Energy Research and Development Division

FINAL PROJECT REPORT

Improving Energy Efficiency and Increasing Water Yield During Membrane Treatment

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Improving Energy Efficiency and Increasing Water Yield during Membrane Treatment is the final report for the Novel Amphiphilic, Anti-adhesive Membrane to Improve Energy Efficiency and Increase Water Yield during Membrane Treatment project (Contract Number EPC-16-011) conducted by Kennedy Jenks Consultants. The information from this project contributes to Energy Research and Development Division's EPIC Program.

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ABSTRACT

Drinking water and wastewater reclamation treatment uses low-pressure membrane filtration, such as microfiltration and ultrafiltration, because it provides superior and consistent water quality compared with traditional filtration. However, membrane treatment processes are energy intensive. This intensity is largely because of the fouling of the membrane over time that impedes water flow, increases energy usage to pump water through the membrane, increases chemical costs to remove foulants, and reduces membrane life. The novel membrane evaluated in this pilot study incorporated amphiphilic, anti-adhesive polymers — which are composed of hydrophilic ("water-loving") and hydrophobic ("water-hating") parts — to slow deposits organic and mineral foulants. These materials theoretically allow for higher water flow through the membranes, increased water yield, and improved energy efficiency. The purpose of this study was to determine the technical and economic potential of the proposed technology and generate recommendations to address any identified issues.

The pilot demonstration performed at California Water Services Bakersfield Treatment Plant indicated that using the amphiphilic membrane could minimize membrane fouling and promote energy efficiency, but that differences in water source or quality affect the extent of performance improvements. The project demonstrated reductions in transmembrane pressures by up to 20 percent, cleaning frequencies by as much as 74 percent, and cleaning effectiveness by as much as 94 percent. The technology reduced overall energy use under all pilot testing conditions by around 6 percent, equivalent to a potential statewide energy reduction of 3.5 gigawatt-hours per year. Unfortunately, chemical degradation of the membrane surface that occurred during testing indicated that further manufacturer work is needed to evaluate special chemical resistance specifications and cleaning protocols that may differ from their other membrane offerings. Pilot testing results suggest that the ultrafiltration membrane module used in this project has potential benefit but is not yet market-ready.

Keywords: microfiltration, ultrafiltration, membrane fouling, amphiphilic, membrane surface modification, polyethersulfone, polysulfone, polysiloxane

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EXECUTIVE SUMMARY

Introduction

Surface water and wastewater reclamation are vital in California's water supply, which must be efficiently treated to save water and energy and improve California's drought resilience. Water filtration is a key treatment step in removing particulates. Low-pressure membrane filtration, such as microfiltration and ultrafiltration, is used for drinking water and wastewater reclamation treatment because it provides superior and consistent water quality compared with traditional media filtration, but membrane treatment processes are very energy intensive. The high-energy demand of low-pressure membranes is caused by deposits of foulant materials (such as particulates, organic and mineral chemicals, microbial materials) on the membrane surface and in membrane pores, which increases the transmembrane pressure over time. There has been much interest in the concept of minimizing membrane fouling to improve energy efficiency of membrane treatment among agencies treating water and wastewater as well as those involved with brackish and seawater desalination.

Currently, the approach used by industry for fouling reduction involves incorporating hydrophilic (water loving) functional groups on membrane surfaces to repel the organic constituents, while other types of foulants continue to deposit on the surface. Unlike strategies that only incorporate hydrophilic functional groups on membrane surfaces to repel hydrophobic (water hating) foulants, the surface modification evaluated in this study involved incorporation of amphiphilic functional groups that are a combination of hydrophilic and hydrophobic functional groups concentrated on the membrane surface to keep away organic and inorganic foulants. The proposed innovation incorporated anti-adhesive functional groups that slow the long-term deposit of foulant and improve cleaning efficiency. This theoretically increases water flow through the membranes, improves energy efficiency, and increases water yield.

Project Purpose

This project assessed the potential for an innovative amphiphilic, anti-adhesive membrane technology to improve the performance of membrane filtration systems used by drinking water and water reclamation agencies. The technology, developed by membrane manufacturer inge/BASF, is designed to minimize attachment of foulants onto membrane surfaces. The technology is past the proof-of-concept stage but required further evaluation under real world conditions before commercialization. The project team collected data to determine the technical and economic potential of the proposed technology and generate recommendations to address any issues that could prevent widespread adoption.

The specific goals of this project included:

- Demonstration that using the proposed membrane for water treatment could substantially reduce fouling and increase the flow of water through the membrane.
- Demonstration that treatment of various types of feed waters (for example, surface water, backwash water, organic spiked water) could successfully use the technology.
- Identification of the range of optimum operating conditions for membrane treatment using the proposed amphiphilic membrane.

- Evaluation of the impact of the proposed amphiphilic ultrafiltration membrane treatment on downstream reverse osmosis treatment often used during water reclamation.
- Collection of operating and maintenance data to develop a cost-benefit analysis of treatment using the proposed membrane for water treatment and water reclamation.

Project Process

The field demonstration pilot project occurred at the California Water Services (Cal Water), Bakersfield Treatment Plant in the Pacific Gas and Electric Company service area. The project evaluated the performance of the proposed amphiphilic membrane and collected data for treatment of surface water, backwash water, and synthetic reclaimed water (organic spiked surface water). The pilot unit consisted of two parallel trains (systems of more than one specific water treatment process or device), one fitted with a conventional hydrophilic membrane and the other with the proposed amphiphilic membrane. The two trains operated at the same flux rate (flow of water through the membrane) and the researchers used differences in the transmembrane pressure to determine fouling resistance and energy efficiency (energy use per unit volume of treated water produced).

The project team measured the volume of water used to backwash the two membranes during the field demonstration to determine water yield (backwash water generated per unit volume of treated water). The team also treated permeate from conventional and amphiphilic membrane through bench-scale reverse osmosis membrane units to evaluate the impact of proposed ultrafiltration treatment on downstream reverse osmosis performance. The researchers performed independent measurement and verification of the energy consuming components of the pilot system and used the collected data to evaluate the feasibility of commercializing the amphiphilic membrane used in the project.

Project Results

Overall results from the project pilot demonstration are summarized below.

- During initial settled water testing, the project membrane consistently outperformed the standard membrane, reducing the pressure required to pump water through the membrane by an average of 20 percent, resulting in electrical usage savings of 7.6 percent. Similarly, the project demonstrated increased water yield using the ultrafiltration membrane but was limited in part by the already-high baseline water recovery of the standard membrane treatment process with this source water.
- Near the end of settled water testing, the performance improvement of the project membrane disappeared. This may have been related to a chemical cleaning performed around this time. When both membrane modules were replaced the next year, the team could not replicate the previous performance of the project membrane when treating settled water. This lack of reproducibility may have been partially attributable to changes in water quality, particularly turbidity (a measure of dissolved and suspended solids in water).
- Testing with organic-spiked water did not demonstrate any membrane performance improvements for the project membrane, although the measured energy usage for feed and backwash pumping was reduced 3.5 percent. The team could not demonstrate any improvement in water yield; however, the effectiveness of the clean-in-place cleaning

process used was dramatically improved for the project membrane relative to the standard membrane.

- Performance of the project membrane when treating backwash water was intermediate to that observed for settled water and organic-spiked water. The pressures required to push water through the membrane were 7 to 21 percent lower with the project membrane than with the standard membrane, and energy use for feed and backwash pumping was reduced by 6.8 percent. As with previous settled water testing, this variability in performance may have been inversely related to changes in water quality, specifically turbidity. No improvement in water yield could be demonstrated; however, a 23 percent improvement in clean-in-place cleaning effectiveness was observed.
- Researchers did not observe any performance improvement from using the project membrane on downstream reverse osmosis. This finding was consistent with similar water qualities of the filtrate produced by both membranes.
- The project team collected fibers from the used modules and analyzed them for the presence of the surface-modifying copolymers polysulfone and polysiloxane. While the percentage of polysulfone present in the project membrane remained at levels identical with that in virgin project membrane fibers, no polysiloxane remained. This result suggested that the polysiloxane had been chemically transformed or degraded, most likely due to daily chemically enhanced backwashes or the less frequent, but harsher clean-in-place procedures. It was impossible to determine when or at what rate the loss of polysiloxane occurred, but it may have been linked to a clean-in-place performed near the end of settled water testing.
- Membrane characterization tests indicated both the project and standard ultrafiltration membrane fibers showed the same foulants, mostly aluminum and silica; however, there was also some evidence of carbon fouling that may have been due to organic matter deposition. The presence of aluminum was due to use of polyaluminum chloride coagulant upstream of the membrane pilot unit at the water treatment plant. The distribution of those foulants on the membrane surfaces was different. On the standard membrane, foulants were more evenly distributed across the membrane surface, while on the project membrane, fouling occurred in patches, with the rest of the membrane surface remaining clean of major fouling. These observations supported the initial project hypothesis that deposition of foulants on the membrane surfaces was affected by the amphiphilic surface modifying polymers in the project membrane.

The pilot demonstration at Cal Water indicated that use of the amphiphilic ultrafiltration membrane can minimize membrane fouling and promote energy efficiency. However, chemical degradation of the membrane surface observed during testing indicates that further work is required on the part of the manufacturer to evaluate special chemical resistance specifications and cleaning protocols that may differ from its other membrane offerings. The results of the pilot testing performed in this project suggest that the project ultrafiltration membrane module has significant potential benefit but is not yet market-ready.

Benefits to California

The researchers used a survey by the American Membrane Technologies Association of low-pressure membrane filtration plants in California to extrapolate benefits observed during pilot testing to statewide projects. The survey indicated that California has around 100 microfiltration/ultrafiltration treatment plants with a total design capacity of approximately 400 million gallons per day. Nearly half of these facilities treat drinking water and the remaining treat wastewater for recycling. Industrial membrane treatment facilities are not included in this list. Based on a survey performed by the California State Water Resources Control Board, an estimated 33 percent of the total recycled water producers are in the Pacific Gas and Electric Company service area, 53 percent in Southern California Edison service area, and 5 percent in San Diego Gas and Electric Company service area.

Estimated Reduction in Energy Consumption

Based on the study findings, a 6.1 percent improvement in ultrafiltration membrane energy from the proposed technology and a 50 percent market penetration would yield a potential energy reduction of 3.5 gigawatt-hours per year and greenhouse gas emission reductions of 1,200 metric tons per year. This estimate does not include energy conservation in industrial membrane processes or membrane bioreactors used in wastewater treatment.

Estimated Reduction in Use of Membrane Cleaning Chemicals

The proposed technology minimizes fouling, extending the time interval between membrane cleaning and, therefore, lowers the amount of chemicals needed for membrane cleaning. Typical chemical requirement estimates range from $0.15 to $0.25 per 1,000 gallons of water treated during microfiltration/ultrafiltration treatment. Results from this study indicated that clean-in-place cleaning frequency could be reduced by up to 74 percent depending on the water source. Based on these findings, and assuming a 5 percent reduction in overall process chemical use, the proposed technology could lower chemical cost by up to $940,000 per year for California rate-payers, assuming market penetration of 50 percent for the proposed technology.

Estimated Reduction in Membrane Replacement

During membrane treatment, membrane elements are periodically replaced because of loss of treatment capacity caused by irreversible fouling. Since the proposed technology lowers the potential for irreversible fouling, the frequency of membrane replacement will be reduced. Results from this study indicated that membrane replacement could be reduced by 39 percent, on average. In combination with the slightly higher price for the proposed module, this reduction could provide savings of around $739,000 each year assuming 50 percent market penetration.

Market Segment and Penetration

A key benefit of the proposed membrane is that incorporating the proposed membrane in an existing membrane treatment facility theoretically requires little or no capital investment; it simply involves replacing the conventional membrane with the proposed membrane unit during the next change-out cycle. Given the small capital investment and the potential project benefits, the return on investment for the proposed technology is less than one year for most membrane treatment facilities.

In no instance did the project ultrafiltration membrane underperform the standard ultrafiltration membrane. Therefore, the project ultrafiltration membrane is anticipated to provide similar or better operational costs, regardless of water quality. Given the performance and the projected cost savings, it is reasonable to assume a 50 percent market penetration for the proposed technology, once appropriate changes in the production process or recommended operating and cleaning procedures have been verified by additional field demonstrations.

Qualitative Benefits to Ratepayers

By supporting deployment and eventual adoption of the proposed technology through the California Electric Program Investment Chart, California investor-owned utility ratepayers will experience qualitative benefits including: 1) improved environmental sustainability of drinking water treatment and water reclamation through reduced energy demand and associated carbon footprint; and 2) greater availability of a locally available water resource through water recycling.

CHAPTER 1: Introduction

This chapter provides a brief overview of the project, project goals and objectives, and report organization.

1.1 Background

Surface waters and wastewater reclamation are vital parts of California's water supply portfolio. The California State Water Resources Control Board policy has set a goal to increase recycled water use from 714,000 acre-feet per year (AFY) in 2015 to 1.5 million and 2.5 million AFY, in 2020 and 2025, respectively. Filtration of water and wastewater is a key treatment step in removing particulates from these supplies. Low-pressure membrane filtration, such as microfiltration (MF) and ultrafiltration (UF), is used for drinking water and wastewater reclamation treatment because it provides superior and consistent water quality compared with traditional media filtration. The California Division of Drinking Water (DDW) has approved low pressure membrane systems as alternative filtration technologies to granular media filtration under its surface water treatment rule for drinking water due to its reliable removal of pathogens and turbidity and, for wastewater reclamation, has included MF/UF as part of the full advanced treatment train, the only treatment train currently accepted for groundwater recharge and surface water augmentation without the need for diluent water (California Code of Regulations, 2018). Low pressure membrane use is expected to increase in the future as water agencies work to meet reliable/consistent water quality and the state's recycled water goals.

Membrane treatment processes are highly effective, but energy intensive. The high energy demand of low-pressure membranes is caused by deposition of foulant materials on the membrane surface (cake formation) and in membrane pores, which increases the transmembrane pressure (TMP). Membrane fouling is a very complicated process that is impacted by hydrophilic (materials with an affinity for water)-hydrophobic (materials that naturally repel water) interactions of the foulants with the membrane surface, as well as other mechanisms such as electric charge interactions and polymer entanglement. Types of fouling materials in feed water include organics in many forms and sizes, as well as minerals, bacteria and their waste products, and algae. Currently, the approach used by industry for fouling reduction involves incorporation of hydrophilic functional groups on membrane surfaces to repel the organic constituents. By only creating a hydrophilic surface, the major organic components in the feed water can be initially repulsed from the membrane surface, but other types of foulants continue to deposit on the surface. These occupied sites then lead to an altered surface, allowing even organic materials to adhere to them over time. This phenomenon results in layered fouling on membrane surfaces that is very difficult to remove.

Unlike surface modifications that only incorporated hydrophilic functional groups on membrane surfaces to repel hydrophobic foulants, the surface modification evaluated in this study involved incorporation of "amphiphilic" functional groups that are a combination of hydrophilic and hydrophobic functional groups concentrated on the membrane surface to keep organic and inorganic foulants away from it. The proposed innovation included incorporation of anti-adhesive functional groups that retard long-term foulant deposition and improve cleaning efficiency. This theoretically allows for higher flow of water through the membranes (that is, higher flux rate), improved energy efficiency, and increased water yield.

1.2 Goals and Objectives

This project assessed the potential of an innovative amphiphilic, anti-adhesive membrane technology (developed by BASF) designed to minimize attachment of foulants onto the membrane surface to improve the performance of membrane filtration systems used by drinking water and water reclamation agencies. This membrane technology is beyond the proof of concept stage (laboratory bench scale/pilot studies), but required further evaluation under real world conditions before commercialization. The primary goal of this project was to pilot test the novel pre-commercial membrane technology that could minimize fouling of membrane surfaces and therefore increase water flow and improve energy efficiency.

The specific goals of this project included:

- Demonstration that membrane fouling could be substantially reduced and the flux rate increased using the proposed membrane for water treatment
- Demonstration that the technology could be successfully used for treatment of various types of feed waters (such as, surface water, backwash water, organic spiked water)
- Identification of the range of optimum operating conditions for membrane treatment using the proposed amphiphilic membrane
- Evaluation of the impact of the proposed amphiphilic UF membrane treatment on downstream reverse osmosis (RO) treatment that is often used during water reclamation
- Collection of operating and maintenance data to develop a cost-benefit analysis of treatment using the proposed membrane for water treatment and water reclamation

BASE Energy performed independent measurement and verification (M&V) of energy-consuming components using standard protocols. The project team used the resulting data to perform economic analyses and to demonstrate achievement of project goals.

1.4 Report Organization

This report is organized as follows:

- Chapter 1: Introduction – This chapter provides a brief overview of the project, its goals and objectives, and the report organization.
- Chapter 2: Technology Review – This chapter introduces the concepts of low-pressure membrane fouling and the impact of membrane surface properties on foulant attachment and removal, and identifies the specific membrane chemistry/surface properties that were evaluated during this project.
- Chapter 3: Methodology – This chapter describes the study approach, the test facilities, and the methods of sample collection and analyses.
- Chapter 4: Treatment of Settled Water – This chapter describes the results of pilot testing of settled surface water.

- Chapter 5: Treatment of Organic-Spiked Water – This chapter describes the results of pilot testing of settled surface water spiked with organic foulants.
- Chapter 6: Treatment of Backwash Water – This chapter describes the results of pilot testing of backwash water.
- Chapter 7: Membrane Characterization – This chapter describes the results of post-treatment membrane autopsies, including an evaluation of surface and foulant characterization and membrane chemistry.
- Chapter 8: Measurement and Verification – This chapter describes the independent verification of energy efficiency results for pilot testing performed in Chapters 4, 5 and 6.
- Chapter 9: Evaluation of Projected Benefits – This chapter describes the projected benefits resulting from statewide implementation of the proposed membrane technology. .
- Chapter 10: Technology Transfer Activities – This chapter provides a summary of the technology transfer activities performed for this project.
- Chapter 11: Product Readiness Plan – This chapter provides a summary of the product readiness plan for the proposed novel membrane technology.
- Chapter 12: Summary and Conclusions – This chapter provides a summary of the key findings and conclusions for this project.

CHAPTER 2: Technology Review

This chapter introduces the concepts of low-pressure membrane fouling and current understanding of the impact of membrane surface properties, such as hydrophilicity or amphiphilicity on fouling resistance.

2.1 Low-Pressure Membrane Fouling

Low-pressure membrane filtration (LPMF) refers to a class of membranes used in water and wastewater treatment to separate suspended and some colloidal contaminants from water. Low-pressure membranes are broadly characterized as either MF membranes, with a pore size between 100 nanometers (nm) and 10 micrometers (μm), or UF membranes, with a pore size between 10 nm and 100 nm. During filtration, water and contaminants are forced towards the membrane and particles larger than the membrane's pore size are retained on the membrane surface. Some material smaller than the membrane pores, such as colloidal particles and dissolved organic matter, may also be retained on and within the membrane pore structure due to electrostatic and hydrophobic interactions between the contaminant and membrane. Over time, suspended and dissolved material (foulants) accumulate on the membrane surface, forming a fouling layer that reduces membrane permeability and results in higher energy demand for operation.

The deposition of foulants and the development of the fouling layer on the membrane occurs in phases. In the first phase, membrane fouling is dominated by membrane-to-foulant interactions in which foulants adsorb onto and within the membrane matrices. These foulants adhere very strongly to the membrane and are often irreversibly attached or can be removed only through prolonged chemical cleaning (Shi, Tal, Hankins, & Gitis, 2014). Following the initial foulant deposition, foulant-foulant interactions dominate and a cake- or gel-like layer begins to form. This fouling layer can offer significant resistance to water permeation but can normally be removed through hydraulic backwashing and chemical clean in-place methods. Because the initial fouling layer is strongly adsorbed to the membrane surface and provides attachment sites for the secondary fouling layer, there has been much interest and research into the membrane surface properties most responsible for foulant attraction and attachment.

2.2 Impact of Membrane Surface Properties on Foulant Attachment

Polysulfone (PSU) and polyethersulfone (PES) are commonly used in the manufacturing of UF membranes due to the low cost, mechanical strength, and chemical stability of the materials (Nady et al., 2011; Zhao, Xue, Ran, & Sun, 2013). Although these membrane materials provide several benefits, they are susceptible to fouling by inorganic and organic contaminants due to the intrinsic hydrophobic and electrochemical characteristics of the polymers (Geise et al., 2010; Nady et al., 2011)). Researchers (Goosen et al., 2005; Howe & Clark, 2002; Shi et al., 2014; Zhao et al., 2013) have shown that hydrophobic interactions are the primary mechanism responsible for the adsorption of nonpolar solutes, hydrophobic particles, and bacteria to the membrane surface. Positively charged divalent cations (such as, magnesium and calcium) present in the filtered water are electrostatically attracted to the negatively charged surface of the PSU and PES membranes and provide bridging sites for negatively charged organic matter to attach to and foul the membrane (Sutzkover-Gutman, Hasson, & Semiat, 2010).

Natural organic matter (NOM) and humic substances found in almost all surface water and biologically treated wastewater are well-known membrane foulants. These organic contaminants are attracted and attach to the membrane because they contain hydrophobic functional groups that interact with the hydrophobic membrane surface (Shi et al., 2014). Jermann et al. (2007) systematically investigated the role of molecular interactions of two model foulants (humic acid and alginate) with a PES UF membrane and found humic acid adsorbed more strongly to the membrane compared with alginate due to attractive hydrophobic forces. In a similar study conducted with raw river water, Howe et al. (2002) demonstrated membrane fouling was dominated by small hydrophobic colloidal particles and the fouling was most severe for membranes with the strongest hydrophobic characteristics.

