Adaptation in the Face of Adversity: The Persistent Trend of Membranes in Water Reuse

Jennifer Ribotti and James Christopher

The process of desalination with membrane technology was first used to make potable drinking water from seawater in the 1960s. Since then, membrane treatment has benefited from several technological advances in membrane process design. These advances have made membrane treatment a more affordable technology for many water utilities. This is of great importance, as diminishing water supply resources and increased regulatory limitations are leaving water utilities with a limited number of alternatives.

As alternative technologies are pilot-tested for potable reuse, which focuses on the treatment of wastewater and reclaimed water to drinking water quality standards, one technology that has continuously proven to produce high-quality purified water is membranes. Although their cost, from both a capital and operational standpoint, has steered utilities to investigate other alternative technologies, their persistent trend in water reuse, in not only one, but in two technologies in the multiple-barrier treatment approach, proves that their resiliency for treatment of adverse water sources will continue to provide solutions for water utilities seeking alternative water supplies. This will only continue to increase the economic viability for membrane treatment as the demand for robust treatment increases.

In the state of Florida, aquifer storage and recovery (ASR), a viable water storage solution of choice for many communities, has encountered challenges due to the discovery of elevated arsenic levels, a naturally occurring element in Florida's aquifer mineralogy, during the recovery cycle testing of ASR facilities. Recently, the application of membrane technology has been demonstrated as a fourth treatment-barrier process in the multibarrier approach for mitigating the potential of arsenic mobilization in groundwater replenishment applications.

This article will provide a review of membrane technologies in water reuse, both in use at the pilot/demonstration and full-scale level, and how they are being applied for treatment of wastewater to purified drinking water across the United States. It will also discuss three representative case studies displaying a variety of membrane technologies that have been applied in potable reuse demonstration studies in Florida and their performance against constantly varying reclaimed water quality. These membrane technologies include ultrafiltration (UF), reverse osmosis (RO), and nanofiltration (NF) membranes in a variety of different application types (submerged, pressurized, gaseous hollow-fiber, low pressure, and high pressure).

Membrane Technologies in Water Reuse

Technological advances in membrane treatment have allowed membranes to be universally applied to treatment of a variety of water sources, including, but not limited to, seawater, surface water, groundwater, wastewater, and reclaimed water. The main driving factors for continuous development and innovation in membrane technologies include the discovery of new and rarer contaminants, the promulgation of new water quality standards, and cost[1]. It's an immutable natural law: if the demand is there, cost tends to fall due to a combination of economies of scale and improvements in manufacturing methods (Judd, 2017)[2]. Although costs associated with membrane technology are typically higher than alternative technologies, they are becoming more economically feasible with the growth of potable reuse implementation due to increasing demand in a technology proven to produce a high-quality, reliable water supply source.

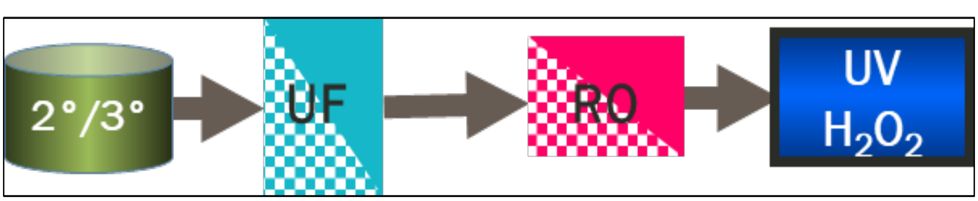

Figure 1. Typical Full Advanced Treatment Train After Secondary/Tertiary Wastewater Treatment

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One aspect of treating wastewater and reclaimed water for potable reuse is that it encompasses three main driving factors, which, when applied to the implementation of potable reuse, has led to its growth in an exponential fashion.

1) Public perception of potable reuse has driven technologies to be able to treat for contaminants down to levels undetectable by outpaced laboratory methods; however, as new and rarer contaminants are discovered, membrane technology has already demonstrated its ability to have removed many of these contaminants (i.e., perfluoroalkyl substances).
2) Diminishing water supplies and drought have driven utilities to implement technologies that have been proven in an effort to expedite the production of a safe, reliable drinking water supply source. This has led to a baseline expectation of the water quality anticipated from a potable reuse treatment train (i.e., equal to or exceeding potable drinking water standards). For example, in California, the state division of drinking water controls pathogens and requires a multibarrier design in groundwater replenishment reuse systems by requiring that the recycled municipal wastewater treatment achieves at least 12-log reduction of enteric viruses, 10-log *Cryptosporidium* oocyst reduction, and 10-log *Giardia* cyst reduction (see Cal. Code Reg. tit. 22 § 60320.108, 60320.208), which equates to a minimum of 99.99999999 percent removal.
3) The race for applying proven membrane technologies for potable reuse in the U.S. (and new ones, such as ceramic membranes) has led manufacturers to think innovatively and cost-effectively. Advancements in membrane technology include membrane materials, coatings, and manufacturing methods.

Many potable reuse demonstration systems in the U.S. have applied UF, RO, or NF

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membrane treatment in a variety of process configurations. The UF is commonly utilized as the first-treatment barrier in the full advanced treatment (FAT) train, generally followed by RO or NF membrane treatment (Figure 1). In one groundwater replenishment application in Florida, UF membrane technology was utilized for post-treatment of purified water for mitigation of dissolved oxygen (DO).

Most potable reuse demonstration plant capacities are greater than or equal to about 0.1 mil gal per day (mgd), or equivalently, ~70 gal per minute (gpm). The largest potable reuse demonstration facility (8 mgd) is run by the Santa Clara Valley Water District (SCVWD) and is known as the Silicon Valley Advanced Water Purification Center (SVAWPC), which uses the FAT train for nonpotable purposes. Its microfiltration process is shown in Figure 2.

The flow of 0.1 mgd (~70 gpm) is a significant threshold value for demonstration of RO/NF-based treatment trains, since 70 gpm is the approximate flow produced by a full-scale (8-in.-diameter element) two-stage RO/NF membrane system. Both Miami-Dade County and City of El Paso (Texas) had pilot systems with multiple parallel 4-in.-diameter RO/NF skids; however, both systems had large, deep bed denitrifying filters at the front of the train, which led to the system capacities being above 0.1 mgd.

