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Field testing of PolyCera®, PES, and PVDF ultrafiltration membranes in municipal tertiary filtration: Impacts of membrane polymer chemistry on fouling, cleaning, energy, and cost

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ABSTRACT

A 6-month pilot-scale field study was conducted to investigate the performance of three polymeric ultra filtration membranes for tertiary filtration within a Southern California municipal water recycling plant. Commercial hydrophilic polyvinylidene fluoride, polyether sulfone, and PolyCera® flat-sheet membranes were packaged identically into Spiral Monolith cross-flow back washable modules. The overall objective of the study was to evaluate the filtrate recovery, energy demand, and operating cost of the three membrane materials in achieving California Title 22 product water quality filtering secondary-treated sewage. All three membranes met California Title 22 filtered water quality criteria throughout the entire testing period due to their small characteristic pore size. The PolyCera membrane was the least fouling prone and, as a result, produced significant benefits in filtrate recovery, energy consumption, and operating cost due to less frequent and intense backwashing requirements. Filtration was maintained for over 5 weeks when operating the PolyCera membrane with an average flux of 33 LMH and filtrate backwashing every 25 min. During this long-term operation, the PolyCera system consumed, on average, 0.035 kWh at an operating cost of $0.016 for every cubic meter filtrate water produced, which is a net savings up to 46% compared to standard systems reported in literature.

Keywords: Water reuse; Advanced polymers; Fouling; Tertiary filtration; Sustainability

1. Introduction

Most municipalities are beginning to target the treatment of municipal sewage for non-potable secondary reuse applications, such as landscape irrigation, industrial cooling, and toilet flushing, to meet growing water needs [1,2]. However, continuous improvements in the economics and robustness of treatment technologies are needed to make secondary reuse a sustainable treatment option [3–5]. Efficient membrane cleaning is key to sustainable operation with the type and frequency of cleaning dependent upon environmental factors, such as the inter facial membrane-foulant interactions and the efficacy of upstream pretreatment. Conventionally, hollow-fiber (HF) membranes composed of polypropylene (PP), polyvinylidine fluoride (PVDF), or polyether sulfone (PES) are used in combination with pre-screen filtration and chemical pretreatment to inhibit fouling, especially from bio-growth.

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Chloramine is the most common as it is mildly oxidizing but a reasonably effective biocide, which does not cause damage to equipment, especially if reverse osmosis is used downstream. In general, typical operating conditions for micro filtration and ultra filtration (UF) membranes treating secondary effluent are 30–40 L/m^2/h (LMH) at 85–93% recovery with typical cleaning protocols consisting of filtrate backwashing every 10–40 min, *in-situ* maintenance chemical cleans every 2–20 d, and recovery cleans-in-place (CIPs) every 2–5 weeks [6–10]. Table 1 showcases several installations along with their typical modes of operation [8,11]. These installations produced water for a wide range of uses, such as boiler feed, seawater barrier maintenance, and ground water recharge.

An ideal membrane for tertiary filtration is one that consistently produces high quality filtrate over its lifetime while consuming as little energy and chemicals as possible. In California, tertiary filtrate needs to meet Title 22 specifications of the California Code of Regulations for industrial and irrigation reuse [12,13]. Qualities such as high permeability, low fouling, 6-4-3 log bacteria-virus-cyst removal classification, and broad-spectrum chemical robustness can enable such a process. Demonstration of the reliability of such a tertiary filtration process can lead to municipal sewage treatment and water recycling paradigms that can improve overall process durability and efficiency. Technology packages for direct potable reuse exist; however, reliability of individual component technologies have forced many to consider incorporation of redundant steps in the treatment train. Such an approach generally leads to an intricate and complex plant, which is expensive to build and operate [14–17]. In this context, the authors aimed to evaluate the techno-economic benefits of conventional and state-of-the-art UF membranes under live tertiary water filtration conditions to determine what material properties most impact sustainability.

2. Materials and methods

2.1. Field conditions and test location

Field tests were conducted using “live” effluent from a post-activated sludge process (ASP) secondary clarifier. The study was conducted at the Michelson Water Recycling Plant operated by Irvine Ranch Water District (IRWD) in Orange County, California. IRWD’s jurisdiction spans the city of Irvine, parts of Newport Beach, Costa Mesa, and a few neighboring towns, serving a community of about 400,000 residential customers and a daytime population of about 0.5 million. IRWD has four key water infrastructure-related functions; namely, providing drinking water, sewage collection, recycled water production, and urban runoff treatment. It has 5 drinking water treatment plants, 2 recycled water plants, 27 wells, 36 reservoirs, 1760 miles of drinking water pipeline, 1070 miles of sewage collection pipeline, 27 wetland treatment sites, and 525 miles of recycled water pipeline (referred to as “purple pipe”). Irvine was the first community in the US to adopt reuse of treated sewage, and is a pioneer of the purple pipe concept in urban planning [18].