In addition to being hydrophobic, zeta potential measurements conducted on PSU and PES membranes have shown the membrane surface to be negatively charged (Cho, Amy, & Pellegrino, 2000). It may be expected that the negatively charged membrane would repel similarly negatively charged organic matter and reduce membrane fouling. However, the membrane charge becomes more neutral when treating waters lower in pH and higher in ionic strength, which reduces the electrostatic repulsion between the membrane and organic foulants (Sutzkover-Gutman et al., 2010). Studies investigating protein fouling have shown the most severe fouling appears at a pH around the isoelectric point of the molecules in solution and the membrane surface (Shi et al., 2014). Similarly, an increase in the solution ionic strength, particularly in cation concentration, can result in the membrane becoming less negative and increased fouling by organic matter (Jermann et al., 2007).

2.3 Membrane Modifications to Reduce Fouling

Most membrane polymers (such as PSU and PES) with stable backbones that exhibit excellent chlorine resistance are intrinsically hydrophobic. In water treatment, hydrophilic membranes show reduced fouling. If membrane surface is hydrophobic, water near the membrane can be displaced by foulants and hydrophobic interactions bind the foulant to the membrane surface. There has been a concerted effort to modify the surface chemistry of membranes to reduce the attraction and adsorption of foulants to the membrane surface. Negatively charged membrane surfaces may also reduce some forms of fouling by electrostatically repelling negatively charged foulants. However, negative membrane surface may attract positively charged foulants (Geise et al., 2010). Many previous efforts have also focused on modifying the membrane surface to be more hydrophilic in order to minimize membrane fouling due to hydrophobic interactions (Rana & Matsuura, 2010).

Generally, hydrophilic modifications to the membrane surface have been found to increase fouling resistance but may reduce membrane permeability depending on the chemical functionalities utilized. Hydrophilic surfaces are thought to attract a strongly bound layer of water molecules, which may buffer the adhesion of hydrophobic foulants; however, surface modifications may restrict the pore entrances resulting in both lower membrane permeability and water flux. Miller et al. (2014) found that polydopamine coatings increased fouling resistance, but reduced water flux and permeability. In contrast, Ding et al. (2016) observed that addition of cellulose nanofibrils increased flux and permeability and reduced fouling. PSU membranes coated with a methyl-based copolymer showed a much higher flux recovery after cleaning compared to unmodified PSU membranes. Nady et al (2011) attributed this result to increased membrane hydrophilicity.

There are several methods, including coating, blending, and chemical grafting, used to improve membrane hydrophilicity. Modifications can be made only to the membrane surface or to the bulk membrane material. Increasing the hydrophilicity of the bulk membrane may reduce mechanical strength (Zhao et al., 2013); however, surface modifications allow modification without affecting the bulk properties (such as tensile strength and chemical resistance). Surface coating techniques have been shown to have a higher fouling mitigation effect compared to techniques that entrap the modifying material with in the membrane matrix (Nady et al., 2011), but one drawback of surface modification by coating or grafting techniques is that membrane resistance to water flow may be increased (Geise et al., 2010).

Although these studies have demonstrated hydrophilic membrane characteristics are desirable, others have shown hydrophilicity may only be effective in deterring initial fouling. Wang et al. (2011) and Maximous et al. (2009) concluded that hydrophilicity limits initial fouling but long-term fouling is dominated by foulant-to-foulant interactions. These findings are not surprising considering the high convective forces pulling foulants towards the membrane surface during filtration and the strong hydrophobic attraction between organic foulants. Because of the inability of the hydrophilic membranes to repel inorganic foulants, and subsequent formation of layered organic and inorganic fouling, a membrane with improved anti-fouling properties and membrane cleaning characteristics would be desirable.

2.4 Amphiphilic, Anti-Adhesive Membrane Surface Properties

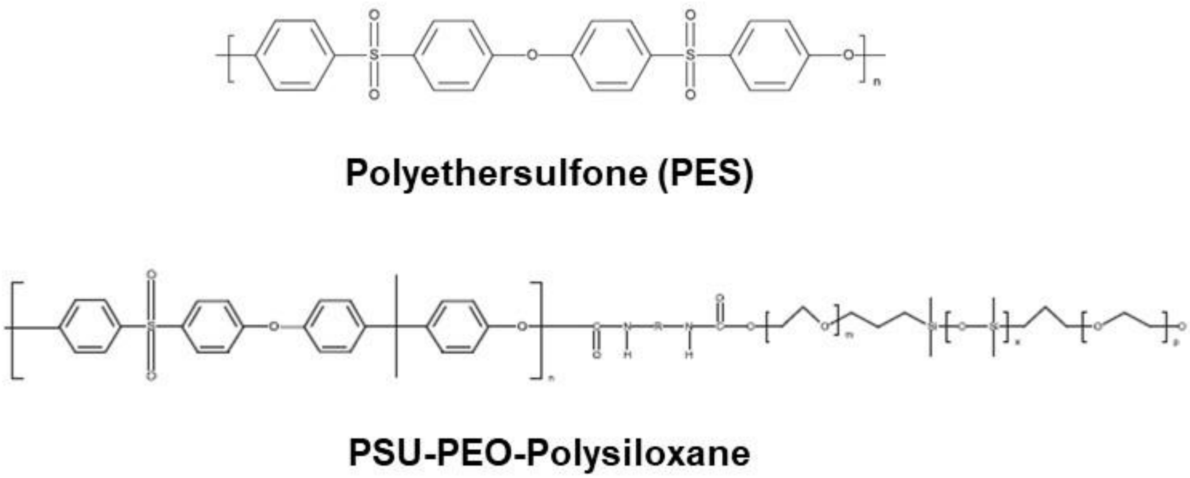
Recently, membranes have been modified with amphiphilic (both hydrophilic and hydrophobic) groups on the membrane surface with the intent of producing membranes with lower fouling propensity and better anti-adhesive properties (Nady et al., 2011). This membrane modification approach was taken by Chen et al. (2016) and Wang et al. (2006) in separate studies with both groups reporting similar improvements in PSU membrane performance. Chen et al. blended amphiphilic polyethylene glycol (PEG) copolymer with a PSU base polymer to produce an amphiphilic membrane with increased permeability, hydrophilicity, fouling resistance, and flux recovery. The permeability increased from approximately 50 liters per meter squared per hour (LMH)[1] for the unmodified membrane to 400 LMH for the membrane modified at the optimum blended ratio (40 percent). The flux recovery after being fouled with bovine serum increased from approximately 70 percent to 85 percent after the modification. Wang et al. modified a UF membrane with amphiphilic pluronic polymer groups using a polymer blending technique and showed that fouling resistance and flux recovery was improved by increasing the length of the amphiphilic chains.

[1] Conversion: 1 LMH is equivalent to 0.588 GFD (gallons/ft^2/day).

2.4.1 Amphiphilic PSU Membrane Using PEO-Polysiloxane

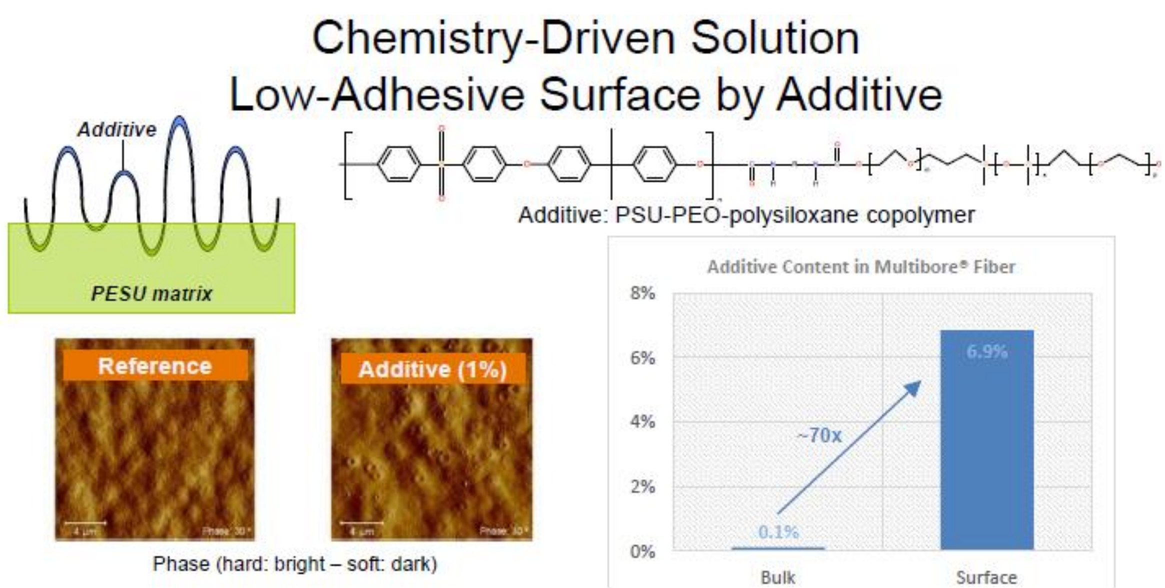
BASF (Greifenberg, Germany), adopting an approach like Wang et al. and Chen et al., has developed the amphiphilic PSU membrane used in this study. This amphiphilic membrane has a surface enriched with the low- or anti-adhesive polyethylene oxide (PEO)-polysiloxane functional groups in a majority hydrophilic PSU membrane matrix. The purpose of the PEO polysiloxane groups is to increase the fouling resistance and ease the cleaning of the PSU membrane. Figure 1 illustrates the chemical structures of these copolymers. Figure 2 provides an illustration and atomic force microscopy (AFM) image of the modified membrane.

Figure 1: Chemical Structure of Relevant Membrane Copolymers



Source: (Heijnen, Martin et al., 2015)

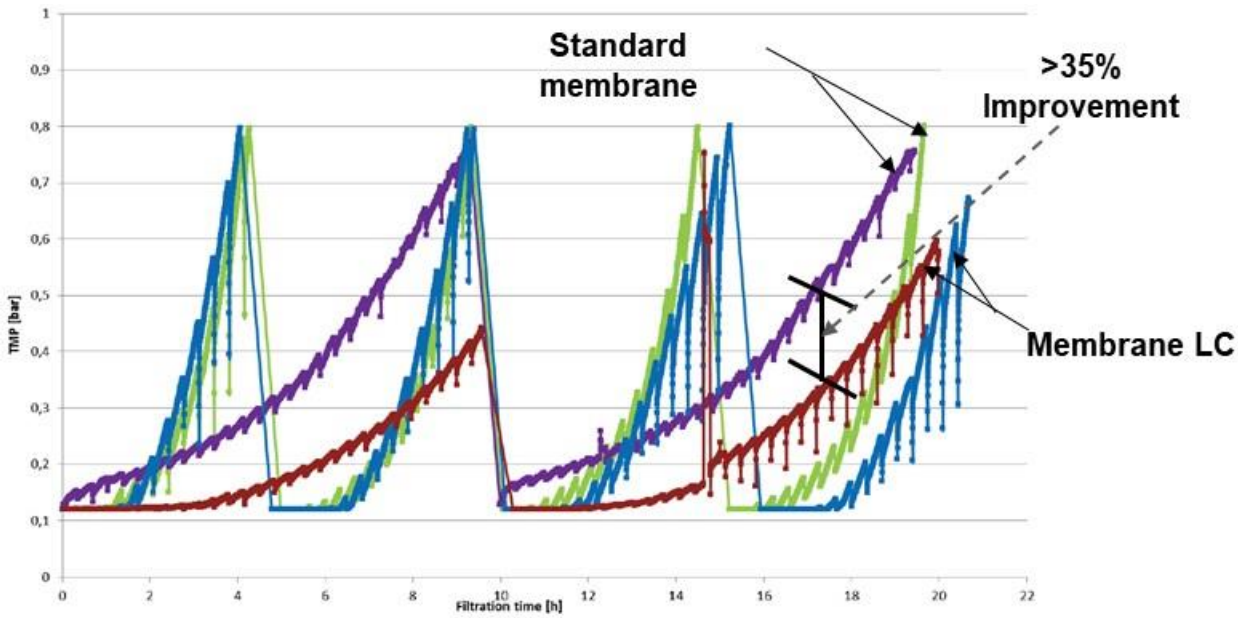
Figure 2: Schematic Drawing, Atomic Force Microscope Membrane Surface Image, and Chemical Composition of New Membrane with Anti-Adhesive Properties



Source: (Heijnen, Martin et al., 2015)

Heinen et al. (2015) reported on short-term tests with this new amphiphilic membrane (referred to as membrane LC) that used synthetic and real (Seine river water) feed solutions for 12 to 24 hours. Figure 3 presents the results from one of the synthetic fouling tests.

Figure 3: Bench-Scale Experiments Conducted with Synthetic Fouling Solution



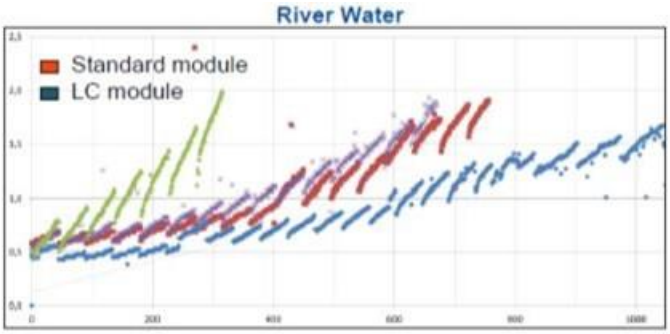
Tests were performed over a period of 20 hours, using standard PSU membrane chemistry at 75 L/m^2-hr (green line) and 150 L/m^2-hr (purple line) and Membrane LC (PSU-PEO-Polysiloxane) chemistry at 75 L/m^2-hr (blue line) and 150 L/m^2-hr (red line).

Source: (Heijnen, Martin et al., 2015)

At lower water fluxes (75 LMH, 44 GFD) the transmembrane pressures (TMP) for the standard membrane (green line) and the proposed membrane (Membrane LC; blue line) were not significantly different (Figure 3). However, as the water flux was increased to 150 LMH (88 GFD), the increase in TMP for the proposed membrane (red line) was much lower (~35 percent after 18 hours) compared with the standard membrane (purple line).

Subsequently, Heinen et al. (2015) performed additional 24-hour bench-scale tests with river water, wastewater, and seawater. Figure 4 shows the results from these 24-hour fouling tests.

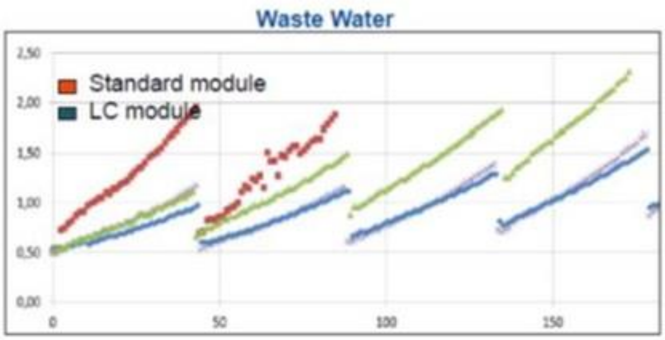
Figure 4: TMP (bar*) as Function of Filtration Volume for Experiments Conducted with (a) Seine River Water, (b) Wastewater, and (c) Seawater



(a)

a. River water: Turbidity 1 – 2 NTU, 50 percent humic substance of natural organic matter (NOM).

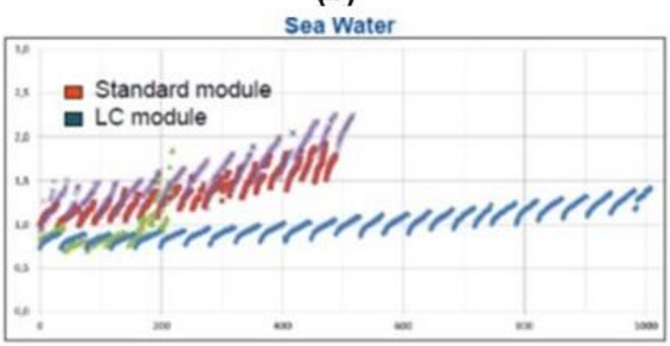
TMP of proposed membranes (blue line) were always lower than that of standard membranes (red line).



(b)

b. Wastewater: Turbidity 1 – 2 NTU, High TSS 88 ppm, 40 percent humic substance of NOM, 8 percent hydrophobic dissolved organic content, low ammonium.

TMP of proposed membranes (blue line) were always lower than that of standard membranes (red line).



(c)

c. Sea water: High mineralization, conductivity 53 µs/cm, Turbidity 25 NTU, 30% humic substance of NOM, 11% hydrophobic dissolved organic content.

TMP of proposed membranes (blue line) were always lower than that of standard membranes (red line).

***Conversion: 1 bar is equivalent to 14.50377 psi.**

Source: Heijnen et al., 2015

Membrane LC outperformed the existing reference membrane with all feed waters tested. For river water (Figure 4a), which has a turbidity of 1-2 nephelometric turbidity units (NTU) and NOM containing 50 percent humic acid, membrane LC showed a TMP of 1 bar (14.5 pounds per square inch [psi]) at 600-minute filtration interval compared with a TMP of 1.8 bar (26.1 psi) for the reference membrane. This represented approximately 40 percent reduction in energy demand.

For a wastewater feed (Figure 4b), with a high total suspended solids (TSS) concentration of 88 mg/L, 40 percent humic substances, and 8 percent hydrophobic dissolved organic carbon (DOC), the difference in fouling propensity between the standard and LC membrane was even more pronounced. During each filtration cycle, the TMP increase was double for the standard membrane compared with the reference membrane.

Finally, for a seawater feed (Figure 4c) with high salt concentration and turbidity around 25 NTU, membrane LC operated at much lower TMP. For example, at the 500-min filtration interval the average TMP of membrane LC was 1 bar compared with the average TMP of the reference membrane of 1.8 bar (26.1 psi), an estimated energy savings of approximately 45 percent.

Overall, the short-term fouling tests clearly demonstrated the energy efficiency of the new amphiphilic membrane LC. The pressure driving force for water production was reduced by as much as 50 percent.

4.2.1.1 Pilot Testing of PSU-PEO-Polysiloxane Membrane

Heinen et al. (2015) also performed long-term pilot tests over a 12-month period using surface water. The tests were designed to determine the efficiency of the amphiphilic membrane by operating it at high water flux (fewer number of modules) without increasing energy demand.

With a surface water containing high but variable TSS (from 3-30 milligrams per liter [mg/L]) and relatively low total organic carbon (2 mg/L TOC), these researchers operated the membrane LC at 105 LMH and half of the TMP compared with the reference membrane operating at 70 LMH (41.2 GFD). Operating at a higher water flux (approximately 50 percent), especially at lower TMP, has significant implications. Specifically, fewer membrane modules would be required resulting in substantially lower backwash volumes and higher water recoveries.

In summary, the results from bench- and pilot-scale testing were encouraging. The new amphiphilic PSU-PEO-Polysiloxane membrane exhibited higher water flux and lower or equivalent operating TMP under all test conditions; however, further evaluation of performance under real world conditions, including energy usage and treated water quality was needed to better assess the market readiness of this new membrane.

CHAPTER 3: Methodology

This chapter describes the study approach, test facilities, and methods of sample collection and analyses.

3.1 Study Approach

This project consisted of five major activities:

- Phase 1, Site Preparation: The California Water Services Company (Cal Water) Bakersfield's site was prepared for pilot testing. This included installation of the pilot unit, ancillary pumps, piping and tankage, as well as obtaining regulatory clearance of pilot waste disposal.
- Phase 2, Settled Surface Water Test: Pilot tests were performed using coagulated, settled surface water, which is the membrane feed water for the full-scale MF system at the demonstration site.
- Phase 3, Organic-Spiked Water Test: Pilot tests were performed using organic spiked surface water as a surrogate for recycled water to evaluate the amphiphilic project membrane market potential for water reclamation.
- Phase 4, Backwash Water Test: Pilot tests were performed using backwash water generated from the full-scale membrane process at the demonstration site. During this phase, the filtrate from the standard and project membrane was also treated by bench-scale RO membrane units to evaluate the impact of proposed UF treatment on downstream RO performance.
- Phase 5, Benefits Evaluation: The benefits evaluation consisted of M&V performed independently by BASE Energy of the energy consuming components of the pilot system as well as other operations and maintenance data collected. The collected data were used in evaluating the feasibility of commercializing the amphiphilic project membrane.

3.2 Test Facilities and Materials

This section describes the testing facilities: including demonstration site, water sources, pilot unit and membranes tested.

3.2.1 Demonstration Site

The pilot demonstration was performed at the Cal Water's Northeast Bakersfield Water Treatment Plant (WTP), which treats surface water from the Kern River (Figure 5). The plant's treatment process consists of pre-treatment with potassium permanganate, coagulation-flocculation (using polyaluminum chloride coagulant) and sedimentation followed by coarse (300-micron) straining, microfiltration, and chlorine disinfection. The treatment plant has a design capacity of 22 MGD. During the test period covered by this report, the plant flows typically were in the range of 8 to 9 MGD.

Figure 5: Aerial View of the Northeast Bakersfield Water Treatment Plant

Source: Google Earth, 2018)

3.2.2 Water Sources

Three water sources were tested during the pilot study.

3.2.2.1 Settled Water

Settled surface water was tested as representative of a typical low-pressure membrane feed water source. The pilot feed water was taken as a side stream of the settled water (downstream of the 300-micron strainer) in the full-scale treatment plant.

3.2.2.2 Organic-Spiked Settled Water

Settled water, spiked with organic material to increase the organic fouling potential as a surrogate for wastewater and other high-organic waters. The pilot feed water was taken as a side stream of the settled water described in Section 3.2.2.1.

A leonardite humic acid extracted from ancient peat deposits in soil was added to the settled water to increase its level of hydrophobic organic foulants. Europonic Fossil Fuel Liquid Humic Acid solution (containing approximately 18 g/L TOC) was fed into the pilot feed water upstream of the UF modules using the pilot plant's chemical dosing system as described in Section 3.2.3.