Figure 2. Silicon Valley Advanced Water Purification Center Microfiltration Process *(courtesy of Santa Clara Valley Water District, 2015)*

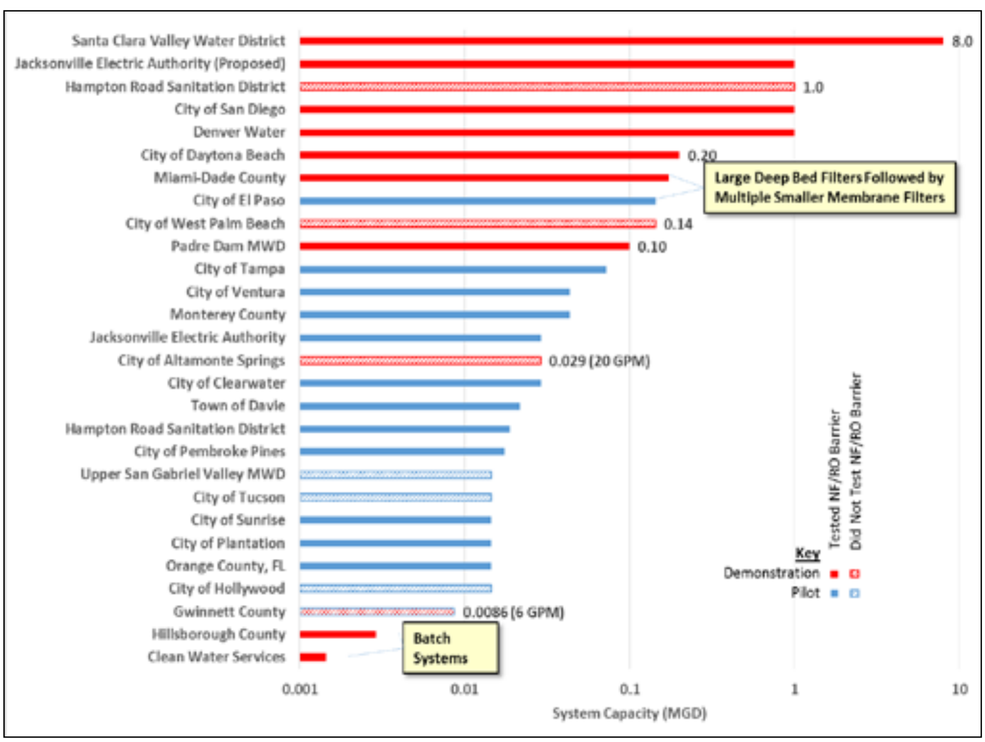

Figure 3. Potable Reuse Pilot and Demonstration Systems in the United States (2018)[3]

Among the 26 potable reuse tests conducted using RO/NF membranes that were evaluated when this article was written, most systems (19, or 73 percent) used 4-in.-diameter membranes, three (12 percent) used 2.5-in.-diameter membranes, and four (15 percent) used 8-in.-diameter membranes. Use of smaller-diameter RO/NF membranes is usually preferred in pilot/demonstration programs to reduce program costs, reduce system footprint, and simplify operations; however, some demonstration systems that have implemented full-scale membranes have helped provide operations staff (with little to no membrane experience) the opportunity to operate and maintain a full-size RO/NF skid.

Since the water quality performance of 4-in.-diameter membranes are well-established in a variety of applications, as comparable to full-size 8-in. membranes, many utilities choose to use 4-in. membranes and invest the cost savings in enhanced water quality sampling, online instrumentation and monitoring, and other program priorities.

Pilot/Demonstration Applications

Florida has been a hot spot for testing of potable reuse, with more than a dozen utilities having conducted pilots or demonstrations at the time this article was written. While many of these projects focused on indirect potable reuse (IPR), utilities are increasingly viewing direct potable reuse (DPR) as a potentially viable alternative water supply.

Florida utilities actively evaluating potable reuse (at the time of this article's writing) include Hillsborough County, City of Daytona Beach, City of Altamonte Springs, City of Clearwater, Jacksonville Electric Authority (JEA), and others. Previous pilot studies focusing on IPR applications may have limited applicability for the more stringent requirements of DPR, since DPR facilities do not have the margin for process upsets that a large environmental buffer provides to IPR facilities; therefore, it has become a priority for DPR testing programs to accumulate an extensive body of monitoring data that can be used as a basis of discussion with regulators for setting performance and treatment redundancy requirements for the implementation of future full-scale DPR systems.

For brevity, Figure 3 shows the capacity of 28 potable reuse test systems across the U.S. (at the time of this article's writing) from the past 30 years (log-scale). The shading of the capacity bars indicates whether the pilot/demonstration system tested RO or NF as part of the multibarrier treatment process. If the system did not, it's a good indicator that the FAT process was not tested. It's noted that 21 of the 28 systems utilized RO or NF as a treatment barrier.

Full-Scale Applications

Each full-scale potable reuse program involved the selection of an advanced water treatment train to achieve specific water quality goals set by regulations or other operational requirements. Table 1 includes a summary of potable reuse treatment trains, capacities, and major process selection factors.

In general, project treatment process selection in California was largely governed by Title 22 Groundwater Replenishment - Subsurface Application rules, which went into effect in 2014, though prior projects were permitted to a similar level of quality. These regulations require the use of RO and a ultraviolet (UV)/advanced oxidation process (AOP) for subsurface injection. Most California projects dispose of their RO concentrate by discharge to a wastewater treatment plant ocean outfall.

Processes in Texas for DPR employed microfiltration (MF) and RO, and either UV or UV/AOP[3]. Both projects also had a brackish river available for RO concentrate disposal.

Select Membrane Technology Case Studies in Florida

The City of Clearwater, Hillsborough County, and City of Daytona Beach have all investigated, implemented, and operated either a pilot or demonstration facility, with advanced treatment technologies, in an effort to address their own unique water supply challenges.

- The City of Clearwater recently completed the design of a full-scale advanced water purification treatment facility, which included three different membrane technologies at the full-scale level, including UF, RO, and UF membrane contactors for IPR. All membrane technologies were pilot-tested for one year in 2013.
- The City of Daytona Beach is investigating UF, as well as both RO and NF technologies, at the demonstration level.
- Hillsborough County investigated UF using submerged membrane technology, as well as RO, for a unique, small-scale DPR application, the first in Florida.

First-Treatment Barrier (and Post-Treatment) Performance: Ultrafiltration/Microfiltration

Both MF and UF are typically used as the first-treatment barrier due to their ability to produce waters extremely low in suspended solids and turbidity. This low-pressure filtration process is used in the potable reuse treatment train as a pretreatment step to the second barrier in the process. They are attributed with high-removal efficiencies of microbial pathogens, suspended solids, or particles, and to a lesser extent, organic colloids. Membranes for UF are typically provided as a flat-sheet or hollow-fiber configuration. Common materials include polyvinylidene fluoride (PVDF) and, less commonly, polyethersulfone (PES). As mentioned earlier, ceramic membranes are becoming increasingly relevant in the potable reuse market.