The Michelson Water Recycling Plant has a daily processing capacity of 20 MGD of municipal sewage, and features two side-by-side 10 MGD trains, one based on a conventional ASP and the second based on an aerobic submerged HF membrane bioreactor. The plant treats the sewage and transports it through a pipeline to a reservoir for storage, and then distributes the water for reuse applications, such as landscape irrigation, office buildings, golf course irrigation, street cleaning, etc. The coexistence of these two process trains provides a unique opportunity for testing various sewage treatment applications at this plant. The Michelson plant was designed to accommodate such pilots from technology vendors and research organizations.

For this project, a test site was constructed on a dirt pad on the eastern side of the secondary clarifier. The site was selected for its proximity to the outfall of the secondary clarifier as well as an accessible tie-in point for power and softened water. The site was prepared in October 2016 to receive the pilot trailer and the pilot time line consisted of two distinct phases: Phase 1 was a short-duration comparative analysis of all three membranes and Phase 2 was a long-term optimization study of the most promising membrane from Phase 1.

2.2. Description of the pilot system

The test equipment consisted of a trailer-mounted filtration system composed of a single UF module tester as well

Table 1
Review of tertiary UF membrane operation

Source water*	UF membrane	Capacity (MLD)	UF flux (LMH)
Secondary Effluent (OCSD, California)	Siemens/Memcor PP-HF	265	34
Secondary effluent (Hyperion, California)	Siemens/Memcor PP-HF	18	31
Secondary effluent (UK)	Asahi Kasei/Pall PVDF-HF	1.6	35
Secondary effluent (Singapore)	Asahi Kasei/Pall PVDF-HF	191	44
Secondary effluent (Spain)	GE/Zenon PVDF-HF	15	28
Secondary effluent (Belgium)	GE/Zenon PVDF-HF	6.9	40
Secondary effluent (USA)	Siemens/Memcor PVDF-HF	265	33

*OCSD = Orange County Sanitation District
MLD = million L/d
LMH = L/m^2/h

as ancillary equipment needed for filtrate backwashing and membrane cleaning (schematic shown in Fig. 1). The introduction of chemicals (i.e., chlorine, acid, and caustic) was done manually. Secondary effluent was externally pumped through a 20-mesh (841 micron) pre-screen filter before entering the system trailer. Concentrate and filtrate effluent were pumped out of the trailer and returned to the secondary clarifier through the recycled activated sludge line.

For testing, the membranes were packaged into 4040 spiral-wound modules (4″ diameter × 40″ length with male filtrate port fittings). Each module was equipped with advanced high channel feed spacers designed for high solids applications (Spiral Monolith™; Water Planet, Inc.; USA). PolyCera (Water Planet, Inc.; USA), PVDF (Synder Filtration, USA), and PES (Synder Filtration, USA) flat sheet membranes were integrated into Water Planet's proprietary Spiral Monolith module design. All membranes had the same 100 kDa nominal molecular weight cutoff and were all packed into identical Spiral Monolith modules with an effective membrane area of 2.5–3.0 m^2. Table 2 depicts the different types of membranes used in the two phases of the study and their characteristics. The system was equipped with digital flow meters, pressure gauges, and an in-line filtrate turbidity meter for remote monitoring via a designated laptop terminal. A mobile Wi-Fi hot spot was used to provide internet access for remote connectivity and system monitoring during Phase 2. The system was equipped with automatic flux maintenance controls, such as filtrate relaxation and backwashing.

2.3. Water quality sampling program and targets

Throughout testing, feed and filtrate water samples were collected and analyzed. Feed samples were collected during operation from a ¼″ sample port just downstream of the UF feed pump. Filtrate samples were collected immediately before entering the on-board backwash tank. All samples were collected following the required protocol of the specific analytical standard method. On-board instrumentation was used to measure pH and conductivity from