3.2.2.3 Backwash Water

Backwash water generated at the full-scale treatment plant's membrane filtration process was tested to evaluate performance with higher turbidity water that might be reclaimed from backwash operations. The backwash water consists primarily of wastewater generated during the cleaning of the microfilter membranes (Pall Corp., Washington, NY), which was collected in the plant's backwash equalization tank. In addition, some rinse water from daily flux maintenance cleaning of the membranes, which containing chlorine and caustic chemicals, also carried over to the backwash equalization tank.

The pilot feed water was taken from the outlet of the full-scale treatment plant's backwash equalization tank and was passed through a 300 micron prefilter prior to pilot treatment.

3.2.3 Pilot Membrane Unit

The demonstration was performed with a skid-mounted UF pilot unit manufactured by BASF installed inside a 20-foot International Organization for Standards (ISO) high cube container (21.5 ft L x 8 ft W x 9.5 ft H). The UF pilot plant consisted of the following major components:

- Two (2) parallel UF trains that were operated independently, each having a capacity of 15 to 70 gpm
- One (1) 132-gallon (500-liter) feed tank with overflow to drain
- One (1) 264-gallon (1000 liter) filtrate tank with overflow to drain
- Two (2) centrifugal feed pumps (one per UF train) with variable frequency drives
- One (1) centrifugal backwash pump (one for both membrane trains) with variable frequency drive
- One (1) 300-micron disc filter (AZUD helix)

The system was delivered complete with interconnecting process pipework, support frame, insulation, air conditioning system, lighting and ventilation. Figure 6 shows interior and exterior views of the pilot unit.

Figure 6: Exterior and interior view of the pilot system

Source: Kennedy/Jenks Consultants

The unit included instrumentation for magnetic flow transmitters, pH and temperature probes, turbidity and conductivity analyzers, and inlet and outlet pressure transmitters. WinCC (Siemens, Malvern, Pennsylvania) supervisory control and data acquisition (SCADA) software automatically logged data from the pilot unit. Operators could control the pilot unit remotely using the system's TeamViewer software.

The pilot unit included automatically controlled chemical dosing systems for pre-treatment (coagulation), pH adjustment, and CEB. The pre-treatment chemical dosing system consists of dosing pumps, injection point, and contact/mixing pipeline. Because no pre-treatment chemical was required, this system was used to add humic acid to the pilot feed water during testing of organic-spiked water. The pilot system operator pre-set the humic acid concentration set point to add the desired amount automatically to each module line feed water. The chemical dosing system for enhanced chemical backwashes (sulfuric acid, caustic soda, and sodium hypochlorite) consisted of dosing pumps, each connected to a chemical feed tank and associated piping. The pilot system operator pre-set the set point to add the desired amounts of cleaning chemicals automatically to the backwash water. All chemicals used in the pilot unit were National Sanitation Foundation (NSF) 60 certified water treatment chemicals, except the Liquid Humic Acid solution.

The pilot unit was connected to the water treatment plant water and waste lines by 2.5-inch diameter polyvinyl chloride (PVC) piping. A Grundfos CRE vertical multistage centrifugal booster pump equipped with a variable frequency drive (VFD) was installed in the pilot unit's feed pipeline to ensure sufficient feed flows to the unit at all times. All excess feed water and membrane filtrate (except when testing organic-spiked water) were returned to the full-scale water treatment process. Other waters generated during testing and deemed non-hazardous but unsuitable for return to the plant's treatment process were disposed of in an on-site holding pond for evaporation. These wastes included backwash waste and membrane filtrate generated during testing of organic-spiked water. A 1000-gallon waste tank was installed next to the pilot unit to collect and blend waste from CEBs and CIP equipment prior to pumping over to the full-scale plant's waste neutralization and disposal system.

3.2.4 Ultra-Filtration Membrane Modules

The pilot testing compared a standard UF module (BASF Dizzer® XL 0.9 MB 80 WT) with a novel project UF module (BASF amphiphilic, anti-adhesive UF membrane contained in a BASF Dizzer® PoLoFlo module), operated in parallel. The membrane had anti-adhesive PEO polysiloxane functional groups in a PSU while the Standard UF membrane material was modified polyethersulfone (PESm).

The project and Standard UF membranes had a nominal pore size of 0.02 µm and combined seven individual fibers in a single capillary reinforced within a support structure. The capillaries were bundled together in a plastic housing to form modules. Each module was approximately 66-inches long, and 10 inches in diameter, with a membrane surface area of approximately 80 square meters (m^2) (855 square feet [ft^2]). Both modules use an inside-to-outside mode of filtration.

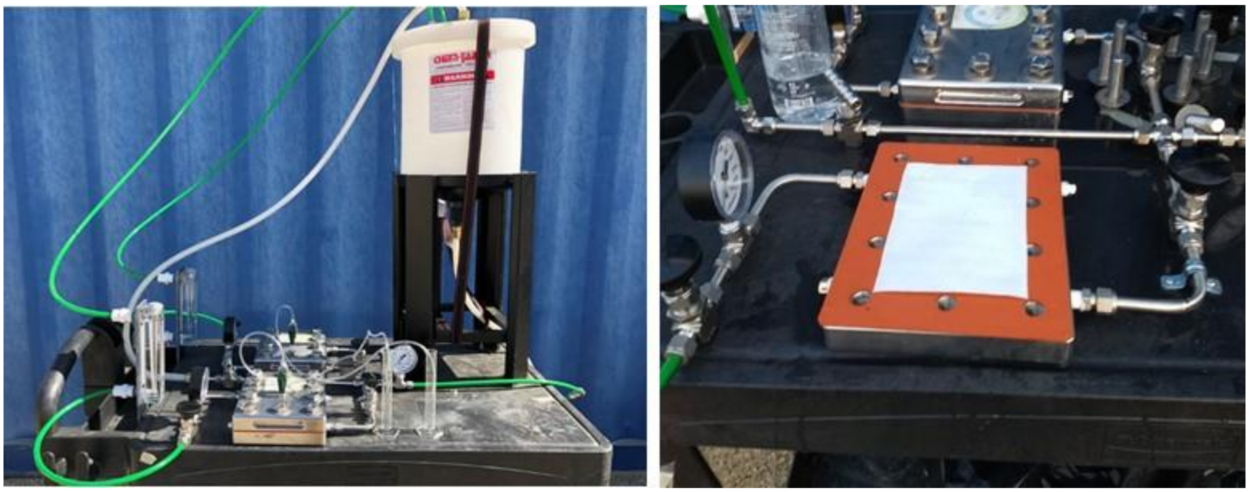
3.2.5 Bench-scale Reverse Osmosis Test Cells

Bench-scale reverse osmosis test cells were used to evaluate the relative effectiveness of the two UF membranes in providing pretreatment for reverse osmosis membrane treatment. Each membrane test cell contained a coupon on ESPA2 reverse osmosis membrane (Hydronautics, Oceanside, California) as well as a feed spacer from an ESPA2-4040 module to approximate mixing conditions in an actual RO module. The active membrane area was 155 cm^2 (24 in^2). Figure 7 shows the bench-scale RO membrane test cells setup.

Filtrate water produced from each UF membrane during the backwash water tests was collected to serve as the feed water to the RO test cells. A rotary vane pump (Procon Series 2) pumped this feed water across two duplicate high-pressure membrane coupon holders. Cross-flow velocities varied between 0.15 and 0.3 feet per second. Permeate fluxes of 3.4 LMH (2 GFD) were maintained throughout each experiment. The water in each test cell was gradually increased to maintain constant flux. The specific flux decline, or unit flux per unit pressure applied, was monitored throughout each test.

Permeate was collected and volumetric flow rates were measured a minimum of once per day. The pressure and flow rate of the concentrate was also measured. The concentrate was recirculated back to the feed tank, gradually concentrating and simulating increased water recoveries and concentration of scalants.

Figure 7: Bench-Scale Reverse Osmosis Membrane Test Cells



Source: Kennedy/Jenks Consultants

3.3 Methods and Procedures

The following summarizes various testing procedures that were utilized during pilot testing.

3.3.1 Water Quality Analyses

Various analytical methods were used in the pilot-scale testing to evaluate the impact of water quality on membrane performance and fouling. Table 1 describes the sampling locations used to monitor water quality.

Table 2 provides a summary of water quality monitoring schedule including analyte, sample type, sampling frequency, and sampling locations. Online water quality probes installed in the pilot unit monitored analytes requiring continuous measurement. The California Water Company plant's water quality laboratory analyzed analytes tested on daily or twice per week basis, while those analytes measured every two weeks were sent to an outside laboratory for analysis. All analyses were performed using the appropriate United States Environmental Protection Agency-approved or Standard Methods-(APHA-AWWA-WEF, 2012) recommended analytical method.

Table 1: Water Quality Sampling Locations

Location	Description
Feed	This sample valve was located downstream of the pilot's strainer and upstream of the pilot feed tank. This location was used to collect grab samples of the water coming into the pilot unit. This location was used to monitor water quality being fed to both UF modules during pilot testing with settled water and backwash water.
Injection 1	This sample valve was located (approximately 25 pipe diameters) downstream of a pre-feed pump chemical injection location and immediately upstream of the project UF module. This location was used to collect grab feed water samples for the project UF module during pilot testing with organic-spiked water.
Injection 2	This sample valve was located (approximately 25 pipe diameters) downstream of a pre-feed pump chemical injection location and immediately upstream of the standard UF module. This location was used to collect grab feed water samples for the standard UF module during pilot testing with organic-spiked water.
Filtrate 1	This location was used to sample filtrate water produced by the project UF module.
Filtrate 2	This location was used to sample filtrate water produced by the standard UF module.
Backwash	This location was used to monitor pH and conductivity of the pilot's backwash water and was only used to monitor performance of membrane cleanings.

Source: Kennedy/Jenks Consultants

Table 2: Water Quality Sampling Schedule

Constituent	Type	Frequency	Location	Method
Turbidity	Online	Continuous	Feed, Combined Filtrate	--
Turbidity	Grab	Daily	Feed, Filtrate 1&2	
pH	Online	Continuous	Feed, Backwash	--
pH	Grab	Daily	Feed, Filtrate 1&2	
Temperature	Online	Continuous	Feed	--
Temperature	Grab	Daily	Feed, Filtrate 1&2	
Chemical oxygen demand (COD)	Grab	Twice per week (Once every two weeks confirmation)	Feed, Filtrate 1&2	SM 5220 D

Constituent	Type	Frequency	Location	Method
Absorbance at 254 nm (UV-254)	Grab	Daily	Feed, Filtrate 1&2	SM 5910 B
Total organic carbon (TOC)	Grab	Once every two weeks	Feed, Injection 1&2 [(a)], Filtrate 1&2	SM 5310 C
Total dissolved solids (TDS)	Grab	Once every two weeks	Feed	SM 2540 D
Total suspended solids (TSS)	Grab	Once every two weeks	Feed	SM 2540 D
Iron (Fe)	Grab	Once every two weeks	Feed	EPA 200.7
Manganese (Mn)	Grab	Once every two weeks	Feed	EPA 200.7
Aluminum (Al)	Grab	Once every two weeks	Feed	EPA 200.7
Silica	Grab	Once every two weeks	Feed	EPA 200.7
Calcium	Grab	Once every two weeks	Feed	EPA 200.7
Conductivity	Online	Continuous	Feed, Backwash	--
Conductivity	Grab	Daily [(b)]	Feed, Filtrate 1&2	SM 2510 B
Free Chlorine Residual	Grab	Daily [(b)]	Feed, Filtrate 1&2	SM 4500-Cl G

Notes:

(a) Injection 1 and Injection 2 were only sampled during pilot testing with organic-spiked water when humic acid was injected into the feed water.

(b) These analyses were only performed during pilot testing with backwash water

Source: Kennedy/Jenks Consultants

3.3.2 Daily Integrity Testing

A daily integrity test was performed on both UF modules. This involved a pressure decay test performed by dewatering the module from the feed side with air pressure. Once feed side pressure reached 100 millibars (mbar) or 1.45 psi, the module was isolated, and a pressure hold test was performed. A pressure drop of less than 10 mbar/min (0.145 psi/min) during this hold test would indicate membrane integrity was consistent with design specifications. Air pressure was then released in a controlled manner to prevent water hammering. The module was flushed with feed water to remove residual air and returned to normal operation.

3.3.3 Membrane Cleaning Procedures

Three different membrane cleaning procedures were used during pilot testing: backwashing, CEB, and CIP. Table 3 summarizes the typical schedule for each of these cleaning procedures.

Table 3: Membrane Cleaning Schedule Summary

Location	Frequency
Backwash	Every 30 minutes except during periods of testing at higher water recoveries.
Chemically Enhanced Backwash (CEB)	Once Daily
Clean-In-Place (CIP)	Prior to changing water sources and as needed during pilot testing (See Table 4 and Section 3.3.3.2).

Source: Kennedy/Jenks Consultants

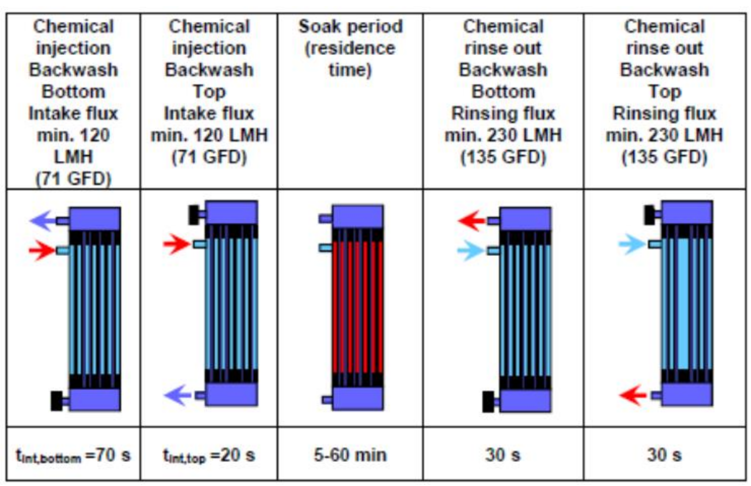
3.3.3.1 Backwash

A backwash was performed to remove loosely attached foulants from the membrane surface and reduce the operating transmembrane pressure. During a backwash, filtrate flowed from the filtrate side to the feed side of the membrane. Backwashes were performed on each module after set period of filtration time (typically thirty minutes) at a backwash flux of 136 GFD (230 LMH).

3.3.3.2 Chemically Enhanced Backwash

Chemically enhanced backwash (CEB) was used to improve the effectiveness of the hydraulic backwash in removing foulants and increasing membrane permeability. The primary difference between a CEB and a backwash is that cleaning chemicals are added to the filtrate during a CEB. Figure 8 illustrates the basic steps used during a CEB.

Figure 8: Chemically Enhanced Backwash Process Steps and Operating Parameters



Source: BASF Inge GmbH

Sulfuric acid (50 percent concentration), caustic soda (25 percent concentration) and periodically sodium hypochlorite (12.5 percent concentration) were used for CEB cleanings. The chemicals were introduced to the filtrate, which flowed at a fixed flux rate of 120 LMH (71 GFD) during the cleaning. The filtrate and chemical were continuously backwashed through the module until the target pH was measured in the backwash waste line. Once the target pH was reached, chemical dosing was stopped, and the membranes were soaked in the cleaning solution for 60 minutes. Following the soaking period, the membrane modules were flushed with filtrate in backwash mode at a flux of 230 LMH (135 GFD) for 30 seconds. A CEB was performed daily on each module.

3.3.3.3 Clean-In-Place

Clean-In-Place (CIP) was used to restore the membrane performance by removing organic fouling and inorganic scaling that were not removed through normal backwashes and CEBs. The CIP involved first an alkaline cleaning (using dilute sodium hydroxide and sodium hypochlorite) followed by a filtrate rinse. The second stage of the CIP involved an acid cleaning (using dilute sulfuric acid solution and sometimes citric acid) followed by a filtrate rinse. The alkaline and acid cleaning wastes were mixed together resulting in a neutralized (pH 6 to 9) waste solution.

Table 4 summarizes the CIPs that were performed during the project. CIPs were performed before switching between water sources, or when one or both modules fell below a minimum level of acceptable performance. CIPs were always performed on both UF modules. For the purposes of this project, minimum acceptable performance was defined as a daily average permeability of approximately 120 LMH/bar (4.9 GFD/psi).

Table 4: Clean-In-Place Performance Summary

CIP No.	Date Performed	Segment Name	Chemicals Used	pH/Chemical Dose	Membrane Exposure Time
1	6/28/17	Alkali	NaOH NaOCl	pH 12 500 ppm	3 hours
1	6/28/17	Acid	H_2SO_4	pH 1.9	3 hours
2	11/2/17	Alkali	NaOH NaOCl	pH 12 500 ppm	3 hours
2	11/2/17	Acid	H_2SO_4	pH 1.9	3 hours
3	11/24/17	Alkali	NaOH NaOCl Detergent	pH 12 500 ppm <0.01%	3 hours
3	11/24/17	Acid	H_2SO_4 Citric Acid	pH 1.5 1.5%	Overnight
4	1/24/18	Alkali	NaOH NaOCl	pH 12.1 500 ppm	Overnight
4	1/24/18	Acid	H_2SO_4 Citric Acid	pH 1.5 1.5%	Overnight
5	4/5/18	Alkali	NaOH NaOCl	pH 12.3 500 ppm	Overnight
5	4/5/18	Acid	H_2SO_4 Citric Acid	pH 1.5 1.5%	6 hours
6	8/27/18	Alkali	NaOH NaOCl	pH 12 500 ppm	Overnight
6	8/27/18	Acid	H_2SO_4 Citric Acid	pH 1.5 1.5%	Overnight

CIP No.	Date Performed	Segment Name	Chemicals Used	pH/Chemical Dose	Membrane Exposure Time
7	9/11/18	Alkali	NaOH NaOCl	pH 12 500 ppm	Overnight
7	9/11/18	Acid	H_2SO_4 Citric Acid	pH 1.5 1.5%	Overnight
8	10/29/18	Alkali	NaOH NaOCl	pH 12 500 ppm	Overnight
8	10/29/18	Acid	H_2SO_4 Citric Acid	pH 1.5 1.5%	Overnight

Notes: Sodium hydroxide (NaOH), sodium hypochlorite (NaOCl), sulphuric acid (H_2SO_4).

Source: Kennedy/Jenks Consultants

3.3.4 Membrane Foulant Characterization

In June 2018, both UF modules in the pilot unit were replaced after approximately one year of testing, which included periods of exposure to both settled water and organic-spiked water. The aged membrane fibers from the removed modules were sampled and analyzed for membrane properties and scalants.

The following characterization tests were performed on selected fibers:

- Scanning electron microscopy (SEM): A beam of electrons scans a sample surface to provide information about the topography of the sample at very small scales (low millimeter to low micrometer range).
- Energy dispersive X-ray spectroscopy (EDX): X-rays penetrate the sample down to a depth of one to several micrometers, providing information on elemental composition of surface foulants and the underlying bulk membrane.
- X-ray photoelectron spectroscopy (XPS): X-rays penetrate the sample surface by a few nanometers, providing information on the chemical nature and elemental composition of the sample surface only.
- Photon nuclear magnetic resonance (^{1}H-NMR): An external magnetic field orients the nuclear spins of organic compounds to characterize the nature, relative location, and concentration of chemical functional groups (in this case, PSU and polysiloxane) in the membrane fiber samples.

At the time of removal, the membranes had been operated approximately two months since the previous clean-in-place operation. Although the membranes received regular backwashes and daily chemically enhanced backwashes during this operating period, the membrane fibers likely contained residual foulants that might have been otherwise removed by clean-in-place operations.

3.3.5 Energy Usage Monitoring

BASE Energy (San Francisco, California) performed M&V of membrane energy use at different operating conditions using the International Performance Measurement and Verification Protocol (IPMVP), Option B, an "Isolation Retrofit" method. The 480 volt motors connected to the pilot membrane unit feed water and backwash pumps were isolated (with electrical metering equipment) to measure only the electrical usage of the pump/motor. Base Energy collected metered data once initial pilot optimization was completed for the entire pilot testing period.

Data loggers on the two feed pumps and backwash pump collected data at a sampling rate of once every 10 seconds. Although both UF modules utilized the same backwash pump, by reviewing pilot operation logs it was possible to analyze backwash power usage separately for the project UF module and the Standard UF module.

CHAPTER 4: Treatment of Settled Water

Chapter 4 presents and discusses the results from the UF pilot testing of settled surface water.

4.1 Testing Program

The objective of the settled water testing was to provide a side-by-side performance comparison of the project UF membrane and a standard UF membrane under typical drinking water treatment conditions. Testing was divided into two periods of operation, designated fall 2017 and summer 2018.

Settled water testing consisted of the following:

- An initial startup and shakedown period (April 28 to June 28, 2017)
- Flux optimization period (July 1 to September 14, 2017)
- Steady state operational periods: Fall 2017 (September 15 to November 1) and Summer 2018 (June 18 to July 8)
- Clean-in-place operations and performance recovery testing (November 2 to December 4, 2017)
- Increased water yield test with project UF membrane (December 5, 2017 to January 3, 2018)

The project UF and Standard UF membrane modules were operated at the same flux, recovery, backwash frequency, and chemical cleaning cycles throughout testing, unless otherwise noted. During any short period when one membrane line was not operating according to specified set points, performance data for both membrane lines was omitted from the data analysis so that only pairs results were compared.

4.2 Problems Encountered

Settled water pilot testing began in April 2017. The initial testing was used to troubleshoot and resolve several hardware issues, including providing enough water flow to the pilot and verifying operation of the chemical dosing system used to perform daily chemically enhanced membrane cleanings. CIP No. 1 was performed on June 28, 2017 to remove foulants accumulated during this period of off-spec operation.