The integrity of a UF/MF system can be confirmed daily via a pressure decay test (PDT), allowing cyst removal disinfection credits to be

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Table 1. Full-Scale Potable Reuse Facilities With Advanced Water Treatment (2018)[3]

Sponsor	State	Facility/Project Name	Type	Treatment	Year Started	Capacity (mgd)
Sanitation Districts of Los Angeles County	CA	Seawater Intrusion Barriers (West Coast Basin, Dominguez Gap, Alamitos Gap)	IPR Groundwater Augmentation (Injection Wells)	By Others (West Basin, WRD, LASAN)	West Coast (1951), Dominguez Gap (1971), Alamitos Gap (1966)	28.8 (81% recycled water, 19% imported)
		Montebello Forebay Spreading Grounds	IPR Groundwater Augmentation (Spreading Basin)	GMF+Cl_2 from WRPs	1962	44 (Recharge)
Orange County Water District	CA	Water Factory 21 (WF 21)	IPR Groundwater Augmentation (Spreading and Injection)	Lime + NH_3 Strip + Recarb + Filt + Train 1: GAC+Cl_2 Train 2: RO	1976-2006 (Replaced by GWRS)	15
		Groundwater Replenishment System (GWRS)	IPR Groundwater Augmentation (Spreading and Injection)	MF+RO+UV/AOP +Decarb+Lime	2008	100 (70 Spreading/30 Injection)
Upper Occoquan Service Authority	VA	Millard H. Robbins, Jr. Regional Water Reclamation Facility (WRF)	IPR Surface Water Augmentation	MF+RO +UV/AOP +$CaCl_2$+NaOH	1978	54
El Paso	TX	Fred Hervey WRF (Hueco Bolson)	IPR Groundwater Augmentation (Spreading Basins and Injection)	Lime+CO_2 +O_3+BAC +Cl_2	1985	10
West Basin Municipal Water District (WBMWD)	CA	Edward C. Little Water Recycling Facility (ECLWRF)	IPR Groundwater Augmentation (Injection) (West Coast Barrier)	Lime+CO_2 +MMF+GAC +Cl_2+SBS	1993, 1995	17.5
Gwinnett County	GA	F. Wayne Hill Water Resources Center (Gwinnett County Department of Water Resources)	IPR Surface Water Augmentation	GMF or UF+ O_3+BAC+O_3	1999	60
Scottsdale Water (City of Scottsdale)	AZ	Scottsdale Water Campus, Arizona, USA	IPR Groundwater Augmentation	O_3+MF +RO+UV +Decarb+Lime	1999	20
City of Los Angeles Department of Public Works, Bureau of Sanitation	CA	Terminal Island Water Treatment Facility (WTF)	IPR Groundwater Augmentation to Dominguez Gap Barrier	MF+RO+UV/AOP(Cl_2) +$CaCl_2$+NaOH	2000 Original 2007 Expansion	2.5 12
Water Replenishment District of Southern California	CA	Leo Vander Lans WTF	IPR Groundwater Augmentation to Alamitos Barrier	O_3+MF +RO+UV/AOP +$CaCl_2$+NaOH	2005/2006	8
	CA	Groundwater Reliability Improvement Project (GRIP)	IPR Groundwater Augmentation to Montebello Forebay Spreading Basins and Injection Wells	MF+RO +UV/AOP(Cl_2) +Lime	2018/2019	11.6
Aurora Water (City of Aurora)	CO	Prairie Waters	IPR Groundwater Augmentation	RBF+SAT+Lime +UVAOP+GMF+GAC	2010	50
Colorado River Municipal Water District	TX	Big Spring	DPR Source Water Augmentation	MF+RO+ UV/AOP	2013	1.78
Wichita Falls	TX	Wichita Falls (Inactive)	DPR Source Water Augmentation	MF+RO+UV	2014-2015	5

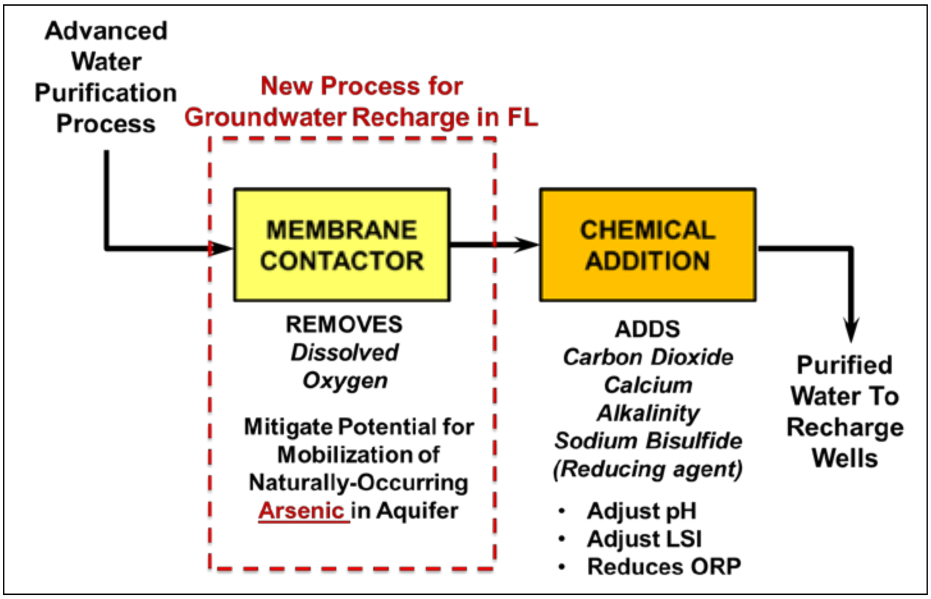

Figure 4. City of Clearwater Post-Treatment Steps

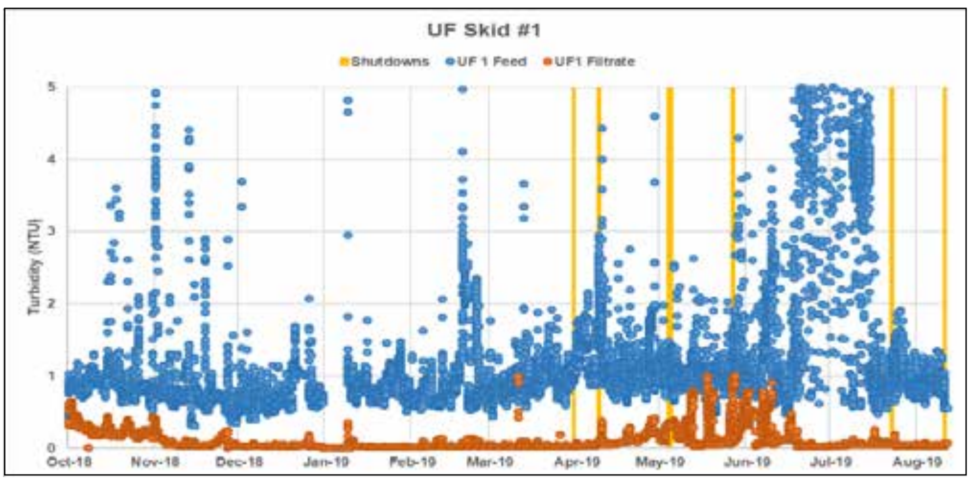

Figure 5. City of Daytona Beach Turbidity Results Consistently Less Than 0.1 Nephelometric Turbidity Units for Skid #1