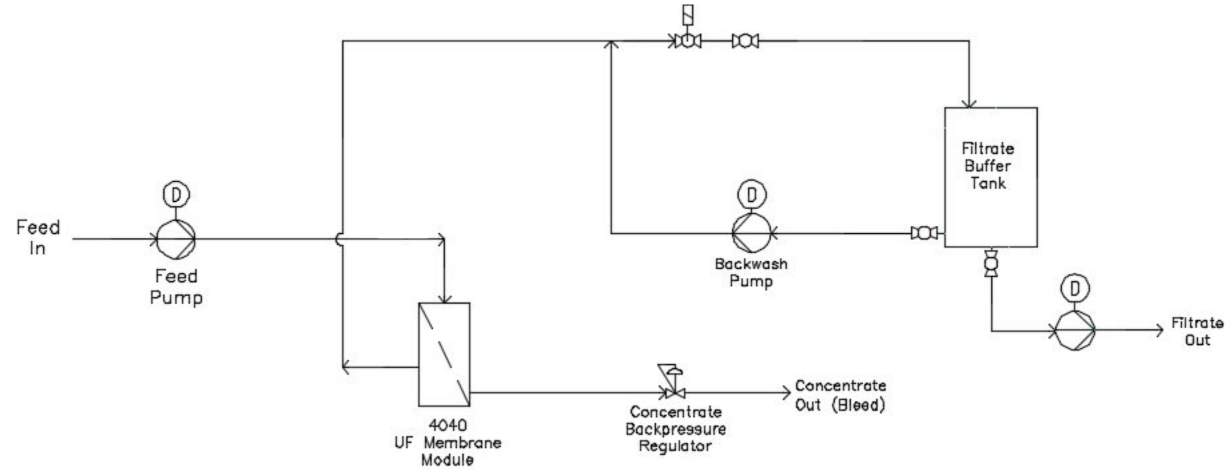

Fig. 1. Diagram of the trailer-mounted ultra filtration system.

Table 2
Membrane properties during both phases of testing

Parameter	Phase 1			Phase 2
	Membrane 1	Membrane 2	Membrane 3	
Membrane material	PolyCera	PVDF	PES	PolyCera
Module type	Spiral monolith	Spiral monolith	Spiral monolith	Spiral monolith
Nominal pore diameter (nm)	20	20	20	20
Membrane pure water permeability (LMH/bar)	232	173	223	253
Operating temperature range (°C)	5–50	5–55	5–55	5–50
Maximum temperature (°C)	85	55	55	85
Operating pH range	1–13	2–10	2–10	1–13
Maximum operating pressure (bar)	6.9	8.3	8.3	6.9
Maximum exposure to chlorine (ppm)	100	180	180	100
Cleaning options	Backwash, chemically-enhanced backwash, clean-in-place	Not backwashable; clean-in-place only	Not backwashable; clean-in-place only	Backwash, chemically-enhanced backwash, clean-in-place

30 mL grab samples (HQ40D; Hach Company, USA). The feed and filtrate turbidity was measured using a GF Signet 3-4150 turbidimeter (Georg Fischer Signet LLC; USA). All remaining analyses were collected on-site and taken to a local laboratory for testing (Test America Irvine; Irvine, CA). VOCs were analyzed following Standard Method 624, which looks for the presence of a select collection of purge able organic molecules ranging from benzene to vinyl chloride. Table 3 summarizes all water quality analyses performed, location of testing, and standard methods followed:

2.4. System operation and membrane cleaning

In Phase 1, experiments were conducted to study the inherent interaction between different membrane polymer chemistries (i.e., PVDF, PES, and PolyCera) with the foulants present in the secondary effluent water. Each membrane was operated over 2–4 consecutive filtration runs, each run spanning approximately six hours of filtration under a constant applied trans-membrane pressure (TMP). After each daily operation, the membrane was cleaned with a 10-min recovery clean consisting of flushing the feed side of the membrane with softened water at 50°C. This feed-side flushing technique targeted the removal of deposited foulants via physical forces, such as temperature-based cake dissolution and convective shear degradation, and will henceforth be referred to as a “physical maintenance clean” or PMC. This cleaning method was chosen for the Phase 1 tests to study the intrinsic interactions between the polymeric surface chemistry and the foulant. Therefore, whatever irreversible fouling was observed could be primarily attributed to the strength of the adhesive interaction between the foulant and the membrane material. No backwashing was applied to any of the membranes during these tests. The Phase 1 study for PolyCera and PVDF membranes lasted 4 consecutive operating cycles (spanning five days) and only 2 consecutive cycles (spanning 3 d) for PES due to logistical constraints. Each membrane was then cleaned following a standard CIP protocol before the membranes were removed and stored in the refrigerator for autopsy. The CIP process followed a standard recipe with the use of softened water heated to 50ºC: 1) feed-side flush with a filtrate flux of 40 LMH, 2) 30-min recirculation with caustic wash at pH 11 with no filtration, 3) feed-side flush with a filtrate flux of 40 LMH, 4) 30-min recirculation with citric acid wash at pH 2.5 and a filtrate flux of 40 LMH, 5) feed-side flush with a filtrate flux of 40 LMH, and 6) 30-min recirculation with caustic bleach wash at pH 11 and 100 ppm free chlorine at a low flux of 10 LMH.