During the fall 2017 test period, CIP No. 2 was performed in early November 2017 after over two months of steady state operation and was ineffective at recovering membrane performance. CIP No. 3 was performed toward the end of November 2017 and successfully recovered performance.

In April 2018, during the summer 2018 test period, a fiber breakage occurred in the project UF module, resulting in failure of the daily integrity test on this membrane. The project UF and Standard UF membrane modules were both removed and a new set of modules from the same manufacturing lots were installed. A short test period was run in June 2018 (summer 2018) to compare the performance of the second set of modules against the first set.

4.3 Feed Water Quality

Settled feed water was monitored continuously for selected parameters and grab samples were collected periodically and analyzed for additional water quality parameters. Table 5 summarizes the settled water quality results from these analyses for fall 2017 and summer 2018 test periods. Unless otherwise noted all parameters reported were analyzed in grab samples.

Table 5: Settled Feed Water Quality

Constituent (number of samples) [(a)]	Unit	All Testing AVG.	All Testing S.D.	Fall 2017 AVG.	Fall 2017 S.D.	Summer 2018 AVG.	Summer 2018 S.D.
Temperature [(b)]	°C	20.8	2.7	19.4	2.2	23.5	0.8
pH (227)	S.U.	7.7	0.1	7.7	0.1	7.8	0.1
Turbidity (227)	NTU	0.4	0.2	0.5	0.2	0.2	0.1
Total Suspended Solids (13)	mg/L	3.0	3.0	1.5	0.7	4.4	3.0
Total Organic Carbon (13)	mg/L	2.0	0.5	1.8	0.3	2.2	0.4
Absorbance at 254 nm (198)	cm^{-1}	0.049	0.020	0.044	0.022	0.056	0.017
Specific UV Absorbance ($SUVA_{254}$) (13)	L/mg-cm	0.028	0.016	0.035	0.017	0.023	0.011
Chemical Oxygen Demand (Lab) [(c)] (13)	mg/L	5.5	7.1	3.6	1.7	7.0	9.9
Chemical Oxygen Demand [(d)] (83)	mg/L	7.2	3.6	6.7	3.5	8.3	3.8
Total Dissolved Solids (13)	mg/L	100	40	105	40	100	45
Calcium (13)	mg/L	10	3.2	10	1.6	10	4.7
Aluminum (13)	mg/L	0.07	0.07	0.07	0.04	0.07	0.07
Silica (13)	mg/L	9.1	1.5	10	1.0	8.1	1.3
Iron (13)	mg/L	<0.1	-	<0.1	-	<0.1	-
Manganese (13)	mg/L	0.012	0.003	0.014	0.002	0.010	0.000

Notes: AVG. = average, S.D. = standard deviation, mg/L = milligrams per liter, S.U. = standard pH units, °C = degrees Celsius, NTU = nephelometric turbidity units, cm^{-1} = per centimeter solution depth, L/mg-cm = liters per milligram per centimeter

a) Number of sample results shown per analyte included both fall 2017 and summer 2018 testing periods. Number of samples for the individual testing periods were more or less equal, (for example for 13 total results, 6 results were from fall 2017 and 7 results were from summer 2018).

b) Data shown is from online temperature monitoring. The data collection interval for this temperature probe was every 5 seconds.

c) Results of twice-monthly chemical oxygen demand results from outside analytical laboratory

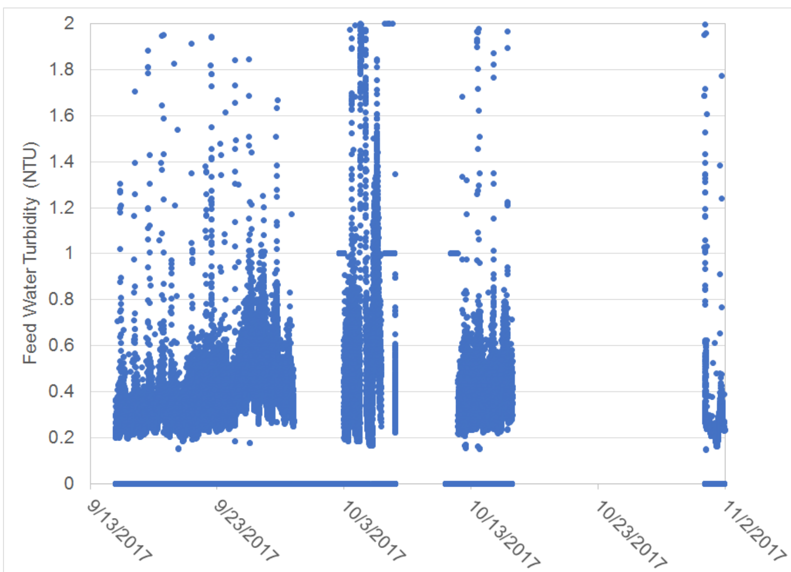
d) Chemical oxygen demand results from twice-weekly grab samples monitored at the pilot site.

Source: Kennedy/Jenks Consultants

The settled surface water quality, with the exception of turbidity, was similar during fall 2017 and spring 2018 pilot test periods. Turbidity values during the fall 2017 test period were approximately 2.5 times higher[2] than those measured during the summer 2018 test period while water temperatures were somewhat lower during the fall 2017 test period. Turbidity is an important membrane foulant, while higher water temperatures reduce resistance to water flow through polymer membranes. Higher feed water turbidity suggests the water had a higher fouling potential during the fall 2017 test period.

Figure 8 shows results of online feed turbidity measurements during fall 2017 pilot testing with settled water. This online meter does not have the same accuracy as laboratory measurements reported in Table 5, but had a greater data collection frequency and therefore provided a more detailed picture of turbidity trends. During this period, the online feed turbidity remained relatively stable until September 24, 2017. At that time, the online feed turbidity temporarily doubled from approximately 0.3 NTU to 0.6 NTU. In October, the feed water turbidity stabilized, but at a somewhat higher value than those observed at the beginning of steady state testing, approximately 0.4 NTU.

Figure 8: Settled Water Online Turbidity Trends (Fall 2017)



Source: Kennedy/Jenks Consultants

The turbidity during the summer 2018 test period was relatively consistent, though at lower values (See Table 5).

4.4 UF Pilot Testing Results

This section describes the settled water pilot testing results of fall 2017 and summer 2018 test periods. The fall 2017 testing included evaluation of membrane performance and impacts of

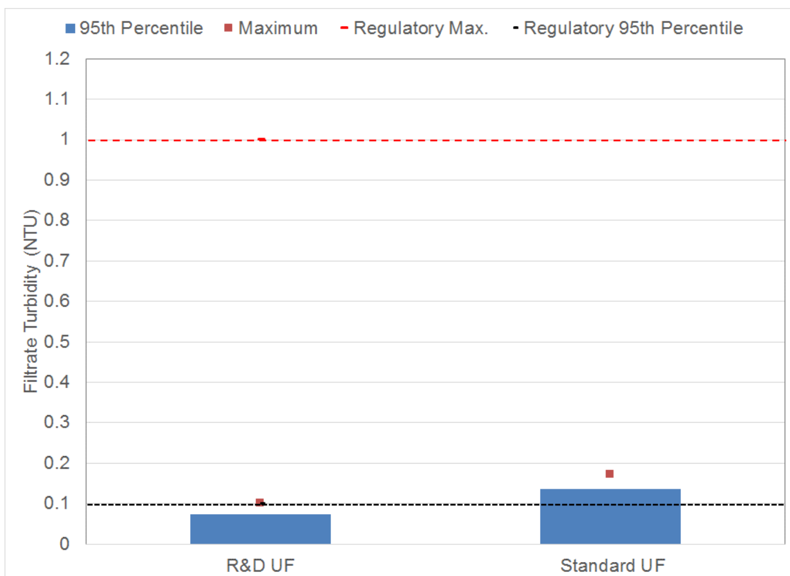
[2] Values of TSS exhibited the opposite trend; however, measured values of TSS were near or at the practical quantitation limit and prone to greater error. Given the observed standard deviations for this analyte, it was not possible to state that apparent differences in the average values for the two time periods were statistically significant.

cleaning effectiveness on performance recovery, while the shorter summer 2018 test period provided only a limited evaluation of membrane performance.

4.4.1 Filtrate Water Quality

The filtrate turbidity for the project and standard membranes was monitored and recorded during pilot testing. The pilot had an online turbidity monitor that measured the turbidity of the combined filtrate from both membrane lines. Because of the inability of this meter to distinguish between filtrate from the project and standard UF membrane, values shown are from daily turbidity grab samples. Figure 9 shows the 95th percentile and maximum filtrate turbidity for both membranes during fall 2017 steady state testing. The filtrate turbidity for both modules was always below the maximum 1.0 NTU California regulatory requirement for membrane treatment of drinking water (USEPA, 2005) throughout the test period with maximum observed turbidities of less than 0.10 NTU and 0.17 NTU measured for the project and Standard membranes, respectively. The filtrate turbidity of the project module was always below the maximum 95th percentile California regulatory turbidity standard for membrane treatment of drinking water (surface water treatment) of 0.1 NTU throughout the test period, while the 95th percentile turbidity of the standard UF module did exceed this value.

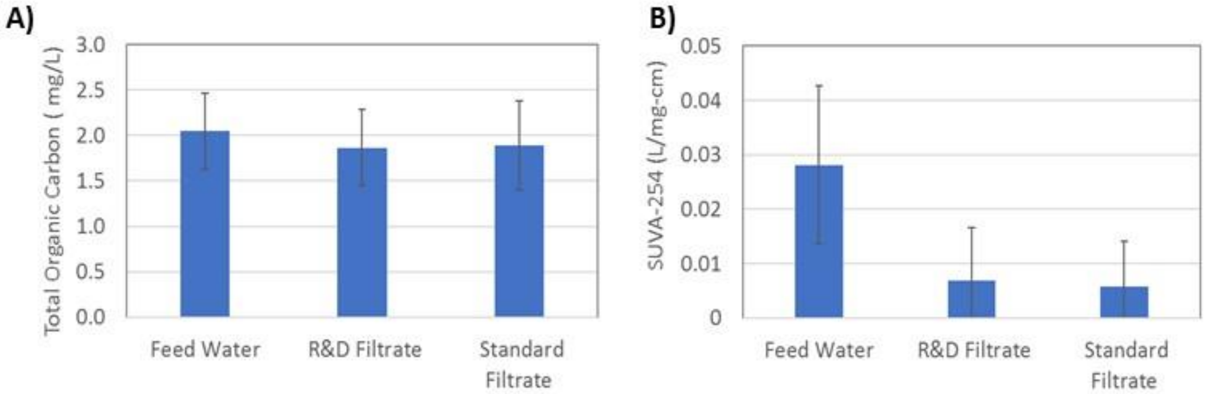
Figure 9: Filtrate Turbidities During Fall 2017 Settled Water Steady State Testing (95th Percentile and Maximum)



Source: Kennedy/Jenks Consultants

Figure 10 shows average values of TOC and SUVA-254 in the water before and after membrane filtration. TOC concentrations were very similar in the feed water and filtrate produced by both UF membranes, indicating that removal of this constituent during membrane treatment was insignificant. The impact of membrane treatment on SUVA-254 was far more significant. SUVA-254 is commonly used in water treatment as a surrogate for aromatic organic matter, or the most hydrophobic and fouling fraction of organic matter. SUVA-254 was strongly reduced by both UF membranes. Thus, aromatic organics may have deposited on the membrane surfaces as a foulant. There was, however, no appreciable difference in SUVA-254 removal between the two UF membranes, suggesting that the same degree of organic deposition occurred on both membranes.

Figure 10: Average TOC and SUVA-254 Concentrations in Feed and Filtrate Water during Treatment of Settled Water (Fall 2017)



A) Average TOC concentrations, B) Average SUVA-254 concentrations.

Source: Kennedy/Jenks Consultants

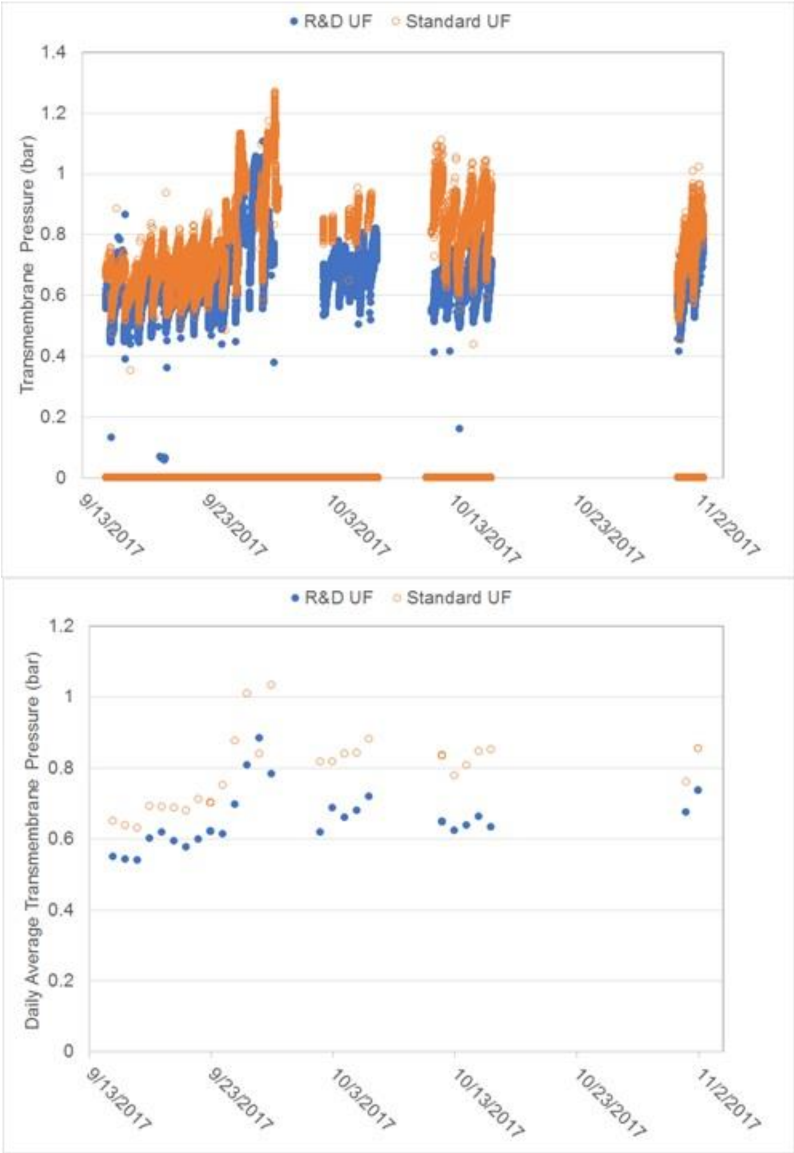
4.4.2 Transmembrane Pressure and Permeability Comparison

4.4.2.1 Fall 2017 Test Period

After an initial period of operation, the feed flow rate to both membrane modules was set to 137 L/min (36.1 gpm), the water flux was maintained at 102 LMH (60 GFD), and the TMP was allowed to vary. Steady-state operation was established on September 11, 2017 and held until November 2, 2018. The pilot unit was not in operation from October 16-30, 2017 to allow for repairs at the East Bakersfield water treatment plant that resulted in a temporary lack of feed water to the pilot unit. Figure 11 shows the continuous TMP and daily average TMP recorded over the steady-state test period for the project UF and standard UF membranes.

The TMP for the project membrane started and remained lower than the TMP for the standard UF membrane for most of the steady-state testing period. The initial TMPs for the project and standard membranes were approximately 0.55 and 0.65 bar (8.1 and 9.8 psi), respectively. The TMP increased approximately linearly through the first two weeks of operation, followed by a steep, but temporary increase in TMP on September 24th. This coincided with a temporary change in the feed water quality including a doubling of turbidity from approximately 0.3 NTU to 0.6 NTU (See Figure 8). The reason for the steep increase in TMP was likely due to the fouling layer becoming more developed due to increased turbidity loading and providing additional resistance to water flow. In October, both the feed water turbidity and module TMPs stabilized, but at somewhat higher values than those observed at the beginning of steady state testing, approximately 0.4 NTU of turbidity and 0.65 bar (9.6 psi) and 0.85 bar (12.5 psi) for the project UF and Standard UF modules, respectively.

Figure 11: Transmembrane Pressure (TMP) During Fall 2017 Treatment of Settled Water (Top) and Daily Average TMP (Bottom)

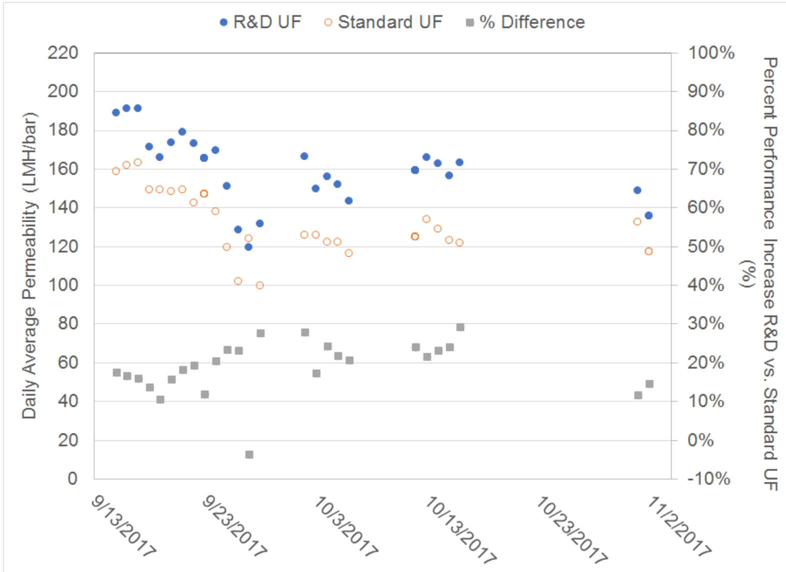


Conversion: 1 bar is equivalent to 14.50377 psi.

Source: Kennedy/Jenks Consultants

Figure 12 illustrates the change in membrane permeability (or unit water flux per unit transmembrane pressure) due to fouling over the steady state testing period.

Figure 12: Permeability and Relative Performance During Treatment of Settled Water (Fall 2017)



Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

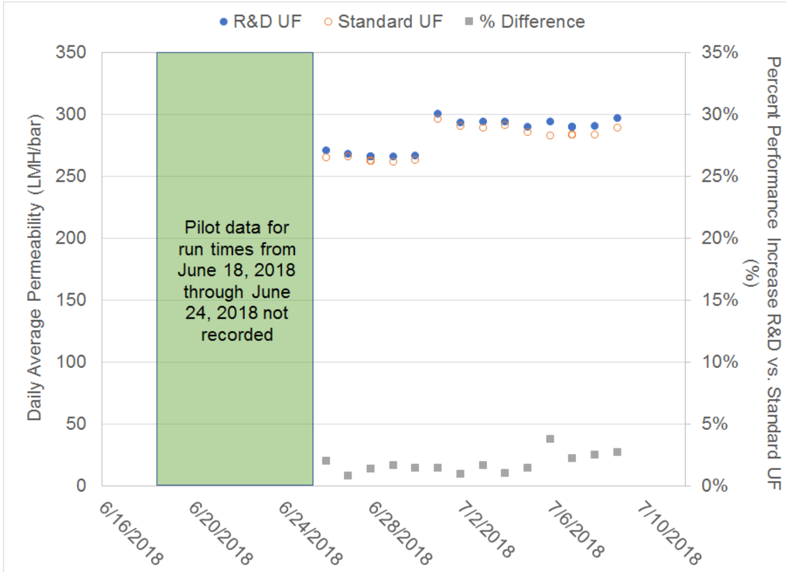
Source: Kennedy/Jenks Consultants

The project membrane permeability was higher than the Standard UF membrane permeability during the full testing period, meaning less pressure was required to produce the same amount of filtered water (filtrate). The permeability of both membranes decreased sharply after the first two weeks of operation, likely due to increased resistance from a fouling layer that was not removed during daily CEB. After this first testing, period, the project and standard membrane permeabilities were more stable through the remainder of the steady-state pilot testing. Although similar trends in permeability were observed for both membranes throughout steady-state testing, the project membrane permeability was, on average, 19 ± 6 percent greater than the standard membrane permeability. This result illustrates the fouling resistance potential of the project membrane, allowing it to operate at lower energy demand and/or long run times between CIP events, thereby reducing chemical cleaning frequency.

4.4.2.2 Summer 2018 Test Period

A short test period using settled water as the feed water source to the pilot was performed in June 2018, after the failed project UF membrane and the original standard UF membrane were replaced. The same flux rate of 102 LMH (60 GFD) previously used during fall 2017 testing was used to allow a comparison between the two sets of data. Figure 13 shows the membrane permeability results from the summer 2018 testing with settled water.

Figure 13: Permeabilities and Relative Performance of Replacement Ultrafiltration Modules During Treatment of Settled Water (Summer 2018)



Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

Source: Kennedy/Jenks Consultants

The permeability of both the project and standard membrane during summer 2018 (Figure 13) was approximately 45 percent and 72 percent higher, respectively, than the initial membrane permeabilities observed during fall 2017 (Figure 12). Additionally, the percent performance increase of the project membrane compared with the standard membrane was much lower during the summer 2018 test (less than 5 percent) than was observed during the fall 2017 test (approximately 20 percent).