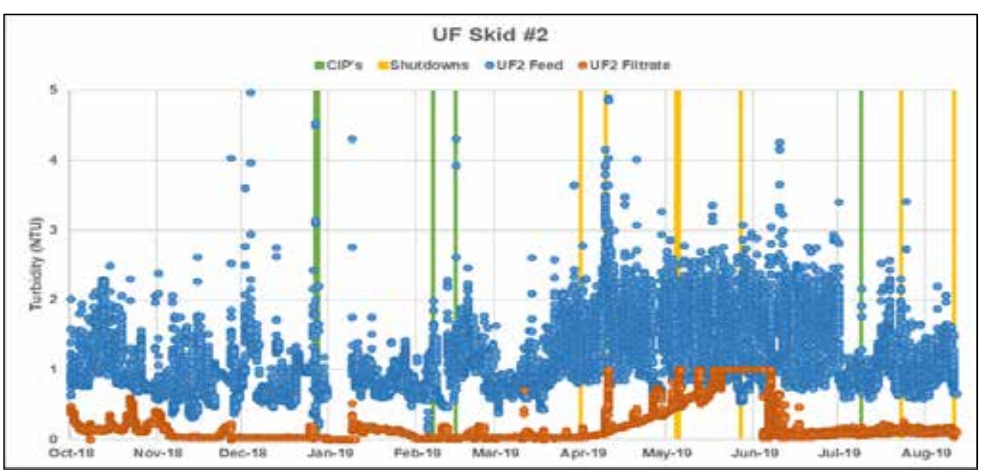

Figure 6. City of Daytona Beach Turbidity Results Consistently Less Than 0.1 Nephelometric Turbidity Units for Skid #2

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verified (e.g., 4-log credit for *Giardia* cysts and *Cryptosporidium* oocysts in the California regulatory framework).

Hollow-Fiber Ultrafiltration Membranes

Hollow-fiber membranes filter water from the outside-in (O/I). They have a proven track record in potable reuse systems over a variety of reclaimed water qualities. The fibers are strong due to a combination of PVDF polymer (an asymmetric membrane with smaller pores in the active filtration area), and a high-porosity substructure. The PVDF membranes offer high chemical resistance (e.g., resistance to chlorine) and are tolerant to temperatures of 40°C. Both the City of Clearwater and City of Daytona Beach have tested hollow-fiber UF membranes.

- The City of Clearwater tested a single vertical DuPont (formerly DOW) SFD-2880 UF membrane in the first barrier of the FAT process.
- The City of Clearwater also tested a hollow-fiber polypropylene membrane in a post-treatment step (after the FAT process) for DO removal (to help control the potential for metals mobilization from the aquifer formation). Figure 4 illustrates the post-treatment process that was tested in the pilot phase and designed at the full-scale level for the advanced water purification facility.
- The City of Daytona Beach has tested a vertical Toray HFU-2020 membrane (UF Skid #1) and vertical DuPont (formerly Dow) SFD-2880XP membrane (UF Skid #2) to date.

Utilizing the UF process at City of Clearwater resulted in significant reductions in turbidity in the reclaimed water prior to delivery to the subsequent RO unit process. Overall, UF filtered-water turbidity was typically less than 0.2 nephelometric turbidity units (NTU), with a 78 percent average removal.

The City of Daytona Beach has experienced filtrate turbidities consistently less than 0.1 NTU; however, ongoing filter construction at the time on the upstream water reclamation facility impeded performance for a short period of time (April - June 2019). This was observed in both UF membranes, which operated in parallel for approximately one year (Figures 5 and 6). The UF Skid #1 had not required a clean-in-place (CIP) step as of August 2019 due to consistent performance.

The City of Clearwater's UF membrane accumulated moderate fouling, as shown by an increase in transmembrane pressure (TMP) in Figure 7. The pilot ran for approximately five

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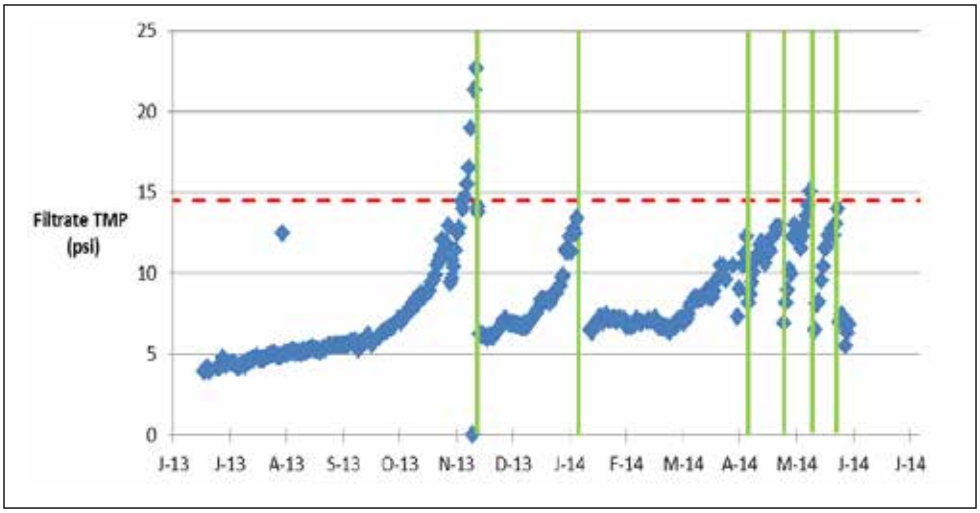

Figure 7. City of Clearwater Transmembrane Pressure Controllable Through Clean-in-Place

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months before requiring its first CIP step (the CIPs are shown as vertical green lines in Figure 7). The UF TMP was controllable through cleaning, which dislodged foulants, such as iron, manganese, and organics.

The City of Daytona's UF Skid #2 accumulated fouling, as shown by several spikes in TMP in Figure 8. The CIPs were able to reduce the TMP by dislodging foulants assumed to be iron and organics. The UF Skid #1 had relatively stable TMP, ranging from 4 to 6 pounds per sq in. (psi) throughout its first year of operation.

A PDT is a useful operational tool for monitoring the state of UF membrane fibers. The PDT levels and membrane fiber pinning repairs can be tracked at full scale as an operational tool for timing pinning maintenance, as needed, for specific UF modules. Broken UF fibers can