Phase 2 was a more conventional 24/7 operation that incorporated standard cleaning methods, such as: (a)*in-situ*, automated filtrate backwashing, (b) intermittent chemical maintenance cleans (CMC), and (c) comprehensive CIPs. The rate of permeability decline and post-clean recovery was used as the primary metrics to determine the optimum execution protocols for all types of cleaning methods. Phase 2 only studied PolyCera membranes; hence, cleaning protocols appropriate for PolyCera membranes, and optimized during Phases 0 and 1, were employed. The CIP process followed the same conventional recipe used in Phase 1. At the conclusion of the study, the PolyCera membrane was cleaned and stored in the refrigerator for autopsy. All membrane autopsies involved an initial visual inspection of each leaf followed by surface fouling analysis using scanning electron microscopy (SEM; Hitachi TM 3030, Hitachi Ltd, Japan) equipped with energy dispersive X-ray spectrometry (EDX; SwiftED 3000, Oxford Instruments, United Kingdom) as well as Fourier-transform infrared spectroscopy (FTIR; Nicolet iS10, Thermo Scientific, USA). Elemental analysis by EDX was used to quantify the relative mass of foulant on each membrane surface after accounting for the elemental contribution of each polymer.

Table 3
Summary of water quality sampling and analytical protocols

Analyte	Sample location	Analysis location	Method	Minimum detection limit
pH	Membrane feed, membrane filtrate	On-site, grab	Electrochemical (SM 8156)	0
Conductivity	Membrane feed, membrane filtrate	On-site, grab	Electrochemical (SM 8160)	0.01 µS/cm
Turbidity	Membrane feed, membrane filtrate	Feed: on-site, grab Filtrate: in-line	Nephelometry (SM 2130B)	0.01 NTU
TSS	Membrane feed, membrane filtrate	Off-site lab	Gravimetric (SM 2540D)	1.0 mg/L
BOD	Membrane feed, membrane filtrate	Off-site lab	Biological (SM 5210B)	2.0 mg/L
TOC	Membrane feed, membrane filtrate	Off-site lab	Combustion (SM 5310B)	1.0 mg/L
Total coliform	Membrane feed, membrane filtrate	Off-site lab	Fermentation (SM 9221B)	1.8 MPN*/100 mL
VOC	Membrane feed, membrane filtrate	Off-site lab	GC/MS (SM 624)	0.5–2.0 µg/L

* MPN = Most probable number.

3. Results

3.1. Water quality and membrane rejection

Table 4 shows that all three polymeric membranes (PolyCera, PVDF, and PES) produced high quality filtrate with respect to the removal of solids and bacteria. The composition of the secondary effluent was reasonably consistent during the 5-month span of the demonstration. The majority of organic carbon present in the water was dissolved and, therefore, not effectively removed by the UF membranes; however, more than 50% of the BOD present was particulate and reduced to levels near or below the detection limit (2.0 mg/L) by all three membranes. All three membranes showed significant and acceptable pathogen removal to meet Title 22 specifications of the California Code of Regulations for industrial and irrigation reuse. Specifically, the primary metric for water quality defined by the Code of Regulations is that filtrate turbidity did not exceed: 1) 0.2 NTU more than 5 percent of the time within a 24-h period and 2) 0.5 NTU at any time [13]. VOC measurement included the collection of, at minimum, three consecutive days of operation and of the 38 VOCs measured, only six were detected above their detection limits in either the secondary effluent or the membrane filtrate: acetone, bromodichloromethane, chloroform, dibromochloromethane, methylene chloride, and toluene. All three membranes produced an increase in several VOCs compared to the influent, which is probably due to the washing out of residual solvents remaining within the membrane sheet from the formulation, post-treatment, and preservation processes, or residual microbial activities. However, the VOC residual within each membrane was easily washed out and should become non-detectable after only a few days of operation.

3.2. Phase 1: Effect of membrane chemistry on irreversible fouling

All three membranes had similar rates of fouling during the first six hours of each filtration run (Fig. 2). This behavior is typically observed with fresh membranes, and can be attributed to the way membrane modules are preserved and how the modules acclimate to a given type of influent water. The first PMC yielded different degrees of flux recovery in the three membranes with the PolyCera membrane recovering the highest percentage of its initial permeability. In addition, the cumulative permeability loss of the PolyCera membrane was much more gradual compared to PVDF: PVDF permeability was reduced to about 25% of its initial permeability after four days of operation and,in contrast, the PolyCera membrane permeability was about 50% of its initial value after four days. PMCs recovered a large fraction of the dynamic fouling layer for the PolyCera membrane as opposed to the PVDF membrane, and similarly the PES membrane. For PolyCera, about 70% of the initial membrane permeability was retained after the four days of operation (with three PMCs). In contrast, with the same type of cleaning regimen, the PVDF membrane only retained about 38% of its initial permeability.

