outfall

(Note: Most of the membrane plants listed utilize brackish water as their source water; Fluid: Fluid System, Hydra: Hydranautics, MSC: Membrane System Corp.)

Once these gases have been removed, the filtrate is dosed with approximately 5-8 mg/L chlorine and 2-3 mg/L ammonia for disinfection and the formation of monochloramine. Following disinfection, the water is transported to a common clearwell where it is blended with conventionally treated (lime-soda) water. Finally, the pH of the blended solution is adjusted with sodium hydroxide to a pH of 9.1 and transferred to one of four storage tanks (1.5, 3, 5, and 8 million gallons) where it awaits distribution. The Town of Jupiter Water System treats the concentrate stream by sulfuric acid addition (pH 5.4) and aeration prior to discharge into the C-18 canal.

4.2. Palm Coast-Palm Coast Water Treatment Plant

The Palm Coast Water Treatment Plant 2 is currently a 1.83 mgd nanofiltration facility. This water treatment plant utilizes source water drawn from the upper Floridian aquifer through four wells. This aquifer provides the utility with a very consistent quality of water during both wet and dry seasons (*e.g.* TDS = 450 mg/L, Hardness = 320 mg/L as $CaCO_3$, and Turbidity 0.15 NTU). Once the ground water is pumped out of the aquifer, it is transported to a common header where it undergoes chemical pretreatment.

The chemical pretreatment for this facility includes the continuous addition of 93% sulfuric acid (250 mg/L) and Flocon 100 (2.2 mg/L), a commercially available polyacrylic antiscalent. Following chemical pretreatment, the source water proceeds to physical pretreatment. The physical pretreatment consists of filtering the water through one of two microfilter housings, each containing a total of 52 microfilters. These microfilters have a nominal pore size of 5 μm and are polypropylene filters manufactured by Vulcan Industries. These filters are replaced when the pressure loss exceeds 4.0 psi (approximately every 500 hours) to ensure proper filtration and avoid excessive energy consumption.

After all pretreatment is complete, the water is pressurized by two Afton multi-stage vertical centrifugal pumps and piped into a two-stage nanofiltration system. This system is divided into two identical trains, each producing just under 1 mgd. Each train contains 18 pressure vessels in the first stage and 9 pressure vessels in the second stage, with seven Dow FilmTec NF 70 membrane elements in each pressure vessel. The nanofiltration system is operated at a recovery of 80%, a flux of 16 gsfd, and a feed pressure of 140 psi. The permeate produced from this nanofiltration system is collected and transported to post-treatment processes.

Following membrane treatment, the permeate stream is directed to a forced aeration tower where undesirable gases (primarily carbon dioxide) are removed. Following degasification, the water is collected and dosed with approximately 6 mg/L chlorine and 1.5 mg/L ammonia. After dosing, the water is directed to a chemical contact chamber, which has a hydraulic residence time of 90 minutes. In this chamber, the chlorine and ammonia undergo a chemical reaction which results in the formation of chloramines. These chloramines provide a residual disinfectant throughout the distribution system. Following degasification and disinfection, the solution is stabilized by the addition of 75 mg/L sodium hydroxide and 1.0 mg/L Calciquest Zink-3, a commercially available corrosion inhibitor. Following post-treatment, the finished water is blended with raw water and placed into a 2 million gallon ground storage tank until it is distributed. The concentrate stream produced during the operation of this facility is discharged in one of two manners. First, if water levels are sufficient, the concentrate stream is blended with canal water at a 1:3 or 1:4 ratio and surface discharged. However, if the water level in the canal is insufficient for surface discharge, the concentrate is pumped directly into a lift station where it is transported to the local wastewater treatment facility.

4.3. Plantation-Central Water Treatment Plant

The City of Plantation contains two membrane water treatment facilities, the 12 mgd Center Water Treatment Plant and the 6 mgd East

Water Treatment Plant. The Central Water Treatment Plant obtains its source water from the Biscayne Aquifer. This surficial aquifer is tapped with eight wells, each 140 feet deep, which can provide a total feed flow rate of 16 mgd. This source water is characterized as a high organic surficial groundwater (*i.e.* TOC= 22 mg/L).

Once the source water is pumped out of the Biscayne Aquifer, it proceeds to the raw water manifold where it is treated with a continuous stream of sulfuric acid 93% to pH of 6.2 (approx. 140 mg/L) and Calgon EL-5600 (1.8 mg/L), a commercially available multi-component antiscalent. Following chemical pretreatment, the water pressure is boosted from well pressure (35 psi) to approximately 140 psi with five two-stage vertical turbine pumps. The pressurized water then passes through a series of 5 μm filters. These filters are contained in five housings, each containing 102 American Water Chemicals string wound polypropylene microfilters and are typically replaced every four months.

Once the chemical and physical pretreatment processes have been completed, the water is piped to the low pressure RO system. This system contains a total of four trains, each producing 3 mgd of treated water. Each train consists of two-stages. All membrane elements contained within this system are manufactured by Koch-Fluid Systems. This system is operated at a recovery of 85% (60% recovery per stage), a flux of 15 gsfd, and a feed stream pressure ranging from 100 psi to 130 psi.

The post-treatment for the permeate stream consists of several physical and chemical processes. Immediately following membrane treatment, the permeate is dosed with TPC-556, a polyphosphate iron sequestrant, (0.4-0.5 mg/L) and sodium hydroxide (12-14 mg/L). This water is then transported to two degasification towers which remove both carbon dioxide and hydrogen sulfide. Following degasification, the permeate stream is dosed with 3-4 mg/L of chlorine gas. The added chlorine reacts with ammonia already contained in the permeate which yields 3-4 mg/L of monochloramine. After the addition of chlorine gas, the water proceeds to a chlorine contact chamber which provides a contact time of forty-five minutes. The final processes involved in the post-treatment of the permeate is the addition of fluoride (0.6-0.7 mg/L) and a zinc orthophosphate corrosion inhibitor (1.5-2.0 mg/L). Following post-treatment, the water is placed into two storage tanks totaling 4.5 million gallons, where it awaits distribution. Unlike other two membrane treatment facilities described above, the City of Plantation has obtained a permit which allows for the deep well (3000 ft) injection of the concentrate stream.

5. Concluding Remarks

Regulations for control of DBPs and pathogens have impacted the technology and costs associated with drinking water treatment and are controlling the selection of water treatment processes. Membrane treatment is the most promising technology to meet these regulatory constraints. Membrane technology is more costly, but has been shown as a superior technology for the control of both DBPs and pathogens, and is currently being used for water treatment in lieu of conventional technology in Florida. Based on the recent regulatory trends and continuous deterioration of fresh drinking water resources, the application of membrane filtration for drinking water treatment is expected to increase dramatically in the twenty-first century, not only in the United States but also in the world.

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