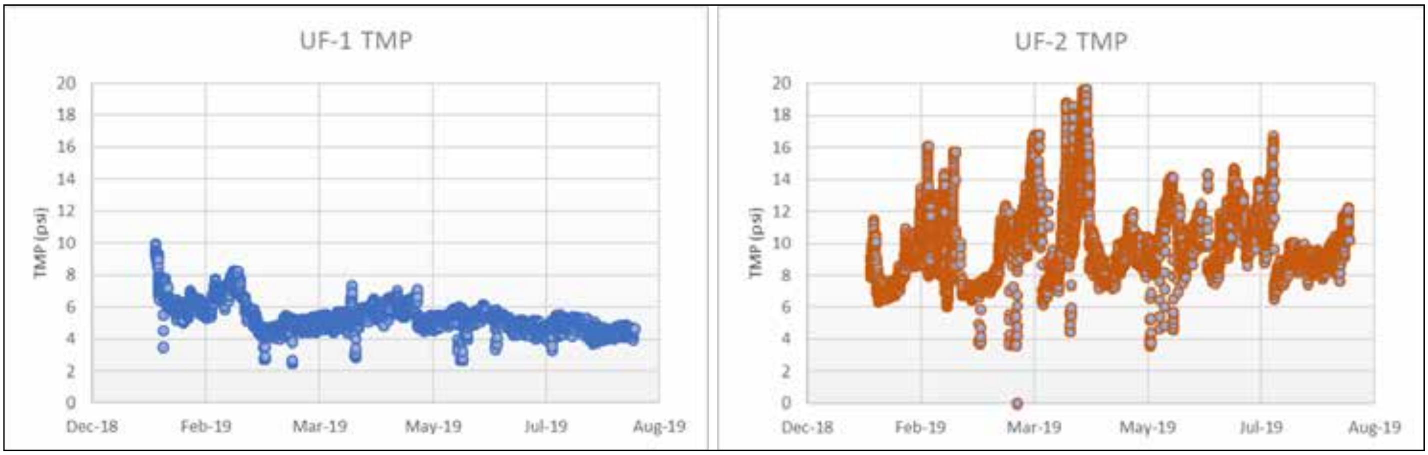

Figure 8. City of Daytona Beach Transmembrane Pressure Controllable Through Clean-in-Place

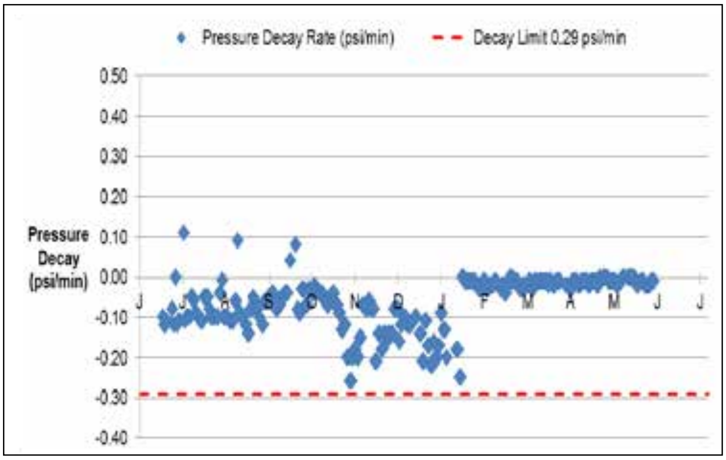

Figure 9. Pressure Decay Remained Relatively Steady Throughout One-Year Pilot Study

Figure 10. Four Membrane Contactors in Series to Provide up to 4-Log (99.99 Percent) Removal of Dissolved Oxygen *(courtesy of City of Clearwater, 2014)*

result in compromised filtration and reduced removal of protozoan pathogens.

For City of Clearwater, a time series of PDT results are shown in Figure 9. Beginning in late October 2013, the results of the PDT began to decrease rapidly from about -0.10 psi/minute to -0.20 psi/minute; through mid-January 2014, the PDT results held relatively steady. In January 2014, the UF vessel was opened, and broken fibers were identified and pinned. After that time, the PDT remained above -0.05 psi/minute, higher than the initially recorded PDT results in June 2013 of about -0.10 psi/minute.

For purposes specific to the groundwater replenishment program at City of Clearwater, a fourth treatment step was included for the conditioning of the water for aquifer recharge. This included a membrane contactor system (hollow-fiber ultrafiltration membranes), as shown in Figure 10, for the reduction of DO from the purified water before post-treatment. The same technology has been used previously in Florida for DO removal for ASR projects.

The hollow-fiber membranes are permeable to gas, but not permeable to water. Unlike the standard application of a UF membrane for water treatment, water passes around the outside surface of the hollow fibers, never entering the fiber itself (Figure 11). A vacuum pump is then used to draw high-purity nitrogen through the inside of the hollow fibers, creating a low-pressure area inside, with very little oxygen present in the sweep gas. The lack of DO inside the fiber creates a driving force for oxygen to diffuse out of the water, through the fiber wall, and into the hollow core, to be carried away by the nitrogen sweep gas mixture.

The pilot was originally designed to utilize either nitrogen and/or carbon dioxide as a sweep gas.

In the City of Clearwater's pilot study, the DO concentration in the reclaimed water was around an atmospheric concentration of 8 mg/L. The membrane contactor system removed around 4 log of DO (down to 1 part per bil [ppb]), but the trace DO sensor experienced difficulties in detecting the low concentration of DO, partly due to location. The sensor was relocated upstream of any potential interferences (lime turbidity from post-treatment chemical addition) and DO was consistently read for the remainder of the pilot study.

In summary, the DO of the purified water ranged from 7 to 9 mg/L, depending on temperature, and was consistently reduced to less than 10 μg/L, as shown in Figure 12.

Flat-Sheet Ultrafiltration Membranes

An alternative to a pressurized hollow-fiber UF membrane is a submerged hollow-fiber UF membrane. This configuration is not commonly seen in potable reuse applications, but is commonly used for media filter retrofits and at large drinking water treatment plants. The membranes are installed cassette-style, very much resembling books in a bookcase[4], which can be observed in Figure 13. Feed water enters the membrane tank and surrounds the hollow fibers contained within. A vacuum is drawn on the inside of the membrane to suck the feed water to the inside of the membrane through many microscopic pores, resulting in clean filtered water. The suction can be created by a pump, or simply by siphon alone. Particulates and bacteria are too large to pass, and so remain in the membrane tank outside of the membrane fibers[4]. Similar to a pressurized UF membrane system, the submerged configuration periodically requires cleaning through water-flow reversal.

- Hillsborough County tested a standard ZeeWeed 1000 UF flat-sheet membrane module, which is composed of PVDF and has an O/I flow path. Membrane integrity is tested using a PDT.