Fouling was predominantly caused by the deposition of particulate and soluble organic matter on the membrane surface and within the pores; thus, “gel-like” fouling as

Table 4
Feed and filtrate water quality throughout full demonstration test

Parameter*	Secondary effluent			PolyCera® filtrate			PVDF filtrate			PES filtrate		
	Min.	Med.	Max.	Min.	Med.	Max.	Min.	Med.	Max.	Min.	Med.	Max.
pH	6.5	6.9	8.9	–	–	–	–	–	–	–	–	–
Temperature, °C	17	24	34	–	–	–	–	–	–	–	–	–
Biochemical oxygen demand, mg/L	2	4.0	6.5	<2.0	<2.0	2.1	<2.0	<2.0	2.0	<2.0	2.1	2.1
Total coliforms, MPN/100 mL	4,500	33,000	540,000	<1.8	4.5	23	<1.8	2.0	4.5	<1.8	<1.8	<1.8
Total organic carbon, mg/L C	5.1	5.6	7.2	5.3	6.2	6.2	4.8	5.7	6.2	5.0	6.2	7.4
Total suspended solids, mg/L	1.0	1.5	4.0	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Turbidity, NTU	0.86	2.0	18	0.01	0.03	0.10	0.01	0.03	0.04	0.01	0.03	0.04
Acetone, µg/L	<4.5	<4.5	12	<4.5	5	10	4.6	11	38	9	10	220
Bromodichloromethane, µg/L	<0.25	<0.25	0.47	1.3	1.75	2.2	0.26	0.47	0.55	1.1	1.1	8.9
Chloroform, µg/L	1.1	1.5	7.2	4.7	7.35	10	1.9	2.2	4.4	3	3	31
Conductivity,mS/cm	0.75	0.85	2.2	–	–	–	–	–	–	–	–	–
Dibromochloromethane, µg/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	0.31	0.34	1.7
Methylene chloride, µg/L	<1.1	<1.1	1.5	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	1.3
Toluene, µg/L	<0.25	<0.25	<0.25	0.44	0.47	0.50	0.65	1.5	3.4	1.9	2.6	4.3

*Data shown for tests during both Phases. Note: Only reporting volatile organic compounds that were measured above the detection limit; the following VOCs were measured below their detection limits in all collected samples: 1,1,1-Trichloroethane, 1,1,2,2-Tetrachloroethane, 1,1,2-Trichloroethane, 1,1-Dichloroethane, 1,1-Dichloroethene, 1,2-Dichlorobenzene, 1,2-Dichloroethane, 1,2-Dichloropropane, 1,3-Dichlorobenzene, 1,4-Dichlorobenzene, 2-Butanone (MEK), 2-Hexanone, 4-Methyl-2-pentanone (MIBK), Benzene, Bromoform, Bromomethane, Carbon disulfide, Carbon tetrachloride, Chlorobenzene, Chloroethane, Chloromethane, cis-1,3-Dichloropropene, Ethylbenzene, Styrene, Tetrachloroethene, trans-1,2-Dichloroethene, trans-1,3-Dichloropropene, Trichloroethene, Trichlorofluoromethane, Vinyl acetate, Vinyl chloride, and Total Xylenes.

well as partial pore blocking mechanisms dominated. This process was largely governed by convective forces (referred to as permeation drag) physically accumulating the foulants onto the membrane surface. As these UF membranes were highly permeable, the convective forces were overwhelmingly large compared to any repulsive intermolecular interactions between the foulants and the membrane material, resulting in convective compression of the organic matter against the membrane. Any inter facial interactions were completely overwhelmed during forward filtration. However, molecular forces played a greater role during membrane cleaning; specifically, the PolyCera membrane showed the greatest recovery and the lowest rate of permeability loss. This suggests that the PolyCera membrane had the weakest adhesive interaction between the membrane surface and the foulant and, thus, was *intrinsically* more cleanable than either PVDF or PES. These results were corroborated by membrane autopsies conducted on the fouled membranes after *in situ* CIP cleaning.

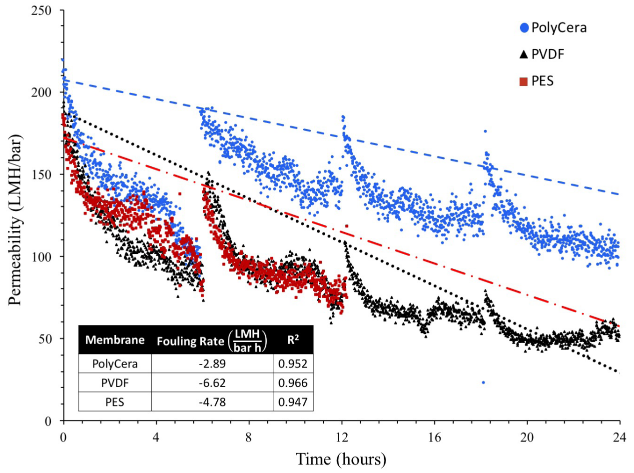

Fig. 2. Permeability decline and irreversible fouling during the filtration of secondary effluent with PolyCera®, polyvinylidene fluoride (PVDF), and polyether sulfone (PES) membranes. Softened water heated to 50°C was used for intermittent physical maintenance cleans.