The reason for the observed difference in results between the fall 2017 and summer 2018 pilot testing of settled water is not clear. Although a new set of UF modules was used during summer 2018 testing, the fibers used in the old and new version of the project UF modules were manufactured at the same time, which would suggest that manufacturing irregularities were not responsible for the change in performance. As summarized in Table 5, the water qualities during fall 2017 and summer 2018 were somewhat different, particularly for turbidity[3]. During the summer 2018 test, the feed water contained 60 percent less turbidity than during fall 2017 pilot testing. The water quality data, as well as the increase in membrane permeabilities, suggests that the fouling potential of the water in summer 2018 may have been too low for the benefits of the modified project surface to be observed.

4.4.3 Water Recovery

The water recovery (that is water yield) for both membranes was fixed at 94.5 percent during the steady-state fall 2017 testing period when both membrane modules were operated at a water flux of 102 LMH (60 GFD). The ability of the project UF module to run at higher

[3] Higher water temperatures can decrease resistance to water flow through polymer membranes, resulting in higher permeabilities. Although the water temperature was slightly higher during summer 2018 testing (23.4 degrees Celsius [°C]) than during fall 2017 testing (19.4 °C), the small 4°C difference is not sufficient to account for the performance difference observed between the two time periods.

recoveries was evaluated after completion of steady state testing. The filtration run time between backwashes for the project UF module was increased incrementally in order to increase water recovery, while the standard UF module was left at 30 minutes (a recovery of 94.5 percent). After increasing the water recovery of the project UF module, both membranes were run for a 15-day period. The water flux was maintained at 102 LMH (60 GFD) during this period, with daily CEB.

The maximum recovery that could be achieved by the project UF module without also sacrificing energy saving benefits was 94.9 percent (run time between backwashes of 32.5 minutes), an increase of 0.4 percent compared with the standard UF module. Increasing the water recovery from the project module above this value resulted in TMPs that were higher than the standard module, meaning that it would require more energy to run the project module at a recovery greater than 94.9 percent than it would to run the standard module at 94.5 percent. At recoveries less than 94.9 percent, the project module required the same or less energy than that required to run the standard UF module.

Potential for increased water recovery with the project membrane was not evaluated during the short summer 2018 test period.

4.5 Performance Recovery and Cleaning Optimization

The backwash and chemical enhanced backwash efficiency and clean-in-place effectiveness were assessed only during the fall 2017 settled water pilot testing.

4.5.1 Backwash and Chemically Enhanced Backwash Efficiency

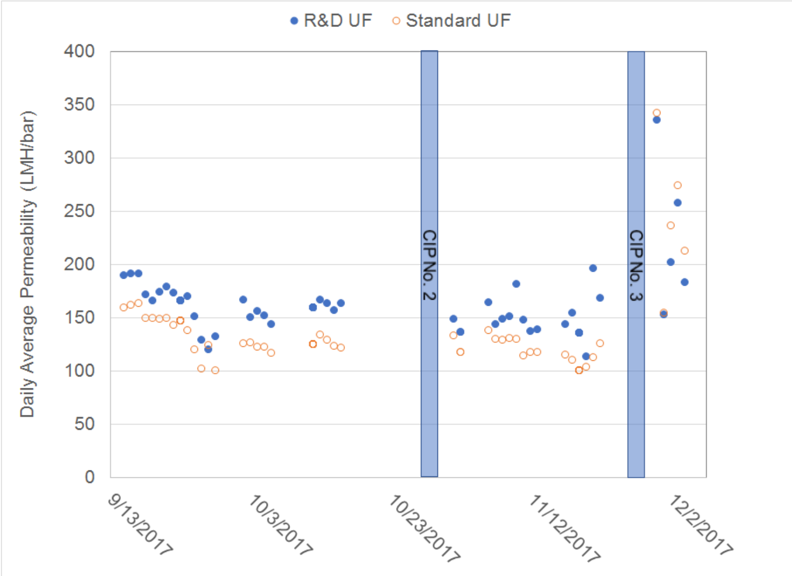
Both membranes exhibited similar performance recoveries following backwash or CEB. The performance recovery (as measured by membrane permeability, or flux per unit transmembrane pressure) following backwashes were 99.0 ± 7.7 percent and 98.8± 3.7 percent for the project and standard UF membranes, respectively. Similarly, performance recoveries following the daily CEB were 98.6 ± 5.1 percent and 99.1 ± 9.3 percent for the project and standard UF membranes, respectively. Routine cleaning (that is that performed at a frequency of daily or higher) performance of the two membranes indicates that the project membrane did not provide noticeably better flux recovery than the standard UF membrane.

4.5.2 Clean-In-Place Effectiveness and Impact on Membrane Operation

After operating the pilot at a sustained flux setting of 102 LMH (60 GFD) for a period of 5 weeks (membrane runtime, not calendar time), the overall permeability (specific flux) of both membranes had declined. Specifically, the project UF permeability declined by 28 percent from 189 LMH/bar (7.6 GFD/psi) to 136 LMH/bar (5.4 GFD/psi), while the standard UF permeability declined 26 percent from 159 LMH/bar (6.4 GFD/psi) to 117 LMH/bar (4.7 GFD/psi).

CIP No. 2 was performed on November 2, 2017. No performance recovery was observed following this CIP, nor was there any difference in the relative performance of the two UF membranes. CIP No. 3 was performed on November 27, 2017. The procedure for CIP No. 3 included addition of citric acid as a chelating agent to the acid soak and both the acid soak and alkali soak times were increased from three hours to overnight to provide better scale removal from the membrane surfaces. Figure 14 shows the impact of CIPs No. 2 and No. 3 on membrane permeability.

Figure 14: Impact of Clean-in-Place on Daily Average Permeabilities During Treatment of Settled Water

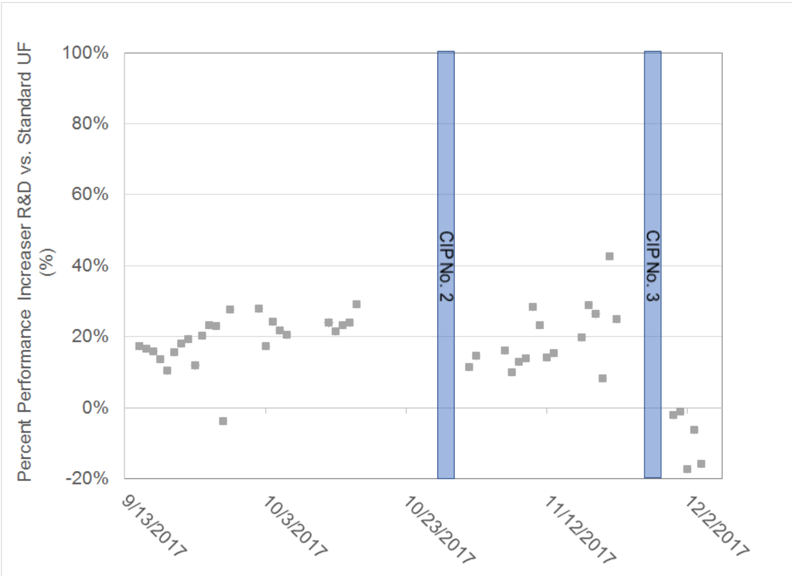


Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

Source: Kennedy/Jenks Consultants

CIP No. 3 resulted in a significant recovery in permeability of both UF modules; however, the relative performance of the modules was dramatically different from that observed prior to CIP No. 3, with the project UF module exhibiting performance similar or slightly worse than the standard UF module. Figure 15 shows impact of CIP No. 3 on the relative performance of the project membrane to the Standard membrane.

Figure 15: Impact of CIP on Relative Performance of Project Ultrafiltration vs. Standard Ultrafiltration During Treatment of Settled Water



Source: Kennedy/Jenks Consultants

The sudden shift in membrane permeability (Figure 14) and percent performance decrease between the project and Standard UF membrane (Figure 15) after CIP No. 3 was unexpected and suggested that the chemical cleaning had either been more effective on the Standard UF relative to the project UF membrane, or that the anti-adhesive functional groups in the project membrane degraded or otherwise become impaired during the chemical cleaning.

The shift in relative performance between the project and standard membranes following CIP No. 3 has important implications. Throughout testing with settled water, including initial testing (pre-September 2017) and during steady-state operation at 102 LMH (60 GFD), the project membrane was observed to provide significant reduction (that is 10 percent or greater) in the transmembrane pressure (and therefore energy) required for water treatment. The sudden change in membrane performance following cleaning raised questions about the long-term ability of the project UF membrane to provide energy savings relative to standard UF membranes. Although initial results with settled water indicate the project membrane has significant promise, further investigation into appropriate cleaning procedures and the stability of the anti-adhesive PEO polysiloxane functional groups will likely be needed before this product is ready for the commercial market.

Because CIPs were always performed on both membranes at the same time, to extrapolate how differences in the rate of specific flux (permeability) decline and CIP effectiveness would impact other operational factors such as chemical cleaning costs and membrane operation lifetime, several parameters were evaluated related to these issues and are summarized in Table 6. These values were derived from the fall 2017 steady-state operating tests and subsequent cleaning evaluations and do not include summer 2018 performance.

Table 6: Membrane Cleaning Performance Parameters for Settled Water

Parameter	Units	Project UF	Standard UF
Rate of TMP Increase [(a)]	bar/day	0.002	0.0052
Initial TMP	bar	0.55	0.65
Max. TMP [(b)]	bar	0.85	0.85
Acceptable TMP increase	bar	0.3	0.2
Time between CIPs	days	150	38
CIP frequency	#/year	2.4	9.5
Improvement in CIP Frequency	%	74.4%	--
CIP Recovery [(c)]	%	100%	100%
Improvement in CIP Effectiveness	%	0.0%	--

Conversion: 1 bar is equivalent to 14.50377 psi.

(a) Rate of TMP increase was calculated based on the actual runtime of the membranes and not the calendar date (that is any times when the pilot was not operational have been excluded from this calculation).

(b) Based on a minimum permeability of 120 LMH/bar (4.9 GFD/psi) and a flux of 102 LMH (60 GFD)

(c) Based on a comparison of membrane permeabilities observed at the start of steady state testing with those observed after completion of CIP No. 3. The value is a measure of irreversible membrane fouling.

Source: Kennedy/Jenks Consultants

Both the rate of TMP increase and the initial TMP for the project membrane were lower than that of the standard membrane, resulting in a significantly lower estimated CIP frequency of 2.4 per year as compared to 9.5 per year. This represents a 74.4 percent reduction in the frequency of CIPs as well as the volume of chemicals needed to perform CIPs.

As evident in Figure 14, following CIP No. 3, both membrane modules exhibited permeability performance greater than that observed at the beginning of steady state testing. During the flux optimization period, some loss of permeability performance was observed after CIP No. 1, but prior to the start of steady state testing. This flux optimization testing was performed at changing flux settings (which can affect the observed permeability of the membrane) and complicated direct comparison of permeability recovery following chemical cleanings. As both the project UF and Standard UF membranes recovered all permeability decline observed during steady-state testing and achieved permeability approximately equivalent to those observed following the most recent effective CIP (No. 1), both membranes were determined to have CIP performance recoveries of approximately 100 percent, indicating that little irreversible fouling occurred on either membrane during the testing period. However; as noted previously, if CIP No. 3 resulted in damage to the project membrane, cleaning protocols may need to be re-evaluated which could lead to different relative CIP recoveries than those reported herein.

4.6 Summary

The relative performance of the two UF membranes was generally consistent during most of the fall 2017 treatment of settled water, during which the project UF membrane outperformed the standard UF membrane. Test periods when this relative performance could not be replicated appeared to correspond to times when the project membrane may have been damaged during membrane cleaning or when improvement in feed water quality resulted in water that had a low fouling potential.

During most of the Fall 2017 settled water steady-state testing, the project UF membrane exhibited permeabilities significantly and consistently higher than those of the standard UF membrane, ranging between -3 percent and 30 percent, with an average of 19 percent. However, a membrane CIP (CIP No. 3) may have resulted in chemical damage of the chemical surface modifications on the project membrane. This possibility is discussed further in Chapter 7 (Membrane Characterization). During the replicate settled water pilot testing performed in summer 2018 with new UF modules, differences in membrane permeabilities were significantly lower (only 2 percent on average). One potential reason for this change may be related to the significantly decreased feed water turbidity levels, resulting in a water with lower fouling potential during summer 2018. It is possible that during treatment of less challenging water, the fouling resistant benefits of the project UF membrane may not be as significant.

The rate of TMP increase exhibited by the project membrane, in combination with the overall lower TMPs observed during the majority of settled water testing suggested that less frequent cleaning would be needed for the project membrane than the standard membrane. Based on the results of fall 2017 steady-state operating performance it was estimated that CIP frequencies could be reduced by 74 percent, reducing the cost of chemicals for membrane maintenance. The effectiveness of those chemical cleanings; however, appear to be similar for both the project and standard UF membranes.

Increased water yield was demonstrated for the project membrane as compared to the standard membrane. By decreasing backwash frequency for the project membrane, water recovery as high as 94.9 percent could be achieved without increasing the TMP required to pump water through the UF membrane above that of the Standard membrane. Operating at equivalent TMP, the standard UF membrane could only achieve 94.5 percent water recovery.

CHAPTER 5: Treatment of Organic-Spiked Water

Chapter 5 presents and discusses the results from the UF pilot testing of organic-spiked settled water.

5.1 Testing Program

The objective of testing settled water spiked with organic matter was to provide side-by-side comparison of the project UF membrane and a standard UF membrane with simulated recycled water. Testing was divided into two periods of operation, designated as Organic-Spiked Water (spring) and Organic-Spiked Water (summer).

The organic-spiked settled water testing consisted of the following:

- A flux optimization period (January 26 to February 20, 2018)
- Steady-state operational periods: spring 2018 (February 21 to March 25, 2018) and summer 2018 (July 9 to 13, 2018)
- CIP operations and performance recovery testing (April 5 to 14, 2017)

The project UF and Standard UF membrane modules were operated at the same flux, recovery, backwash frequency, and chemical cleaning cycles throughout testing, unless otherwise noted. During any short period when one membrane line was not operating according to specified set points, performance data for both membrane lines was omitted from the data analysis so that only pairs results were compared.

5.2 Problems Encountered

CIP No. 4 was performed on January 24, 2018 to remove foulants accumulated during the previous phase of pilot testing. The organic-spiked water pilot testing began in February 2018. The spring 2018 organic-spiked water testing continued through the end of March 2018. CIP No. 5 was performed in early April 2018.

Shortly after completion of CIP No. 5, a fiber breakage occurred in the project UF module, resulting in failure of the daily integrity test on this membrane line. The project UF and Standard UF membrane modules were removed and a new set of modules were installed. The summer 2018 organic-spiked water testing was performed in July 2018 and used to compare the performance of the second set of modules against the first set.

5.3 Feed Water Quality

Membrane feed water was monitored continuously for selected parameters and grab samples were collected periodically and analyzed for additional water quality parameters. Table 7 summarizes the results from the analyses for the spring 2018 and summer 2018 organic-spiked water pilot tests. Due to an unanticipated schedule change at the water treatment plant, no bi-weekly grab samples were collected during the short summer 2018 pilot testing event. Therefore, some water quality analytes are not available for this time period. Unless otherwise noted all parameters were monitored were analyzed in grab samples.

Table 7: Organic-Spiked Feed Water Quality

Constituent (number of samples) [a]	Unit	All Testing AVG	All Testing S.D. (Range)	Spring 2018 AVG	Spring 2018 S.D. (Range)	Summer 2018 AVG	Summer 2018 S.D. (Range)
Temperature [b]	°C	14.7	5.3	12.1	2.4	23.9	0.7
pH (18)	S.U.	7.83	0.11	7.85	0.13	7.79	0.07
Turbidity (18)	NTU	0.33	0.23	0.43	0.22	0.14	0.01
Total Suspended Solids (2)	mg/L	<2.5	--	<2.5	--	--	--
Total Organic Carbon (4)	mg/L	5.8	(4.4 – 7.0)	5.8	(4.4 – 7.0)	--	--
Absorbance at 254 nm	cm^{-1}	--	--	--	--	--	--
Specific UV Absorbance ($SUVA_{254}$)	L/mg-cm	--	--	--	--	--	--
Chemical Oxygen Demand (Lab) [c] (4)	mg/L	14.3	(<2.5 - 28)	14.3	(<2.5 - 28)	--	--
Chemical Oxygen Demand [d]	mg/L	--	--	--	--	--	--
Total Dissolved Solids (2)	mg/L	102	(52-152)	102	(52-152)	--	--
Calcium (2)	mg/L	16.9	(12.5-21.3)	16.9	(12.5-21.3)	--	--
Aluminum (2)	mg/L	0.33	(<0.02 - 0.64)	0.33	(<0.02 - 0.64)	--	--
Silica (2)	mg/L	9.5	(7.7-11.3)	9.5	(7.7-11.3)	--	--
Iron (2)	mg/L	<0.1	--	<0.1	--	--	--
Manganese (2)	mg/L	0.038	(<0.01-0.07)	0.038	(<0.01-0.07)	--	--

AVG. = average, S.D. = standard deviation, mg/L = milligrams per liter, S.U. = standard pH units, °C = degrees Celsius, NTU = nephelometric turbidity units, cm^{-1} = per centimeter solution depth, L/mg-cm = liters per milligram per centimeter

(a) Number of sample results shown per analyte were for both spring 2018 and summer 2018 testing.

(b) Data shown is from online temperature monitoring. The data collection interval for this temperature meter was 5 seconds.

(c) Results of twice-monthly chemical oxygen demand results from outside analytical laboratory

(d) Chemical oxygen demand results from twice weekly grab samples monitored at the pilot site.

Source: Kennedy/Jenks Consultants

After addition of humic acid to the full-scale treatment plant's settled water, the resulting total organic carbon was 5.8 mg/L, or approximately 2.8 times higher than the organic carbon content of the water tested during settled water pilot testing (see Chapter 4). Similarly, the COD concentration of 14.3 mg/L of the organic-spiked water was approximately 50 percent higher than that observed during settled water testing. The organic fouling potential of the organic-spiked water was therefore increased. Levels of other constituents (for example turbidity, pH, TDS) were similar for both water sources; however, levels of calcium (67 percent) and aluminum (300 percent) were also higher in the organic-spiked water[4] used in this phase of pilot testing than the settled water testing during the previous phase. Higher concentrations of these minerals could suggest a higher mineral scaling potential as well.

During summer testing with organic-spiked water, the feed water turbidity was 30 percent lower than during earlier spring testing. Additionally, the water temperature during summer testing (23.9 °C) was significantly higher than during spring testing (12.1 °C). Both of these parameters would be anticipated to impact membrane performance.

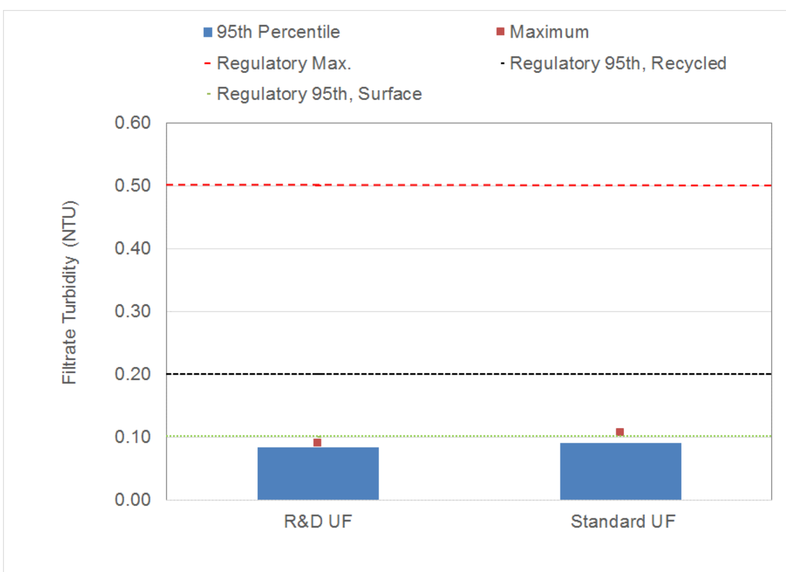
5.4 UF Pilot Testing Results

This section describes the pilot testing results for organic-spiked water treatment during spring and summer 2018 testing. The Spring 2018 testing included evaluation of membrane performance and impact of cleaning effectiveness on performance recovery, while the shorter summer 2018 test period with organic-spiked water provided a more limited evaluation of membrane performance.

5.4.1 Filtrate Water Quality

The filtrate turbidity for the project and standard membranes was monitored continuously and recorded during the pilot study. Figure 16 shows the 95th percentile and maximum turbidities for both membranes.

Figure 16: Filtrate Turbidities Observed During Spring Treatment of Organic-Spiked Water (95th Percentile and Maximum)



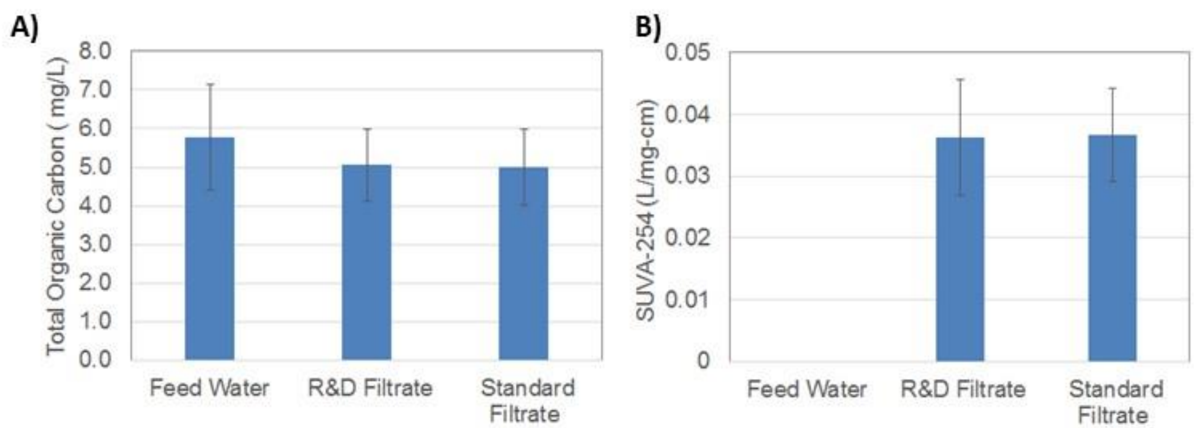
Source: Kennedy/Jenks Consultants

[4] The increase in these two constituents was due to their higher levels in the settled water prior to spiking with humic acid during this testing phase, and not due to the humic acid itself.