Because of the limited runtime of the Hillsborough County pilot (three days),

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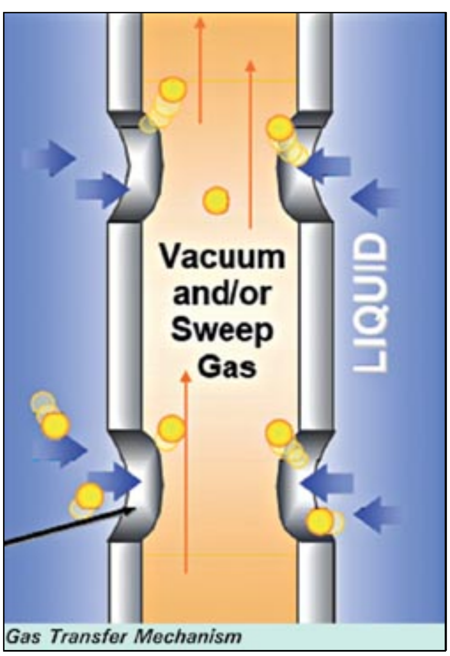

Figure 11. Basic Operation of a Hollow-Fiber Membrane Contactor

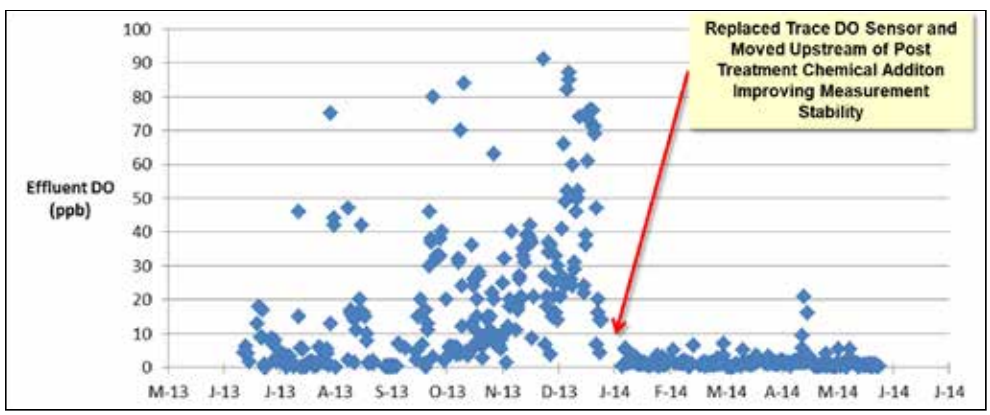

Figure 12. City of Clearwater 4-Log Removal of Dissolved Oxygen Achievable With Membrane Contactors

Figure 13. Building Block Design of an Immersed Ultrafiltration Membrane System *(courtesy of Suez [Formerly GE], 2016)*

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performance monitoring was critical to assess the integrity of the treatment barriers. The pilot UF process was assessed by PDTs, turbidity monitoring, and particle counts. The performance monitoring method, anticipated result, and frequency of testing have been summarized in Table 2.

The UF pilot achieved a pathogen log reduction of 3.4, verified through an MS-2 coliphage challenge study. In combination with the other treatment barriers, the pilot achieved over 15, 16, and 17-log removal of viruses, *Cryptosporidium*, and *Giardia*, respectively.

Ceramic Ultrafiltration Membranes

A ceramic membrane can be used in lieu of a traditional polymeric UF membrane in water and/or wastewater application. It can be formed from a variety of metal oxides, such as aluminum and titanium oxides. Ceramic membranes are essentially chemically inert and can be operated at high temperatures, unlike typical polymeric membranes. Instead of utilizing hollow-fiber membranes, ceramic membranes use pores, made by pouring a dispersion of coarse ceramic material and a binder into a mold. An example of a ceramic membrane is shown in Figure 14. Currently, reproducibility of the membrane formation process on a large commercial scale is rather poor and costs are much higher compared to PVDF membranes.

Ceramic membranes also have an inside-out (I/O) configuration and require a much higher backwash flux rate than a typical polymeric membrane. Table 3 illustrates the differences in characteristics as compared to commonly used PVDF UF membranes.

Advantages of using a ceramic membrane versus a polymeric membrane include:

- Three to five times higher flux rate
- Less membrane area
- High-suspended solids tolerance
- High chemical resistance
- Ease of maintenance
- Longer life cycles
- Ability to recover permeability

Disadvantages may include:

- Production cost
- Use not widely established in the U.S. (small market)
- Typically requires pretreatment (coagulant aid)
- More efficient with higher solids loading (potable reuse is relatively lower in solids)

The City of Daytona Beach acquired four Nanostone CM-151 ceramic membranes for testing in one of its ultrafiltration skids; however, due to the high influent turbidity of the reclaimed water (and effects on the reclaimed water from the upstream construction at the time), the ceramic membrane required the addition of a coagulant. The city decided not to test the ceramic membrane during the two-year testing period.

Table 2. Performance Monitoring Methods by Process

Process	Method	Anticipated Result	When Tested
MF/UF	Pressure Decay Test (Critical Control Point)	<0.27 psi/minute at 14 gfd flux for >4-log *Cryptosporidium*, According to Suez	Test Daily, Before and After Batch Production
	Effluent Turbidity	<0.3 NTU 95% of the Time	Continuously
	Influent and Effluent Particle Counts	>1.5 LRV Bacteria Range (<5 µm) >2.0 LRV Protozoa Range (4-15 µm)	Grab Samples Before and After Batch Production
	MS2 Seeding and Sampling	>4 LRV Bacteriophage	Seeding Study After Batch Production

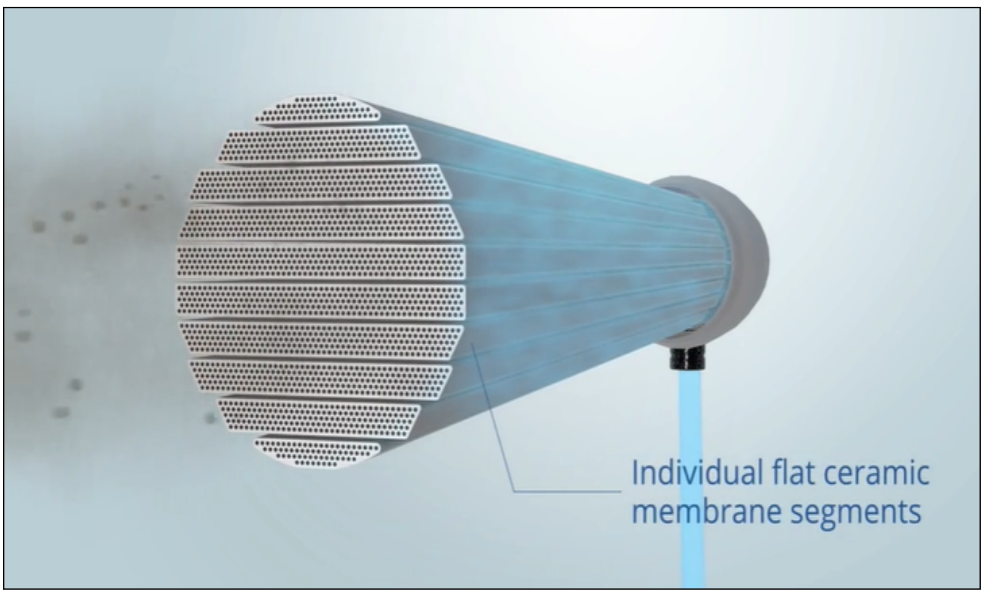

Figure 14. Ceramic Membrane Design
(courtesy of Nanostone)

Table 3. General Comparison of Ceramic Membrane (Nanostone CM-151) to Commonly Used Polyvinylidene Fluoride Ultrafiltration Membranes

Nanostone (CM-151)	DOW (SRD-2880XP)	Toray (HFU-2020)	Scinor (SMT600-P72)
Ceramic	PVDF	PVDF	PVDF
Inside Out	Outside In	Outside In	Outside In
100 to 140 gfd	30 to 50 gfd	30 to 50 gfd	30 to 50 gfd
223 gfd (BW)	54.3 gfd (BW)	46.5 gfd (BW)	46.5 gfd (BW)
258 ft²	829 ft²	775 ft²	775 ft²
0.03 micron	0.03 micron	0.01 micron	0.10 micron
75.5" height	92.9" height	85" height	85" height
8.3" diameter	8.9" diameter	8.5" diameter	7.8" diameter

Second-Treatment Barrier Performance: Reverse Osmosis

The RO is the second barrier in the FAT process and consists of a pressure-driven treatment process that utilizes semipermeable membranes to separate dissolved constituents from water. Contaminants removed by RO typically include organics, pharmaceuticals and personal care products (PPCPs), inorganics, heavy metals, and viruses. Thin-film composite membranes are commonly used in water treatment, as they provide high-salt rejection rates at low-operating pressures.