Surface characterization of irreversible membrane fouling suggest that the PolyCera membrane was less fouled and more easily cleaned than its PVDF and PES counterparts. Significantly more foulant material was visually observed on the post-cleaned PES and PVDF membranes than PolyCera (Fig. 3) and with an associated sliminess to the touch. The PolyCera membrane had much less foulant on its surface and was not characterized by the same slimy feel. However, due to the strong color of the PolyCera polymer, it may have simply been more difficult to visually detect surface deposition, which is why higher resolution SEM images were also taken. SEM images confirm that both PVDF and PES surfaces had much more foulant deposition. A uniform blanket of foulant was observed for both membranes without any of the virgin membrane exposed. On the other hand, the

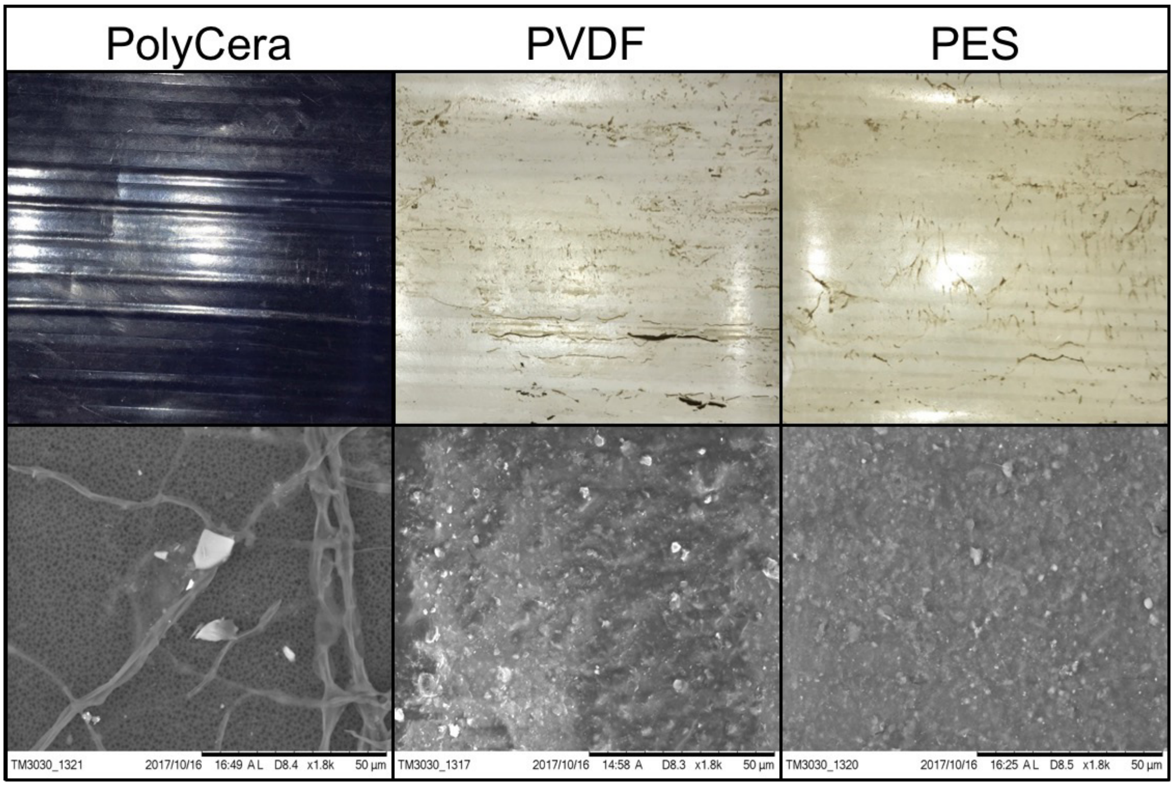

Fig. 3. Surface photographs (top row) and scanning electron microscope images (bottom row) for all three membranes after Phase 1 filtration and membrane cleaning.

clean PolyCera membrane and its exposed pore structure could still be seen with the occasional strand of a gelatinous foulant strewn across.

In addition to surface imaging, EDX was performed to analyze the relative degree and type of membrane fouling. EDX analysis quantified the elemental composition of each membrane surface down to a thickness of approximately 1 μm. After stoichiometrically factoring out the membrane polymer, the elemental composition and concentration of the surface foulant was calculated and presented in Table 5 as weight of foulant per weight of membrane. Irreversible membrane fouling was an order of magnitude smaller for the PolyCera membrane than either the PVDF or PES membranes. This result can be seen relatively uniformly for both carbon-based and inorganic foulant material. In general, the degree of irreversible fouling followed the hydrophobicity of the membrane polymers with PVDF being the most fouled and PolyCera being the least for all observed foulants. FTIR analysis of the foulant material showed strong peaks at 1636 and 1540 cm^{-1}, which is indicative of the C=O (Amide I) and N-H (Amide II) protein and polysaccharide functional groups typically present in biologically-active waters, such as soluble microbial products and extracellular polymeric substances [19,20].