The filtrate turbidity for both modules was always below the maximum 1.0 NTU and 0.5 NTU California regulatory standards for membrane treatment of drinking water (US EPA, 2005) and recycled water (CCR, 2018), respectively, throughout the test with maximum observed turbidities of less than 0.09 NTU and 0.11 NTU measured for the project and Standard membranes, respectively. The filtrate turbidities of the project and standard modules were also always below the maximum 95th percentile California regulatory turbidity standard for membrane treatment of drinking water (surface water treatment) of 0.1 NTU throughout the test, as well as the maximum 95th percentile California regulatory turbidity standard for membrane treatment of filtered wastewater (that is, recycled water) of 0.2 NTU.

Results from Figure 16 showed that both UF membranes provided near identical performance in turbidity removal. The average values of TOC and SUVA-254 in the water before and after membrane filtration were measured (Figure 17). TOC concentration of the feed water was reduced by 0.7 mg/L or 12 percent in the filtrate water produced by both UF membranes, indicating small removal of this constituent during membrane treatment. Although TOC removal was low, more TOC was retained by the membranes during treatment of organic-spiked water (0.7 mg/L) compared with treatment of settled water (0.1 mg/L, see Figure 10). This supports the conclusion that the organic fouling potential of the organic-spiked water was higher than that of the settled water alone. Neither UV nor SUVA-254 data were available for the organic-spiked feed water during this testing phase. However, there was no appreciable difference in SUVA-254 levels between the two UF membrane filtrates, suggesting that a similar degree of organic deposition occurred on both membranes.

Figure 17: Average TOC and SUVA-254 Concentrations in Feed and Filtrate Water During Treatment of Organic-Spiked Water (spring)



Average TOC concentrations, B) Average SUVA-254 concentrations.

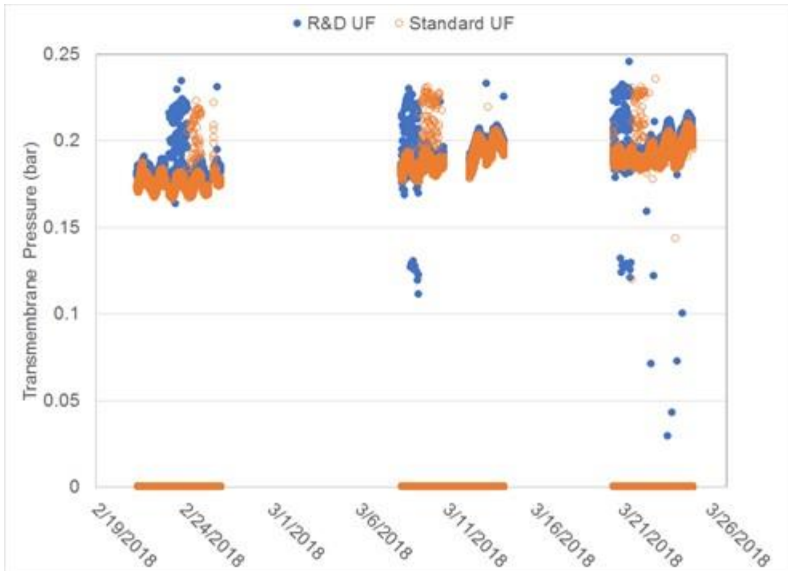
Source: Kennedy/Jenks Consultants

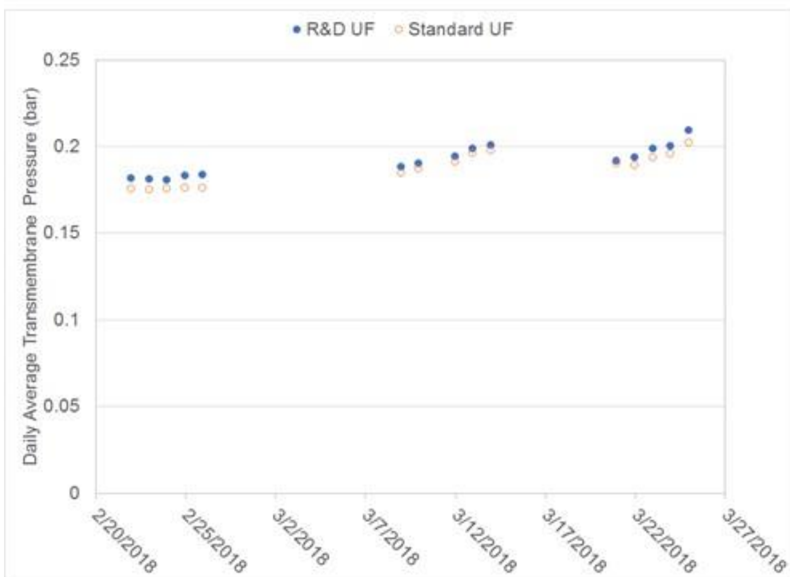
5.4.2 TMP/Permeability Comparison

After an initial period of operation, the feed flow rate to both membrane modules was set to 57 L/min (15 gpm), the water flux was maintained at 42.4 LMH (25.1 GFD), and the transmembrane pressure (TMP) was allowed to vary. Brief periods of testing performed at higher flux could not be sustained without dramatic declines in membrane performance for both modules. This result supported that addition of humic acid to the water had significantly increased the fouling potential of the water, that is, to such an extent that previously achievable flux levels during settled water tests could not be maintained for even short periods of time.

Steady-state operation at 42.4 LMH (25.1 GFD) was established on February 21, 2018 and was continued until March 25, 2018. The pilot unit was not in operation between February 26 and March 8, 2018 due to a lack of feed water. Figure 18 provides the TMPs and daily average TMPs recorded over the pilot testing period for the project UF and Standard UF membranes.

Figure 18: Transmembrane Pressure (TMP) During Spring Steady-State Treatment of Organic-Spiked Water (Top) and Daily Average TMP (Bottom)





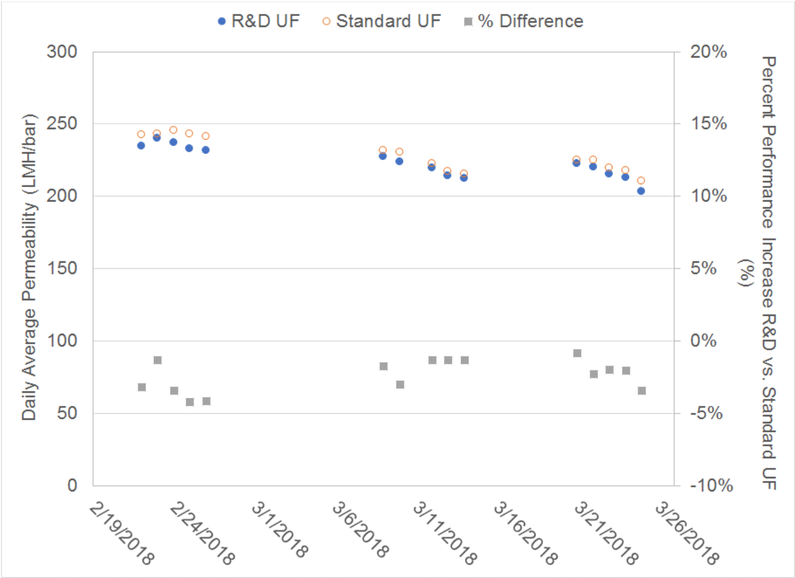
Conversion: 1 bar is equivalent to 14.50377 psi.

Source: Kennedy/Jenks Consultants

The TMP for the project membrane started and remained comparable to the TMP for the standard UF membrane over most of the testing period. The initial TMP for the project and standard membranes was approximately 0.18 bar (2.6 psi). The TMP increased linearly throughout the four-week period of steady-state operation, ending with TMPs of approximately 0.2 bar (2.9 psi) for both membrane modules.

Figure 19 illustrates the change in membrane permeability and relative performance of the two modules due to fouling over the testing period.

Figure 19: Permeabilities and Relative Performance During Treatment of Organic-Spiked Water (spring)



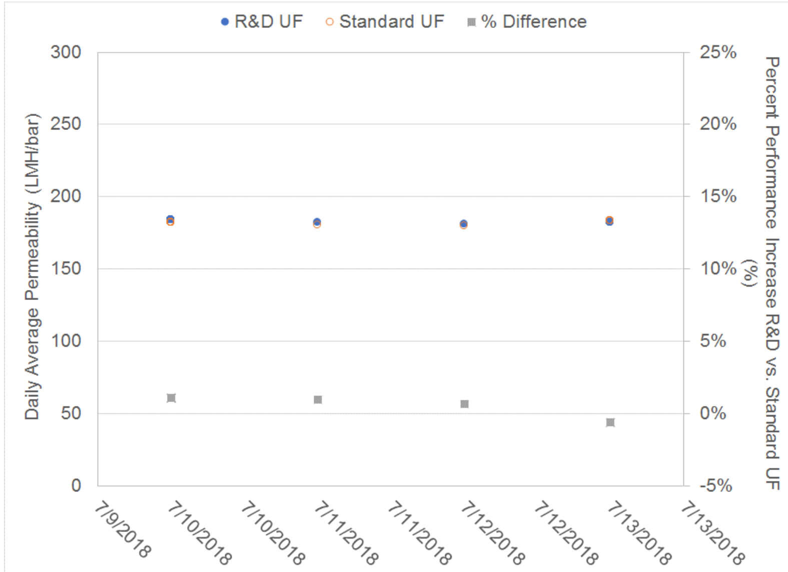
Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

Source: Kennedy/Jenks Consultants

The membrane permeability for the project membrane was very similar; if slightly lower, than the Standard UF membrane permeability during the full testing period. The permeability of both membranes decreased gradually during the four-week testing period, likely due to increased resistance from a fouling layer that was not removed during daily CEBs. Although similar trends in permeability were observed for both membranes tested, permeability of the project membrane was on average 2.4 percent lower than the Standard membrane. This result suggests that the project membrane was no more resistant to fouling than the standard membrane during this testing with organic-spiked water.

As discussed in Chapter 4, a CIP operation performed at the end of settled water testing and just prior to the start of testing with organic-spiked water may have altered the performance of the project membrane. The project UF and Standard UF membrane modules were removed and a new set of modules were installed in June 2018. To compare the performance of the second set of modules against the first set, a short period of testing using organic-spiked settled water as the feed water source to the pilot was performed in July 2018. Figure 20 shows the pilot testing results from the summer 2018.

Figure 20: Permeabilities and Relative Performance of Replacement Ultrafiltration Modules Treating Organic-Spiked Water (summer)



Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

Source: Kennedy/Jenks Consultants

The permeability of the project and standard membranes (both approximately 180 LMH/bar (7.2 GFD/psi)) were lower than the initial membrane permeability of 200 to 230 LMH/bar (8.0 to 9.2 GFD/psi) observed during the spring test with organic-spiked water (Figure 18) in spite of lower feed turbidity and higher water temperatures. Additionally, the percent performance increase of the project membrane as compared with the standard membrane was insignificant in the spring 2018 test (less than 2 percent). This is consistent with the relative performance of the two modules during spring 2018 testing.

No performance improvement by the project membrane relative to the standard membrane was observed during testing of water with higher levels of organic foulants (that is organic-spiked water), even though different module sets were tested in spring 2018 and summer 2018.

5.4.3 Water Recovery

The water recovery (that is water yield) for both membranes was fixed at 86.7 percent during the steady-state period (water flux of 42.4 LMH or 25.1 GFD). Because no relative improvement in treatment performance was observed for the project UF compared with the Standard UF module when treating organic-spiked water, the ability of the project UF module to run at higher recoveries than the Standard UF was not evaluated. Given the similar performance of both membranes, no increased water yield with the project membrane could be demonstrated.

5.5 Performance Recovery and Cleaning Optimization

The backwash and chemical enhanced backwash efficiency and CIP effectiveness were assessed only during the spring 2018 organic-spiked settled water pilot testing.

5.5.1 Backwash and Chemical Enhance Backwash Efficiency

Both membranes exhibited similar performance recoveries following backwash or CEB. The performance recovery (as measured by membrane permeability, or flux per unit pressure) following backwashes were 99.7 ± 1.2 percent and 99.6± 1.4 percent for the project and standard UF membranes, respectively. Similarly, performance recoveries following the daily CEB were 98.9 ± 2.6 percent and 98.2 ± 3.6 percent for the project and standard UF membranes, respectively. Routine cleaning (that is that performed at a frequency of daily or higher) performance of the two membranes indicates that the project membrane did not provide noticeably better flux recovery than the standard UF membrane.

5.5.2 Clean-In-Place Effectiveness and Impact on Membrane Operation

After operating the pilot at a sustained flux setting of 42.4 LMH (25 GFD) for a period of four weeks in spring 2018, the overall permeability (specific flux) of both membranes had declined somewhat. project UF permeability declined by 14 percent from 234 to 200 LMH/bar (9.4 to 8.0 GFD/psi), while the standard UF permeability declined by 16 percent from 246 to 212 LMH/bar (9.8 to 8.5 GFD/psi).

CIP No. 4 was completed on January 30, 2018, just before start of testing with organic-spiked water. Due to an unavailability of feed water, the pilot was shut down for two weeks with the membranes soaking in a dilute chlorine solution to prevent biofilm growth. A "clean water" flux test at 42.4 LMH (25 GFD) with settled water performed prior to start of steady-state operation with organic-spiked water resulted in permeabilities of 230 LMH/bar (9.2 GFD/psi) and 240 LMH/bar (9.6 GFD/psi) for the project UF and Standard UF, respectively. CIP No. 5 was performed on April 5, 2018 following completion of steady state testing with organic-spiked water. "Clean water" flux tests performed with settled water following CIP No. 5 resulted in permeabilities of 219 LMH/bar (8.8 GFD/psi) and 214 LMH/bar (8.6 GFD/psi) for the project and standard UF membranes, respectively. These results indicated that the CIP recovered 95 percent of the project UF membrane performance following treatment of water high in organic foulants. Little recovery in performance of the standard UF membrane was observed. In this case, the CIP was more effective for the project UF membrane than the standard UF membrane.

Following CIP No. 5, the pilot was returned to normal settled feed water (that is no organic additives) and run at a flux of 102 LMH (60 GFD) to replicate testing conditions evaluated in earlier pilot testing phases (see Chapter 4). In this instance, the difference in performance could most likely be attributed to differences in CIP cleaning efficiency. The project UF exhibited an average permeability of 287 LMH/bar (11.5 GFD/psi) and the standard UF exhibited an average permeability of 236 LMH/bar (9.4 GFD/psi). This represented a performance increase by the project UF module of greater than 20 percent, consistent with earlier observations during Fall 2017 pilot testing with settled water (as described in chapter 4). Unfortunately, after two days of testing at this condition, a fiber breakage occurred in the project UF module, preventing a longer evaluation of whether this performance recovery by the project UF module was sustainable.

Because CIPs were always performed on both membranes at the same time, to extrapolate how differences in the rate of specific flux (permeability) decline and CIP effectiveness would impact the operational factors such as chemical cleaning costs and membrane operation lifetime, several parameters were evaluated related to these issues and are summarized in

Table 8. These values were derived from the spring 2018 steady-state operating tests and subsequent cleaning evaluations and do not include summer 2018 performance.

Both the rate of TMP increase and the initial TMP for the project membrane were similar for the project and the standard membrane, resulting in similar estimates of CIP frequency of 3.8 per year and 4.0 per year for the project and Standard UF, respectively. This represents a small 5.3 percent reduction in the frequency of CIPs as well as the volume of chemicals needed to perform CIPs.

As noted above, following CIP No. 4, the project UF membrane recovered approximately 95 percent of the permeability performance observed at the start of testing with organic-spiked water, while the standard UF membrane showed little (1 percent) performance recovery. This represents a significant improvement in the project UF membrane as compared to the standard UF membrane. CIP effectiveness determines the build-up of irreversible fouling on the membrane surface. Poor CIP effectiveness indicates that irreversible fouling will accumulate quickly and shorten the operating lifetime of the membrane. Conversely, good CIP effectiveness will extend membrane lifetimes (with the caveat that any damage caused to the membrane by CIP chemicals could act to shorten operating life).

Table 8: Membrane Cleaning Performance Parameters for Organic-Spiked Water

Parameter	Units	Project UF	Standard UF
Rate of TMP Increase (a)	bar/day	0.0018	0.0019
Initial TMP	bar	0.18	0.18
Max. TMP	bar	0.35	0.35
Allowable TMP Increase	bar	0.17	0.17
Time between CIPs	days	96	91
CIP frequency (b)	#/year	3.8	4.0
Improvement in CIP Frequency	%	5.3%	--
CIP Recovery (c)	%	95.0%	1.0%
Improvement in CIP Effectiveness	%	94.0%	--

Conversion: 1 bar is equivalent to 14.50377 psi.

(a) Rate of TMP increase was calculated based on the actual runtime of the membranes and not the calendar date (that is any times when the pilot was not operational have been excluded from this calculation).

(b) Based on a minimum permeability of 120 LMH/bar (4.9 GFD/psi) and a flux of 42.4 LMH (25.1 GFD)

(c) Based on a comparison of membrane permeabilities observed after completion of CIP No. 3. (that is before testing with organic-spiked feed water) with those observed after completion of CIP No. 4 (that is following completion of testing with organic-spiked feed water). The value is a measure of irreversible membrane fouling.

Source: Kennedy/Jenks Consultants

5.6 Summary

No significant performance benefit was observed for the project UF as compared with the standard UF when treating organic-spiked water, during initial (spring) or replicate (summer) testing. The TMP required to push water through the membranes, the rate of TMP increase, the water yield and the estimated CIP cleaning frequency of both membranes were very similar. Although little performance benefit was observed in these parameters the performance recovery of the project UF module after a CIP was far more significant than that of the standard UF module, representing a 94 percent improvement in cleaning efficiency.

This result suggests that, although no performance benefit was observed during treatment, the fouling layer that developed on the project UF membrane was more easily cleaned, leading to less irreversible fouling. This result suggests that when treating water high in organic foulants, the major benefit of the project membrane over the standard UF membrane is cleaning effectiveness. Less build-up of irreversible foulants on membrane surfaces could potentially result in longer-term energy savings or longer membrane operating lifetimes after multiple cleaning cycles.

CHAPTER 6: Treatment of Backwash Water

The results from the UF pilot testing of backwash water are presented and discussed in this section.

6.1 Testing Program

The objective of backwash water testing was to provide side-by-side performance comparison of the project UF membrane and a standard UF membrane under more challenging water quality conditions than the settled water. Treatment and recovery of backwash water can also potentially improve the overall efficiency of the UF process.

The backwash water testing included the following:

- Initial operating period to achieve steady state conditions (July 24 to August 29, 2018)
- Steady state operation (September 14 to October 15, 2018)
- Membrane backwash and chemical enhanced backwash operations
- Clean-in-place operations and performance recovery testing (October 16 to November 7, 2017)
- Pretreatment for reverse osmosis (November 16 to December 6, 2018)

The project UF and Standard UF membrane modules were operated at the same flux, recovery, backwash frequency, and chemical cleaning cycles throughout testing, unless otherwise noted. During any short period when one membrane line was not operating according to specified set points, performance data for both membrane lines was omitted from the data analysis so that only pairs results were compared.

6.2 Problems Encountered

Pilot testing with backwash water began on July 24, 2018 with the new membranes installed in June 2018. CIP No. 6 was performed in August 29, 2018 to remove foulants accumulated during the previous phases of pilot testing with these new membranes. Issues encountered with the chemical dosing system for the cleaning system made it impossible to maintain stable performance during the first few weeks of the backwash water tests. After resolution of this problem, CIP no. 7 was performed on September 12, 2018. Following steady state testing, CIP no. 8 was performed on October 16, 2018. No performance recovery was observed on either module and CIP no. 9 was performed on October 29, 2018.

6.3 Feed Water Quality

Backwash water samples were collected regularly and analyzed for multiple water quality parameters. Table 9 provides the results from the analyses of grab samples collected during backwash water pilot tests. Unless otherwise noted all parameters were monitored were analyzed in grab samples.

Table 9: Backwash Feed Water Quality

Constituent (number of samples)	Unit	Average	S.D.
Temperature [(a)]	°C	22.6	1.5
pH (45)	S.U.	8.26	0.67
Turbidity (45)	NTU	3.85	1.92
Total Suspended Solids (6)	mg/L	14.8	8.2
Total organic carbon (6)	mg/L	3.4	1.2
Absorbance at 254 nm (49)	cm^{-1}	0.16	0.045
Specific UV Absorbance ($SUVA_{254}$) (6)	L/mg-cm	0.045	0.018
Chemical Oxygen Demand (Lab) [(b)] (6)	mg/L	9.6	8.8
Chemical Oxygen Demand [(c)] (17)	mg/L	19.6	5.1
Total Dissolved Solids (6)	mg/L	129	58
Electrical Conductivity (28)	µS/cm	228	80
Calcium (6)	mg/L	12.7	3.3
Aluminum (6)	mg/L	0.59	0.80
Silica (SiO_2) (6)	mg/L	8.9	1.2
Iron (6)	mg/L	<0.1	--
Manganese (6)	mg/L	0.12	0.14
Free Chlorine (45)	mg/L as Cl_2	1.73	1.77

AVG. = average, S.D. = standard deviation, mg/L = milligrams per liter, S.U. = standard pH units, °C = degrees Celsius, NTU = nephelometric turbidity units, cm^{-1} = per centimeter solution depth, L/mg-cm = liters per milligram per centimeter

(a) Data shown is from online temperature monitoring. The data collection interval for this temperature meter was 5 seconds.