Both NF and RO are two very similar

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technologies; the NF is a looser membrane and has a higher salt passage than RO membranes. Although they still reject most of the same constituents, they may allow more minerals (salts) to pass through. Because of this, they may require less energy than an RO system. The NF systems are ideal for potable reuse applications since reclaimed water tends to have a lower concentration of total dissolved solids (TDS).

The integrity and performance of an RO/NF system are key performance indicators, such as normalized permeate flow, differential pressure, silt density index (SDI), salt rejection, and normalized specific flux.

The City of Clearwater, Hillsborough County, and City of Daytona Beach have all tested RO membranes.

- The City of Clearwater tested 4-in. and 2-in. DuPont (formerly DOW) XFRLE-4040/2540 RO membranes in the second barrier of the FAT process.
- The City of Daytona Beach tested a full-scale 8-in. DuPont (formerly DOW) BW30XFRLE membrane (RO Skid #1) and LG NanoH2O membrane (RO Skid #2). Both membranes are low-energy brackish RO membranes. It intends to test an ultra-low-pressure brackish water RO membrane (Toray TMG20D-400) and energy-saving low-fouling NF membrane (Hydranautics ESNA1-LF-LD).
- Hillsborough County tested a 4-in. Suez (formerly GE) AG4040FM RO membrane.

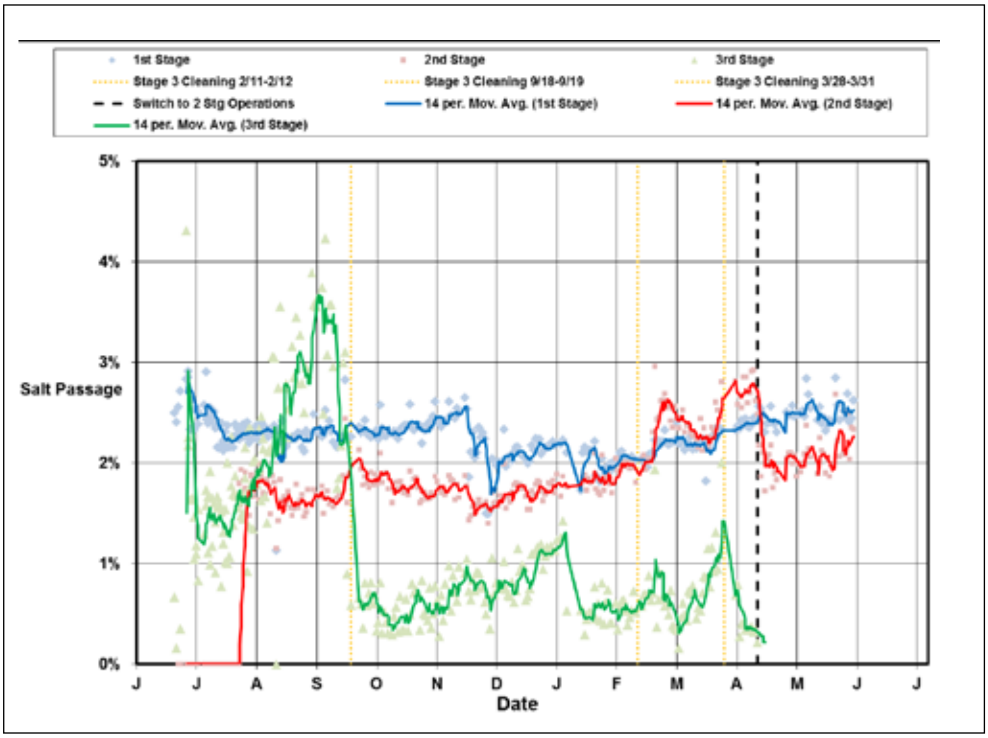

Figure 15. City of Clearwater Normalized Salt Passage is Normal

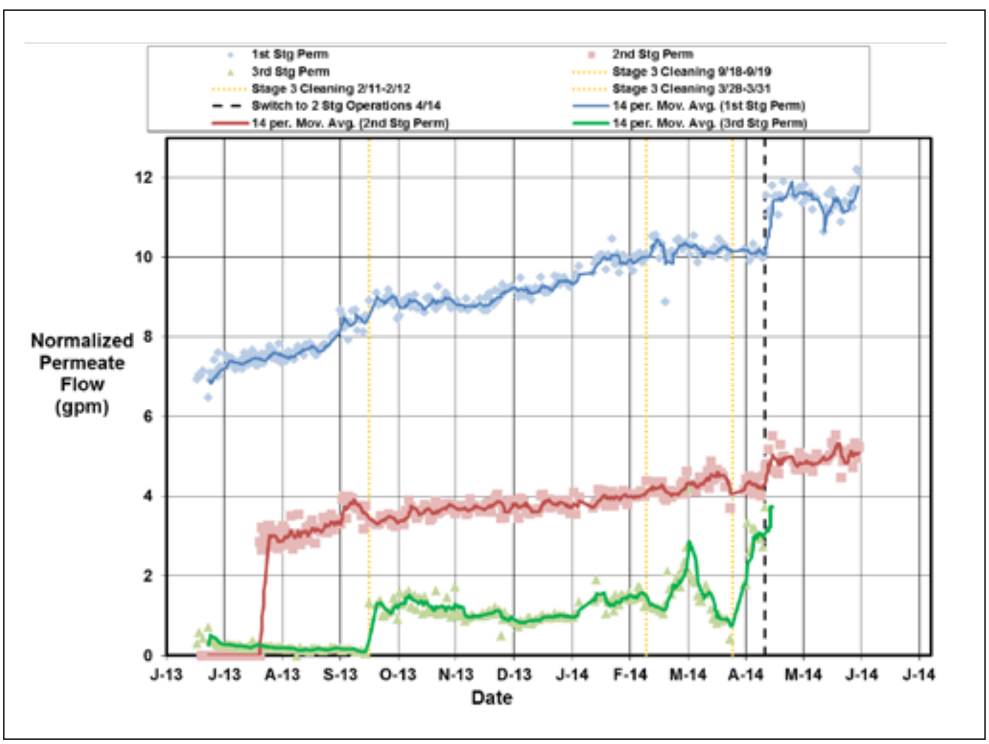

Figure 16. City of Clearwater Normalized Permeate Flow was Steady

The City of Clearwater tested two RO configurations (three-stage at 84 percent recovery and two-stage at 82.5 percent recovery). The average flux during both periods was 11.6 gal per sq ft per day (gfd).