If extrapolated out, these results suggest that under a given set of conventional cleanings, the PolyCera membrane should have a lifetime twice that of PVDF and PES or require a cheaper cleaning protocol to achieve the same performance. As a result of this fouling behavior, the PolyCera, PVDF, and PES membranes had measured specific energy consumptions of 0.017 kWh/m^3, 0.023 kWh/m^3, and 0.028 kWh/m^3, respectively. Therefore, the observed improvement in fouling resistance and net savings in energy have rendered the PolyCera membrane to be the ideal candidate for Phase 2 optimization studies.

Table 5
Post-cleaned foulant deposition after Phase 1 secondary effluent filtration by PolyCera, PVDF, and PES using quantitative energy dispersive X-ray elemental analysis

	Foulant deposition (mg foulant/g membrane)		
Foulant elemental composition	PolyCera	PVDF	PES
C	119	6894	1210
O	40	2787	401
Si	5.7	412	40
Ca	6.9	230	55
Fe	0.0	170	26
N	0	158	43
S	11	121	29
P	1.1	121	35
Al	2.3	121	17
Cl	9.2	85	23
Mg	1.1	61	9
K	2.3	36	6
Na	2.3	24	14

3.3. Phase 2: Long-term membrane performance testing and optimization

After observing the intrinsic benefits of the PolyCera material chemistry over conventional polymers in Phase 1, system performance was analyzed and optimized under continuous operation. Operating flux and cleaning frequency were the primary variables used for system tuning while permeability loss, energy efficiency, and operating costs were the calculated metrics used to analyze performance. Intermittent CMCs were utilized throughout to recover membrane permeability and minimize flux loss due to fouling. This mode of cleaning was performed by manual feed-side recirculation of an 8-gallon batch of sodium hypochlorite solution for 1 h at ambient temperature and unadjusted pH. The solution was prepared by adding bleach to softened tap water to attain a final free chlorine concentration of approximately 88 ppm, which resulted in a solution pH of approximately 9. Overall, the UF system followed the parameters summarized in Table 6, which was either within range or better than those typically found in the field [8,11]. Most conventional membrane filtration systems operate with a dynamic TMP to maintain constant filtrate production or flux. In "constant flux" mode, the driving force, or TMP, is gradually increased over time as greater pressure is required to counter the enhanced resistance to permeate flow due to membrane fouling. This mode of operation typically results in exacerbated fouling caused by compaction of the foulants on the membrane surface and enhanced adsorption of foulants within the membrane pores. This study focused on a "constant pressure" mode of operation,

Table 6
Comparison of operating conditions between the optimized demonstration system and conventional operation

Parameter	Conventional membrane operation	Optimized PolyCera® operation
Flux, LMH	20–40 (constant)	72 (initial) 33 (average)
Recovery, %	85–93	93
Backwash		
Frequency, min	10–38	25
Flux, LMH	90–120	85
Duration, s	20–45	30
Maintenance cleans		
Frequency, d	1–20	6
Temperature, °C	Ambient	Ambient
Cl_2 concentration, mg/L	500–1000	88
Soak duration, min	15–30	60
Recovery cleans-in-place		
Frequency, d	14–36	38
Temperature, °C	Ambient-50	50
Acid wash pH	1.5–2.5	2.5
Caustic wash pH	11–12.5	11
Cl_2 concentration, mg/L	500–1000	100
Duration, h	6	4

where the TMP is held constant at the value observed to produce a target initial filtrate flux. Constant pressure operation does not convolute the mechanisms of membrane fouling due to variations in the TMP, and generally lowers overall energy consumption while increasing membrane sustainable performance and life [21–23].

During the continuous 24/7 mode of operation, initial filtrate fluxes of 33 and 72 LMH were studied to determine the sustainable system flux at which throughput is maximized while minimizing irreversible membrane fouling. Fig. 4 shows that although the rate of fouling was more dramatic when operating at 72 LMH initial flux, begun on day 21, there was no significant impact on the efficacy of maintenance cleans. Therefore, a higher net production of water could be achieved without sacrificing membrane lifetime or energy efficiency.

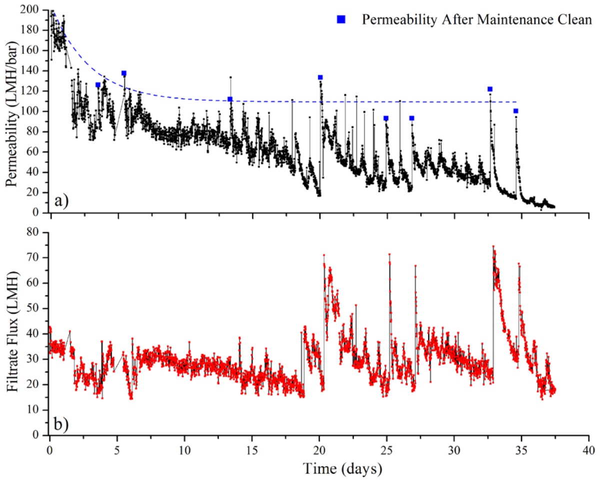

Fig. 4. Membrane permeability (a) and operating flux (b) during constant pressure operation of PolyCera® ultra filtration membranes to treat secondary effluent. Blue dots indicate the initial permeability after bleach maintenance cleans.