(b) Results of twice-monthly chemical oxygen demand results from outside analytical laboratory

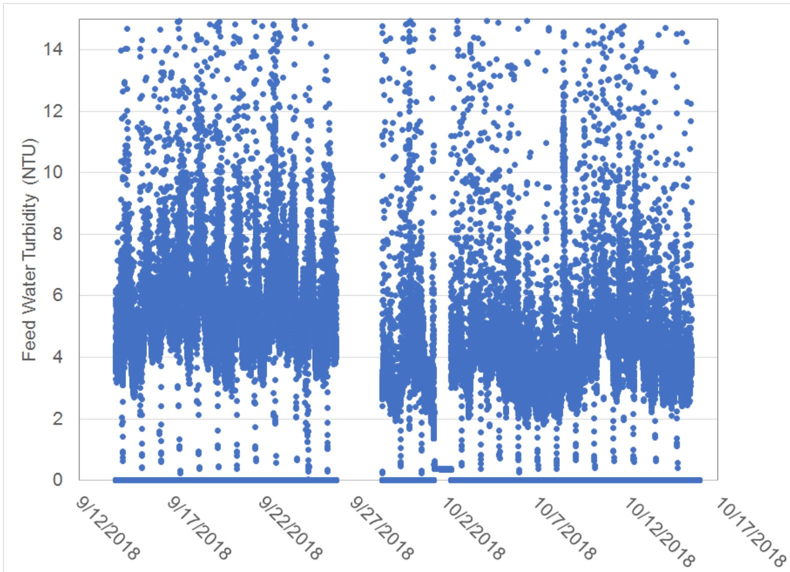
(c) Chemical oxygen demand results from twice-weekly grab samples monitored at the pilot site.

Source: Kennedy/Jenks Consultants

The backwash water quality, except for higher turbidity and total organic carbon concentrations, was generally similar to that of other feed water sources. The turbidity of the backwash water was approximately one order of magnitude higher than was observed during settled water or organic-spiked water testing. The total organic carbon of the backwash water (3.4 mg/L) was intermediate between that observed for the settled water (2.0 mg/L) and the organic-spiked settled water (5.8 mg/L).

Figure 21 shows results of online feed turbidity measurements during pilot testing with backwash water. This online meter does not have the same accuracy as laboratory measurements reported in Table 9, but had a greater data collection frequency and therefore provided a more detailed picture of turbidity trends. Turbidity varied throughout the day with the higher turbidities observed around 6:00 pm at night. During September, feed turbidity typically ranged from approximately 4 to 8 NTU. The pilot unit was not in operation between September 25 and 27, 2018 due to a temporary lack of feed water. After this period and for the remainder of the backwash water testing, feed water turbidities were approximately 2 NTU lower, typically ranging from 2 to 6 NTU. TSS levels measured in grab samples throughout this testing period did not exhibit a similar trend; however, fewer TSS results were available for this period and those results were highly variable, making it difficult to identify clear trends in the data.

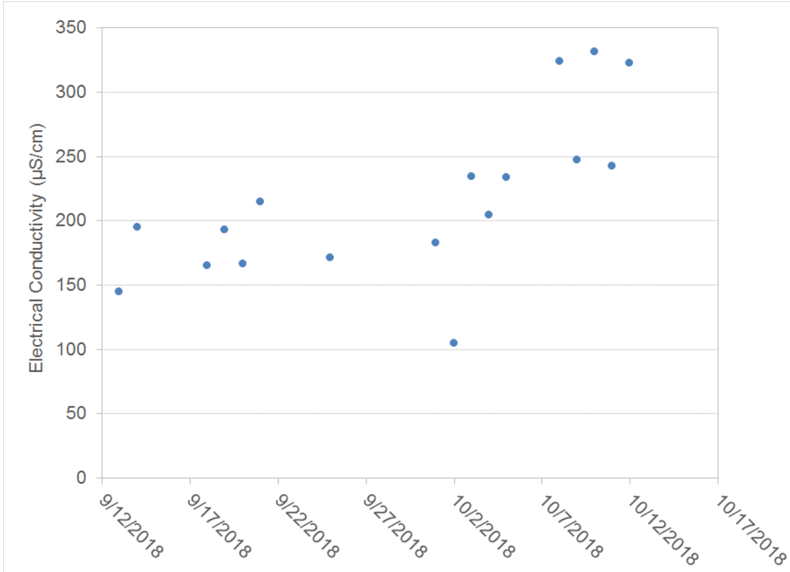
Figure 21: Backwash Water Online Turbidity Trends



Source: Kennedy/Jenks Consultants

Towards the end of steady state testing, a shift in the electrical conductivity levels (as measured in daily grab samples) was observed beginning on October 8, 2018 (Figure 22). During the first four weeks of steady-state tests, the conductivity varied between 100 and 250 micro Siemens per centimeter (µS/cm). During the last week of steady-state tests (beginning on October 8. 2018), conductivity concentrations shifted upwards and consistently stayed at or above 250 µS/cm for the remainder of backwash water pilot tests. Although conductivity is not itself hazardous, it does indicate a shift in water quality. No other water quality parameters monitored during testing, including online measurements and grab sample results (listed in Table 9), exhibited a similar trend, but it was possible that another unmonitored foulant in the water could have exhibited similar trends as conductivity and impacted membrane performance.

Figure 22: Backwash Water Electrical Conductivity Trends



Source: Kennedy/Jenks Consultants

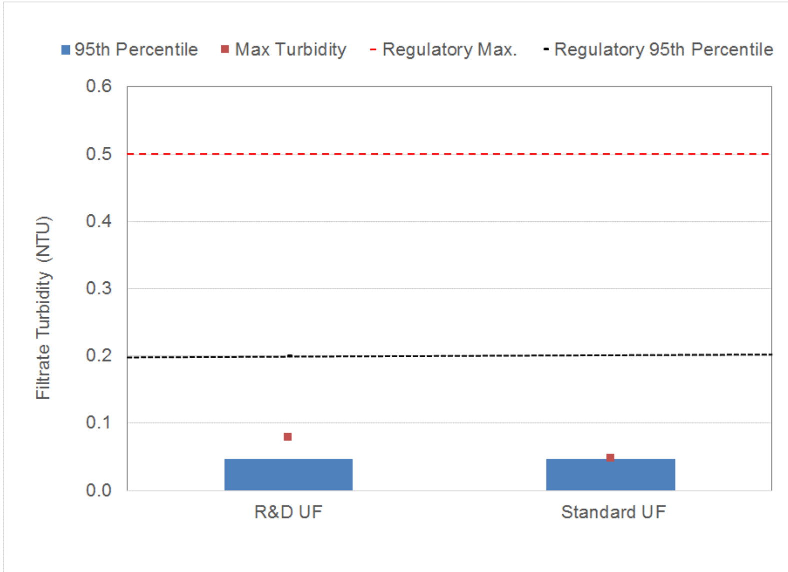
6.4 UF Pilot Testing Results

The following section summarizes and discusses the pilot performance during the steady-state treatment of backwash water.

6.4.1 Filtrate Water Quality

The filtrate turbidity for the project and standard membranes was monitored and recorded during the backwash water testing. Figure 23 shows the 95th percentile and maximum turbidity for both membranes. The filtrate turbidity for both modules was always below the maximum 1.0 NTU and 0.5 NTU California regulatory standards for membrane treatment of drinking water (US EPA, 2005) and recycled water (CCR, 2018), respectively, throughout the test with maximum observed turbidities of less than 0.08 NTU and 0.05 NTU measured for the project and Standard membranes, respectively. The filtrate turbidities of the project and standard modules were also always below the maximum 95th percentile California regulatory turbidity standard for membrane treatment of drinking water (surface water treatment) of 0.1 NTU throughout the test, as well as the maximum 95th percentile California regulatory turbidity standard for membrane treatment of filtered wastewater (that is, recycled water) of 0.2 NTU.

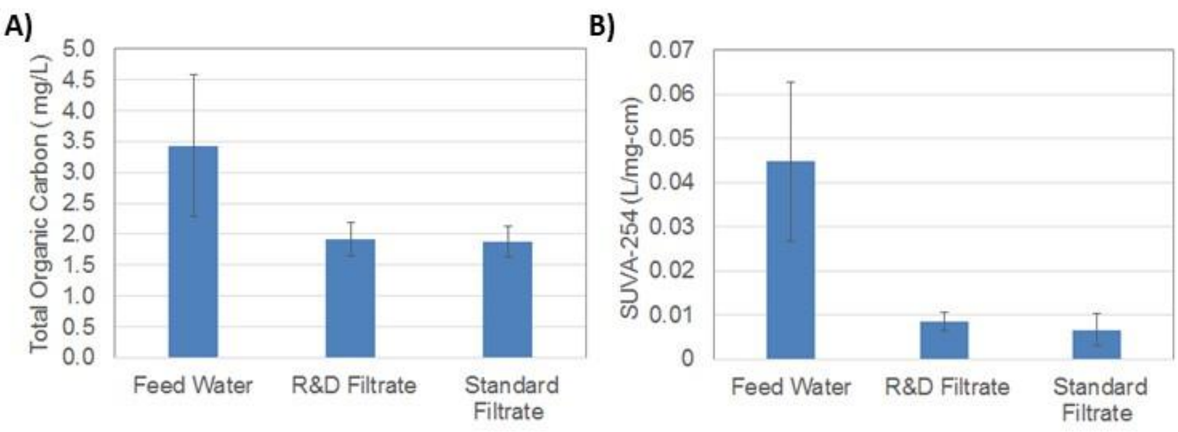
Figure 23: 95th Percentile and Maximum Observed Filtrate Turbidities During Steady-State Treatment of Backwash Water



Source: Kennedy/Jenks Consultants

Figure 24 shows average values of total organic carbon and SUVA-254 in the water pre-and post-membrane filtration. TOC concentration was reduced approximately 41 percent in the filtrate water produced by both UF membranes relative to feed water, indicating significant removal of this constituent during membrane treatment. The impact of membrane treatment on SUVA-254 (a reduction of approximately 80 percent for both membranes) was more significant. $SUVA_{254}$ is commonly used as a surrogate for aromatic organic matter, which is the most hydrophobic and most fouling fraction of organic matter. This suggests that similar amounts of potentially fouling organic deposition occurred on both membranes.

Figure 24: Average TOC and SUVA-254 Concentrations in Feed and Filtrate Water during Treatment of Backwash Water



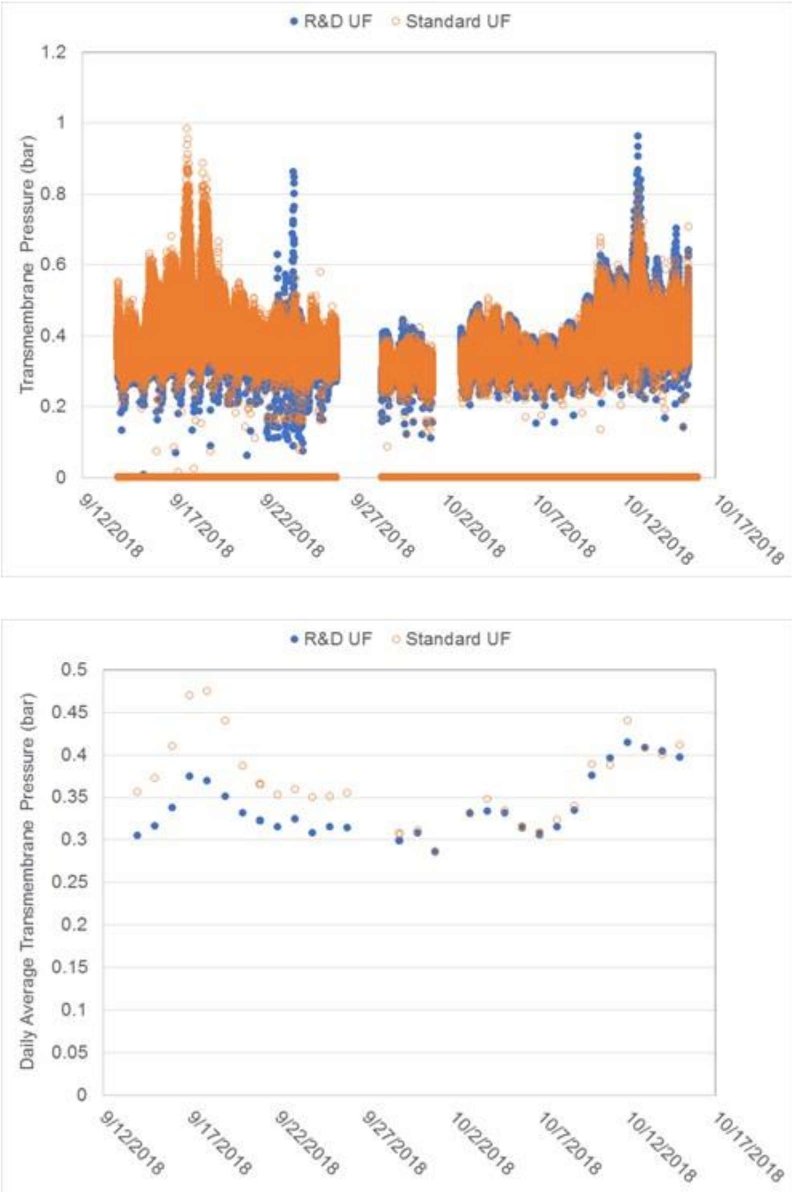
A) Average TOC concentrations, B) Average SUVA-254 concentrations.

Source: Kennedy/Jenks Consultants

6.4.2 Transmembrane Pressure and Permeability Comparison

After an initial period of operation, the feed flow rate to both membrane modules was set to 57 L/min (15 gpm) resulting in a water flux of 42.4 liters per meter squared per hour (LMH) or 25.1 gallons per foot squared per day (GFD), allowing the TMP to vary. Steady-state operation was established on September 13, 2018 and testing was completed on October 16, 2018. The pilot unit was not operated September 25-27 and October 1 due to a temporary lack of feed water. Figure 25 shows the TMP and daily average TMP recorded over the pilot testing period for the project UF and standard UF membranes.

Figure 25: Transmembrane Pressure (TMP) During Treatment of Backwash Water



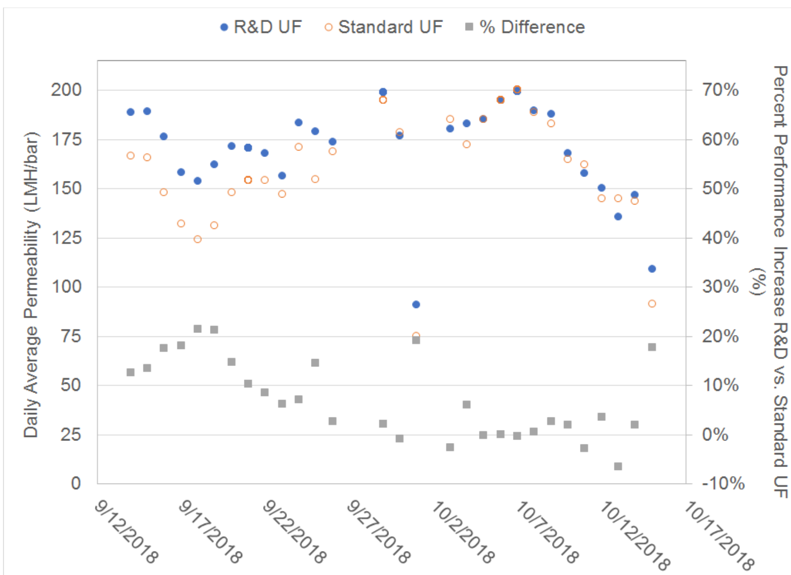
Transmembrane Pressure (upper panel) and Daily Average Transmembrane Pressure (lower panel) . Conversion: 1 bar is equivalent to 14.50377 psi.

Source: Kennedy/Jenks Consultants

The TMP for both membranes varied throughout the testing period. The TMP for the project membrane remained lower than the TMP of the standard UF membrane for the first half of the testing period. During this time period, the TMP for the project UF ranged from 0.3 to 0.36 bar (4.4 to 5.3 psi), while the TMP for the standard UF ranged from 0.35 to 0.47 bar (5.1 to 6.9 psi). In October, the TMPs of both modules were approximately 0.3 bar (4.4 psi) and throughout the next two weeks increased unsteadily up to a TMP of 0.4 bar (5.9 psi).

Figure 26 illustrates the change in daily average membrane permeabilities due to fouling over the testing period. The permeability of the project UF membrane was variable but steady over the first 4 weeks of testing (until October 9, 2018), during which the average permeability observed for this membrane was 182 LMH/bar (7.3 GFD/psi). During the last week of the steady-state test, the permeability of the project membrane declined steadily from this average value down to 108 LMH/bar (4.3 GFD/psi), a reduction of 41 percent. At the start of steady state testing, the performance of the standard UF membrane was lower than that of the project membrane (by 10 percent to 20 percent). In the last days of October, the permeability of the standard UF membrane increased to match that of the project membrane and there was essentially no relative performance difference between the two UF membranes until the end of the steady-state test.

Figure 26: Permeabilities and Relative Performance During Steady-State Treatment of Backwash Water



Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

Source: Kennedy/Jenks Consultants

The feed water turbidity was highest during the first two weeks of the steady-state testing period. At the end of September 2018, the pilot was shut down briefly to clean a clogged feed pump. When treatment resumed, the turbidity of the feed water was significantly lower (see Figure 21) and remained lower throughout the remainder of steady-state testing with backwash water. After the reduction in feed water turbidity the observed performance improvement of the project membrane disappeared and the permeabilities of both modules, but particularly the standard UF, improved.

The decrease in permeability observed for both modules after October 9,2018 coincided with a noticeable increase in the conductivity of the backwash water (see Figure 22) discussed in Section 6.4.1. Although there was no similar trend in other water quality parameters measured, free chlorine concentrations became more variable during this period, including numerous occurrences of chlorine concentrations (as high as 5 mg/L) that were 25 to 100 percent higher than what was observed earlier in the steady state testing. The water quality change that occurred after October 9, 2018 was likely related to the steep drop in performance of both membranes.

The permeability of the project membrane was higher than that of the standard UF membrane during the first half of the testing period. The permeability of both membranes initially increased and then gradually decreased in the second half of the testing period, likely due to increased resistance from a fouling layer that was not removed during daily CEB. Although similar trends in permeability were always observed for both membranes tested during the first two weeks of testing, the project membrane permeability was on average 20 percent greater than the standard membrane. This result illustrates the potential of the project membrane to be more resistant to fouling, operate at lower energy demand, and/or a reduced chemical cleaning frequency. During the latter half of the testing period, this performance difference disappeared, indicating that the project UF was no more resistant to fouling than the standard UF during that period. One potential reason for this dramatic shift may be the decrease in feed water turbidity that occurred around the same time, resulting in a water with lower fouling potential. It is possible that during treatment of less challenging water, the fouling resistant benefits of the project UF may not evident or needed.

6.4.3 Water Recovery

The water recovery (that is water yield) for both membranes was fixed at 86.7 percent during the steady-state period, operated at a water flux of 42.4 LMH (25 GFD). Because no relative improvement in treatment performance was observed for the project UF as compared with the standard UF module after completion of steady-state pilot test, the ability of the project UF module to run at higher recoveries than the standard UF was not evaluated for the backwash water. Given the similar performance of both membranes, no increased water yield with the project membrane could be demonstrated.

6.5 Performance Recovery and Cleaning Optimization

Assessments of backwash and chemical enhanced backwash efficiency were performed during pilot testing of backwash water, as was CIP effectiveness.

6.5.1 Backwash and Chemically Enhanced Backwash Efficiency

Both membranes exhibited similar performance recoveries following backwash or chemically enhanced backwash. The performance recoveries (as measured by membrane permeability, or flux per unit pressure) following backwashes were 100.3 ± 3.3 percent and 99.7 ± 1.8 percent for the project and standard UF membranes, respectively. Similarly, performance recoveries following the daily CEB were 99.7 ± 3.5 percent and 100.3 ± 4.7 percent for the project and standard UF membranes, respectively. Routine cleaning (that is that performed at a frequency of daily or higher) performance of the two membranes indicates that the project membrane did not provide noticeably better flux recovery than the standard UF membrane.

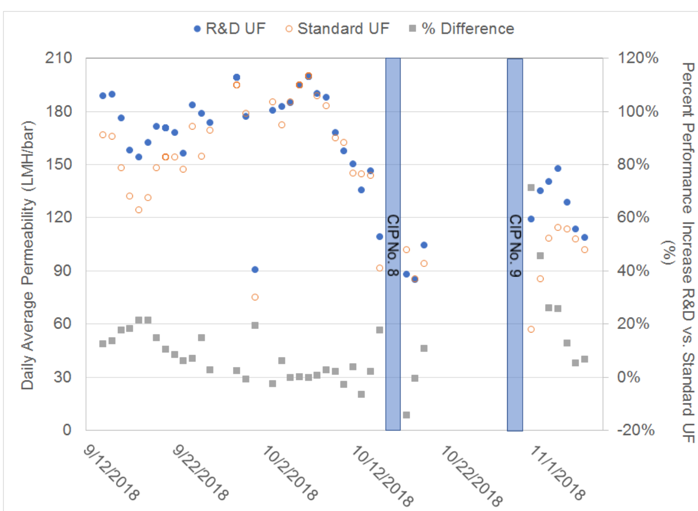
6.5.2 Clean-In-Place Effectiveness and Impact on Membrane Operation

After operating the pilot at a sustained flux setting of 42.4 LMH (25 GFD) for a period of five weeks, the overall permeability (specific flux) of both membranes had declined. project UF permeability declined 41 percent from an average of 182 LMH/bar (7.3 GFD/psi) to 108 LMH/bar (4.3 GFD/psi), while the standard UF permeability declined 47 percent from 172 LMH/bar (6.9 GFD/psi) to 91 LMH/bar (3.6 GFD/psi).