- The three-stage system showed signs of scaling in the third stage only.
- The two-stage system did not show any signs of scaling during operations.

The City of Daytona Beach will test an NF membrane in its second year of operation.

The membranes consistently produced water with low TDS and low total organic carbon (TOC), while maintaining a high-salt rejection. Membrane CIPs appeared to be beneficial in removing fouling from the third stage. The first and second stages did not require cleaning during the one-year period because they did not show any signs of fouling through net declines in permeate flow. No major effects from the increase in normalized permeate flow were seen on water quality performance and contaminant removal in the pilot. Normalized salt passage and permeate flow are summarized in Figures 15 and 16.

The City of Daytona Beach has experienced relatively stable normalized permeate flow in both RO skids throughout the first six months of operation of its first year (Figures 17 and 18). Declines in permeate flow were observed from April to June 2019 (coinciding with spikes in turbidity from the water reclamation facility), particularly in the second stage. Several CIPs were initiated in an effort to restore permeate flow.

A cleaning study performed on a second-stage tail-end membrane element indicated that scaling was not a concern and that a free chlorine breach may have caused some membrane degradation. Fouling seems to have been a concern for both membrane systems; however, after cleaning with a proprietary manufacturer cleaning chemical solution, permeate flow was restored to even higher-than-starting permeate-flow conditions.

Despite highly variable water quality due to seasonal/tourist influences, the membrane systems have proven to be robust and have not shown any indication of irreversible fouling.

Because of the limited runtime of the Hillsborough County pilot (three days), performance monitoring was critical to assess the integrity of the treatment barriers. The pilot RO process was assessed by specific conductance, TOC, and the MS-2 coliphage testing. The performance monitoring method, anticipated result, and frequency of testing have been summarized in Table 4.

The RO pilot achieved a pathogen log reduction of 2.3, verified through an MS-2 coliphage challenge study. In combination with the other treatment barriers, the pilot achieved over 15, 16, and 17-log removal of viruses, *Cryptosporidium*, and *Giardia*, respectively.

Summary

It's evident that membrane technology has been able to adapt in the face of adversity with advances in technology. In this article, the application of membrane technologies was summarized for potable reuse applications on both the pilot/demonstration and full-scale level. While RO has always been considered a staple technology for desalination, it's now an integral part of the multibarrier full advanced treatment process. The multibarrier advanced treatment process using membrane technology has proven its efficacy relative to regulatory water quality requirements, even as new and rarer contaminants are discovered.

With time, these technologies, including advancements being investigated today (ceramic membranes), will continue to become more cost-effective as their implementation becomes a reality for many utilities experiencing (or beginning to experience) limited potable water supply conditions.

New scientific breakthroughs will lead to enhanced understanding of the significance of criteria found in both water and wastewater and their significance to human health. New regulations will be needed to reflect this enhanced biological and chemical understanding. To meet future water resource management and water reuse challenges effectively, cities must embrace the "one water" concept[5].

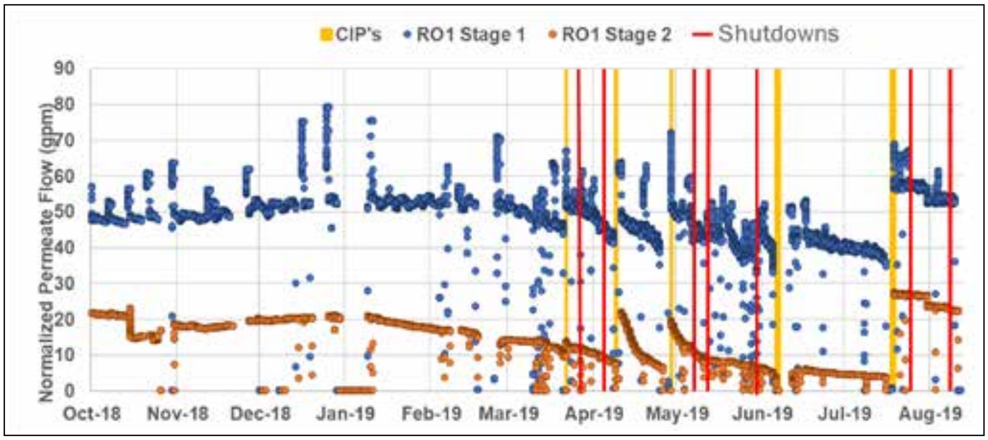

Figure 17. City of Daytona Beach Normalized Permeate Flow for Reverse Osmosis Skid #1

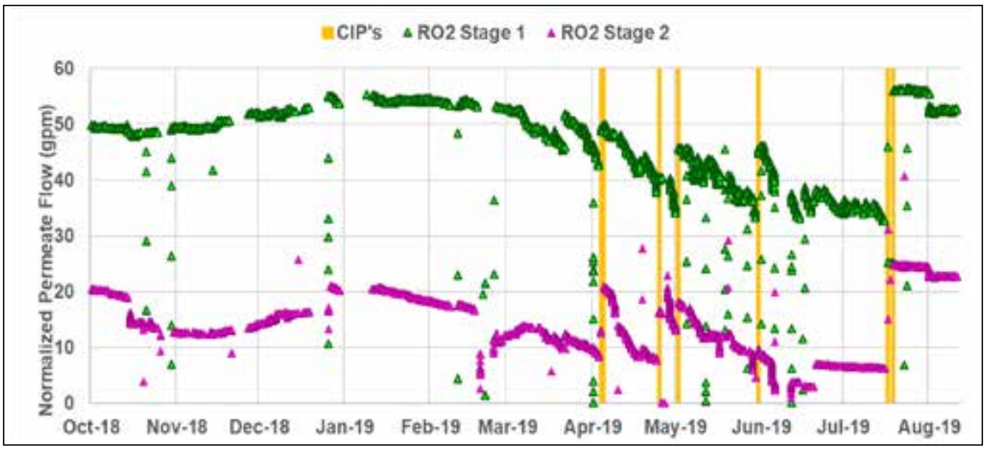

Figure 18. City of Daytona Beach Normalized Permeate Flow for Reverse Osmosis Skid #2

Table 4. Performance Monitoring Methods by Process

Process	Method	Anticipated Result	When Tested
RO	Specific Conductance (Critical Control Point)	>90% Reduction (>1.0 LRV)	Grab Samples Before, During, and After Production
	Total Organic Carbon	>90% Reduction (>1.0 LRV)	Grab Samples Before and After Batch Production
	MS2 Seeding and Sampling	>4 LRV Bacteriophage	Seeding Study After Batch Production

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