Cleaning frequency was studied by varying the time between CMCs from every 2 d to every week. Although there was variability in the amount of permeability recovered per CMC, Fig. 4 shows that, on average, irreversible fouling stabilized after an initial conditioning phase within the first week of operation. Specifically, all CMCs recovered membrane permeability to approximately 115 LMH/bar or 60% of the initial clean membrane permeability. Phase 2 concluded after 900 h, or 5.5 weeks of operation, after which the membrane lost approximately 96% of its permeability down to 7 LMH/bar. A chemical CIP was then performed which recovered membrane permeability back to 136 LMH/bar or 72% of the original clean membrane value. For this reason, it was determined that sustainable operation could be achieved when operating the membrane in constant pressure mode with an initial filtrate flux of 72 LMH and a cleaning schedule of every 6 d for maintenance and every 38 d for full CIPs. These operational settings allowed for sustainable maintenance of filtrate production and irreversible fouling that was highly competitive with respect to energy consumption and operating costs as compared to conventional tertiary filtration systems (Table 7). The PolyCera system achieved the same high quality filtrate, but at lower operating costs due to the improved clean ability of the PolyCera polymer. A less aggressive cleaning schedule utilizing a lower concentration of free chlorine and a modest cleaning frequency resulted in a significant reduction in the use and cost of cleaning chemicals.

Table 7
Comparison of membrane cleanability, energy efficiency, and operating costs between different membrane tests for the filtration of secondary effluent

Reference	Membrane	Source water	CIP Recovery (% of clean membrane permeability recovered after CIP)	SEC (kWh/m^3)	Operating costs* (\$/m^3)
This study (2–5 m^3/d)	PolyCera® – SM (water planet)	Secondary effluent	68% (Only 1 CIP studied)	0.035	0.016
LACSD/MWDSC (2012) – field testing (218–270 m^3/d) [11]	PVDF-HF (Siemens/Memcor)	Secondary effluent	61% (First CIP) 38% ± 10% (Average over 16 consecutive CIP's)	N/A	N/A
J. Qin et al. (2004) – field testing (150 m^3/d) [24]	PES-HF (Pentair/Norit)	Secondary effluent	N/A	0.100	0.020
M. Raffin et al. (2012) – survey of existing reuse plants (1.6–375 MLD) [8]	1) PVDF-HF (Asahi/Pall) 2) PVDF-HF (Asahi/Pall) 3) PVDF-HF (GE Zenon) 4) PES-CT (Pentair/Norit) 5) PVDF-HF (GE Zenon) 6) PVDF-HF (Siemens/Memcor)	Secondary effluent	N/A	1) 1.4 2) 0.4 3) 0.1 4) 1.1 5) 0.18 6) 0.26	N/A
K. Bourgeous et al. (2000) – field testing (112 m^3/d) [25]	PS-HF (Koch)	Secondary effluent	N/A	0.040	0.030

*Costs calculated from chemicals and energy consumption per net volume water produced. SEC = specific energy consumption, CIP = clean-in-place, PVDF = polyvinylidene fluoride, PES = polyether sulfone, PS = polysulfone, HF = hollow fiber, SM = spiral monolith, CT = capillary tube, and MLD = million L/d.

These savings compounded with the absence of air scouring, which is typically needed to mitigate fouling for hollow fiber membranes, resulted in significant savings in energy consumption and consumables.

Although significant information has been collected from the current work, a long-duration study is needed to determine the impact of membrane material on sustainable flux, CIP clean ability, and membrane lifetime. Phase 3 is currently being pursued in which the irreversible fouling and replacement frequency will be studied over multi-year operation.

4. Conclusions

- With secondary effluent as the source water, all three polymeric membranes, PolyCera, PVDF, and PES, produced a high quality recycled water that consistently met the criteria for reuse (conforming to California Title 22 specifications).
- The PolyCera polymer was intrinsically less fouling prone and more cleanable than conventional PVDF and PES polymers.
- Sustainable filtration of secondary effluent was maintained by the PolyCera membrane for over 5 weeks under the following conditions:
  - Sustainable flux of 33 LMH and
  - A modest cleaning schedule of 88 ppm chlorine maintenance clean every 6 d and a full clean-in-place every 38 d.
- Improved PolyCera clean ability allowed for operation with a modest cleaning schedule and without the need for energy-intensive air scouring, resulting in significant savings in operating cost up to 46% as compared to reported tertiary filtration systems using conventional UF membrane polymers.

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