CIP No. 8 was performed on October 17, 2018. No performance recovery was observed following this CIP, nor was there any difference in the relative recovery of the two UF modules. After a short pilot shutdown to repair the chemical dosing system (the effectiveness of CIP No. 8 was not affected by this malfunction), CIP No.9 was performed on October 29, 2018. The procedure of CIP No. 9 was identical to that of CIP No. 8. Figure 27 illustrates the individual membrane permeabilities and relative performance (percent differences) of the membranes before and after CIPs No. 8 and No. 9.

CIP No. 9 resulted in a significant recovery in permeabilities of both UF modules, but not to levels observed at the start of steady-state treatment of backwash water. In addition, the relative performance of the modules was dramatically different than that observed just prior to and just after CIP No. 8, with the project UF module again exhibiting better performance than the standard UF module. The permeabilities of both modules were significantly higher than the observed performances at the end of the backwash water steady-state tests. The permeabilities of the project UF module after CIP No. 9 ranged from 108 LMH/bar (4.3 GFD/psi) to 148 LMH/bar (5.9 GFD/psi), while those of the standard UF module ranged between 56 LMH/bar (2.2 GFD/psi) and 114 LMH/bar (4.6 GFD/psi). The recovery of the project UF permeability was greater than that of the standard UF, resulting in relative performance increases of as high as 71 percent. Gradually the performance of the standard UF increased to match that of the project UF and by the seventh day of testing after CIP No. 9, the relative performance improvement of the project UF had decreased to approximately 5 percent.

Figure 27: Impact of CIP on Daily Average Permeability and Relative Performance During Treatment of Backwash Water



Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

Source: Kennedy/Jenks Consultants

Because CIPs were always performed on both membranes at the same time, to extrapolate how differences in the rate of specific flux (permeability) decline and CIP effectiveness would impact the operational factors such as chemical cleaning costs and membrane operation lifetime, several parameters were evaluated related to these issues and are summarized in Table 10.

Table 10: Membrane Cleaning Performance Parameters for Backwash Water

Parameter	Units	Project UF	Standard UF
Rate of TMP Increase [(a)]	bar/day	0.0066	0.0066
Initial TMP	bar	0.3	0.3
Max. TMP	bar	0.35	0.35
Allowable TMP Increase	bar	0.05	0.05
Time between CIPs	days	8	8
CIP frequency [(b)]	#/year	45.2	45.2
Improvement in CIP Frequency	%	0.0%	--
CIP Recovery [(c)]	%	70.0%	57.0%
Improvement in CIP Effectiveness	%	22.8%	--

Conversion: 1 bar is equivalent to 14.50377 psi.

(a) Rate of TMP increase was calculated based on the actual runtime of the membranes and not the calendar date (that is any times when the pilot was not operational have been excluded from this calculation).

(b) Based on a minimum permeability of 120 LMH/bar (4.9 GFD/psi) and a flux of 42.4 LMH (25.1 GFD)

(c) Based on a comparison of membrane permeabilities observed at the start of steady state testing (that is before with those observed after completion of CIP No. 9.

Source: Kennedy/Jenks Consultants

The quality of the backwash water (particularly turbidity) varied significantly during testing. This resulted in more erratic TMP trends than was observed during testing with other water sources. No clear increase in TMP was observed for the standard UF or the project UF. Only data from October 2017 was used to establish an estimate of cleaning frequency, as this period corresponded to a time when the feed water turbidity was relatively stable and the rate of TMP increase for both membranes was more or less linear (see Figures 20 and 24). Because this analysis neglected earlier TMP data when the performance of project UF was better than that of the standard, it is anticipated that these estimates of CIP cleaning frequency will conservatively underestimate the performance of the project membrane. For this water source, the rate of TMP increase and the initial TMP for the project membrane were identical for the project and the standard membrane, resulting in the same estimate of CIP frequency of 45.2 per year for both the project and Standard UF, respectively.

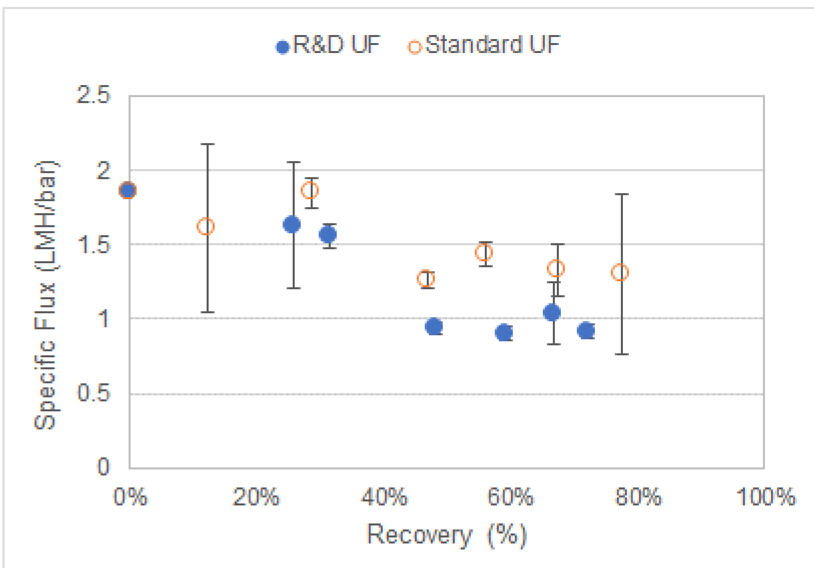
As evident in Figure 27, following CIP No. 9, both membrane modules exhibited incomplete recovery of permeability performance. Taking the average of permeability observed after CIP No. 9 and comparing to the initial permeability (as noted in section 6.5.2) for each membrane, CIP performance recoveries of 70 percent and 57 percent were calculated for the project UF and standard UF, respectively. This represented a moderate (22.8 percent) improvement in the CIP effectiveness of project UF membrane as compared to the standard UF membrane. CIP effectiveness determines the build-up of irreversible fouling on the membrane surface. Poor CIP effectiveness indicates that irreversible fouling will accumulate quickly and shorted the operating lifetime of the membrane. Conversely, good CIP effectiveness will extend membrane lifetimes (with the caveat that any damage caused to the membrane by CIP chemicals could act to shorten operating life).

6.6 Results of Bench-Scale RO Testing

The relative effectiveness of each UF membrane as a pre-treatment for RO was assessed using backwash water as the feed water. The specific flux (permeability) decline of each RO membrane test cell was measured in duplicate for each UF module at varying RO water recoveries. Figure 28 provides the results of these tests.

The two UF membranes were similarly effective as pretreatment for RO. Considering the relative error of the duplicate measurements for each UF line, there was no significant difference between either membrane at the range of water recoveries tested (from 0 percent up to approximately 80 percent). This result suggested that there is little difference between the two membranes effectiveness for removal of water constituents that can pass through the UF membrane and foul downstream processes. This is consistent with the total organic carbon and SUVA-254 results presented in Figure 24, where no difference was observed for levels of these two parameters in the UF filtrates. Similarly, the near identical filtrate turbidity results presented in Figure 23 also supports the conclusion that the two UF membranes were similarly effective as a pretreatment process for RO.

Figure 28: Reverse Osmosis Specific Flux Decline with Project Ultrafiltration and Standard Ultrafiltration Pretreatment



Conversion: 1 LMH/bar is equivalent to 0.04 GFD/psi.

Source: Kennedy/Jenks Consultants

6.7 Summary

The relative performance of the two UF membranes varied during treatment of backwash water. The changes in performance appeared to correlate with water quality changes in this challenging wastewater matrix.

During the first two weeks of steady state testing, the project UF membrane exhibited membrane permeability higher than those of the standard UF membrane, the difference ranging between two percent and 21 percent, with an average of 10 percent. This initial performance result illustrated the potential of the project membrane to be more resistant to fouling, operate at lower energy demand, and/or a reduced chemical cleaning frequency than the standard membrane. During the latter half of the testing period, however, this difference disappeared and no difference in membrane permeabilities was observed, indicating that the project UF membrane was no more resistant to longer-term fouling than the standard UF membrane. One possible reason for this dramatic shift may have been the decrease in feed water turbidity, resulting in a water with lower fouling potential. It is possible that during treatment of less challenging water, the fouling resistant benefits of the project UF may not be evident or needed.

The rate of TMP increase, the water yield and the estimated cleaning frequency of both membranes were very similar. Although little performance benefit was observed in these parameters, the performance recovery of the project UF module after a CIP was better than that of the standard UF module, representing a 23 percent improvement in cleaning efficiency.

When the filtrate produced by each UF membrane was in turn used as the feed water to two bench-scale reverse osmosis (RO) membrane test cells, no RO performance improvement by use of the project membrane was observed. This result was consistent with trends in filtrate water quality previously observed during this pilot testing. During earlier testing of settled water, organic-spiked water as well as backwash water, levels of foulants or foulant surrogates (that is turbidity, total organic carbon and specific ultraviolet absorbance at 254 nm [SUVA-254]) in the filtrate water produced by both UF membranes were consistently similar. If the filtrate water produced by the two UF membranes were the same, then there would be little anticipated benefit on downstream processes.

CHAPTER 7: Membrane Characterization

Chapter 7 presents and discusses the results of autopsies (characterization) of the tested membranes.

7.1 Testing Program

Autopsies were performed on sample fibers taken from the original project and standard UF membranes removed from service in June 2018. The following characterization tests were performed on selected fibers:

- Scanning electron microscopy (SEM): A beam of electrons scans a sample surface to provide information about the topography of the sample at very small scales (low millimeter to low micrometer range).
- Energy dispersive X-ray spectroscopy (EDX): X-rays penetrate the sample down to a depth of one to several micrometers, providing information on elemental composition of surface foulants and the underlying bulk membrane.
- X-ray photoelectron spectroscopy (XPS): X-rays penetrate the sample surface by a few nanometers, providing information on the chemical nature and elemental composition of the sample surface only.
- Photon nuclear magnetic resonance (^{1}H-NMR): An external magnetic field orients the nuclear spins of organic compounds to characterize the nature, relative location, and concentration of chemical functional groups (specifically, PSU and polysiloxane) in the membrane fiber samples.

The membranes had been in operation, treating settled water, for approximately 2 months since the previous clean-in-place operation prior to being removed. Although the membranes received regular backwashes and daily chemically enhanced backwashes during this operating period, the membrane fibers would likely contain residual foulants that might have been removed by CIP operations.

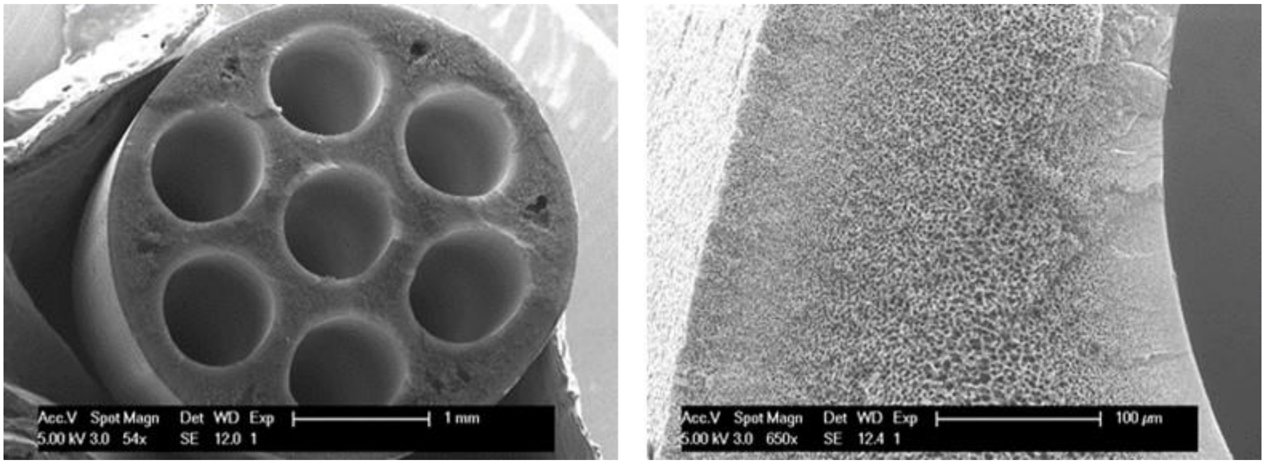
7.2 Results

The following sections present and discuss the results of examining selected fibers taken the aged standard and project membranes.

7.2.1 General Condition

Figure 29 provides examples of low-resolution (long length-scale) SEM images collected during this study. The seven capillaries present in each fiber bundle are visible at millimeter-scale resolution (left panel). At higher resolution (100 micrometer-scale) the distribution of membrane pores is visible, with larger, water-transporting pores present in the support layer and smaller, particle-rejecting pores present at and just below the membrane active layer (right panel of Figure 29).

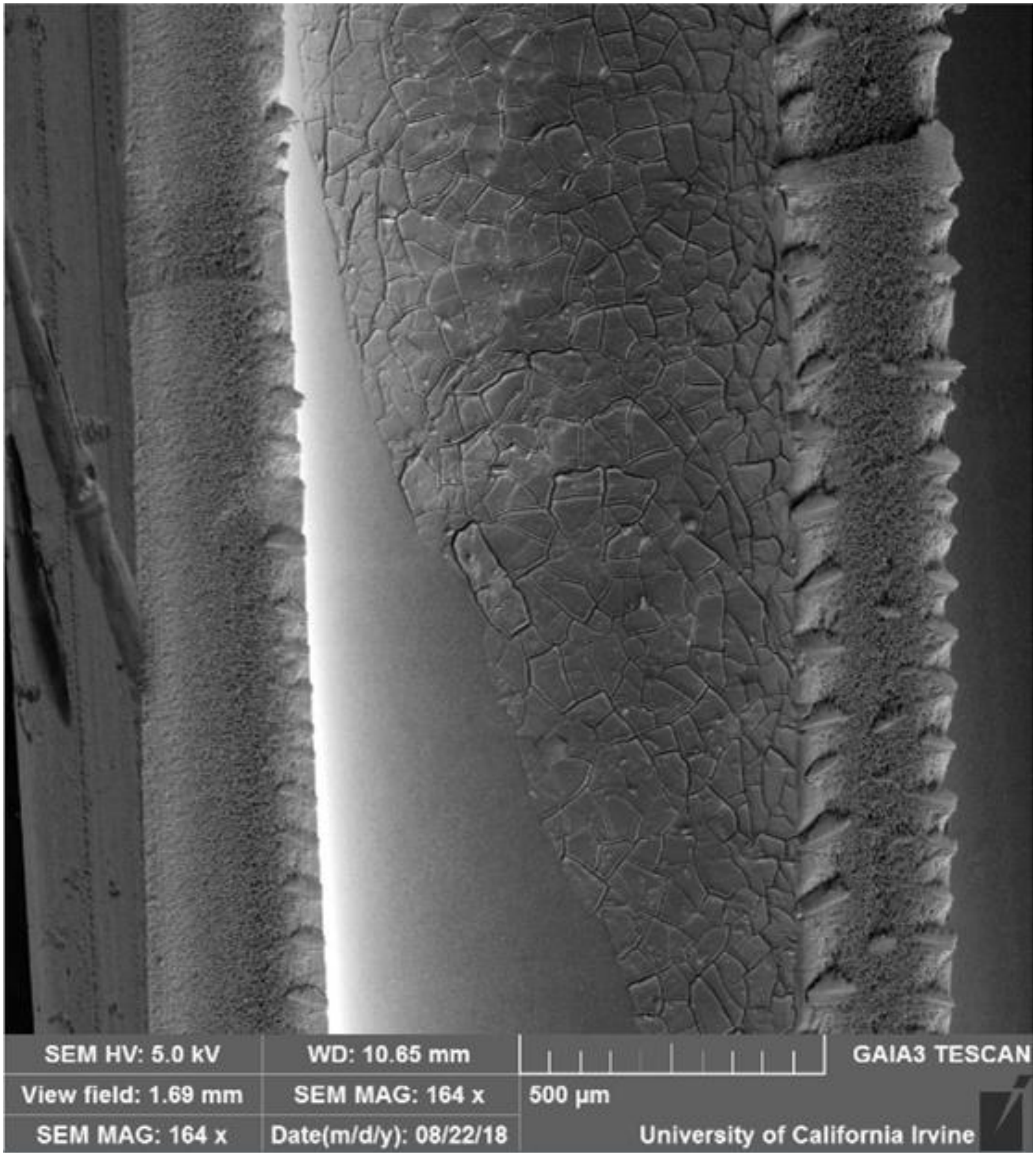
Figure 29: SEM Image of Membrane Fiber (Left) and Close Up of Pore Structure (Right)



Source: Kennedy/Jenks Consultants

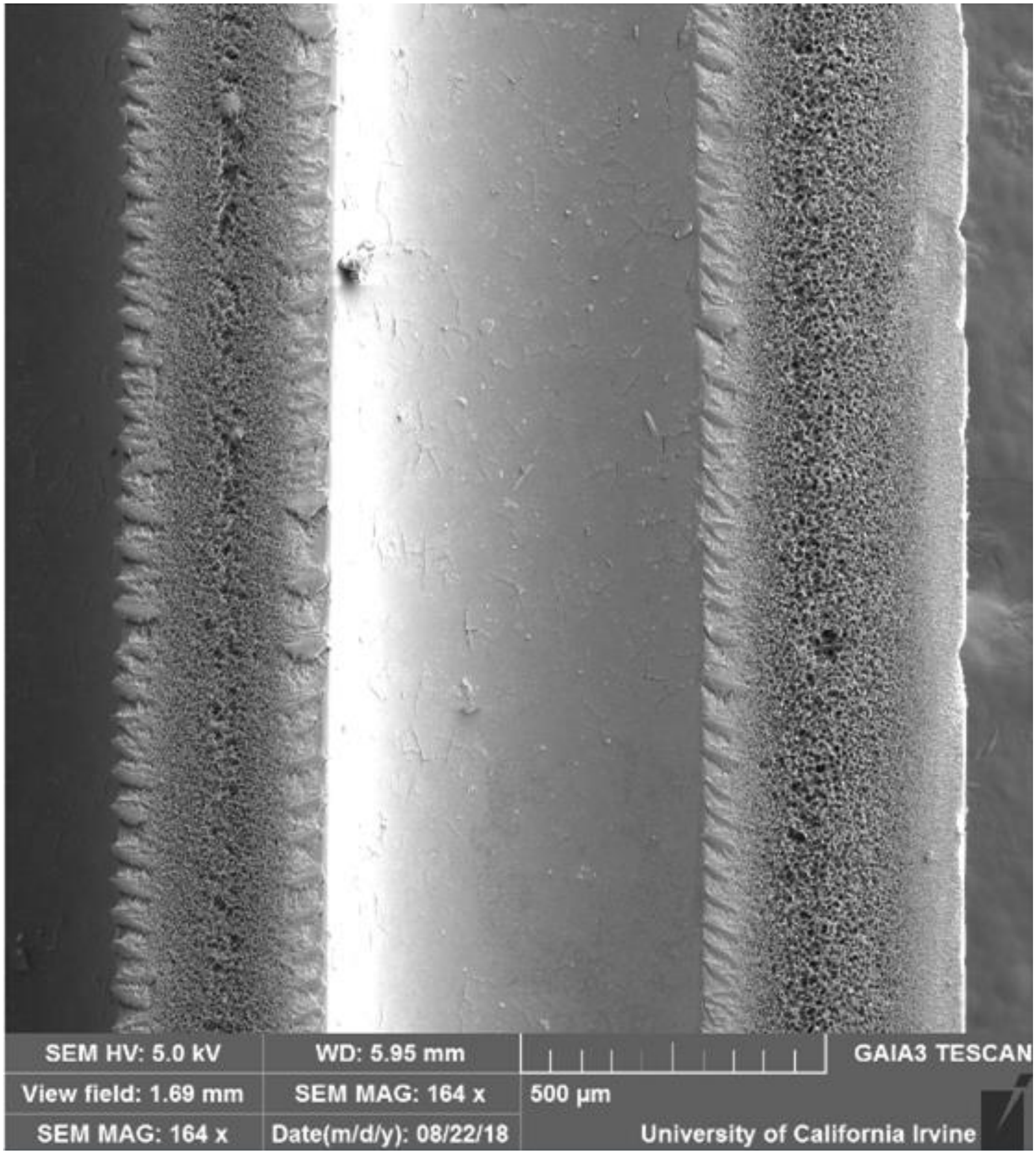
Figure 30 provides a large-scale SEM scan for an project membrane fiber, which shows both clean areas and other areas covered with particularly bad fouling. However, two other project fiber lumens (inside of capillaries) examined had no visible fouling. In contrast, Figure 31 shows the standard membrane fibers were more consistently fouled with a relatively thin-looking fouling layer that gave the membrane surface an uneven texture with small crystalline deposits.

Figure 30: SEM Scan of Longitudinal Cross-Section of Aged Project Membrane Fiber



Source: Kennedy/Jenks Consultants

Figure 31: SEM Scan of Longitudinal Cross-Section of Aged Standard Ultrafiltration Membrane Fiber



Source: Kennedy/Jenks Consultants

7.2.2. Membrane Fouling

Scanning electron microscopy combined with energy dispersive X-ray spectroscopy (SEM-EDX) and XPS were used to characterize surface foulants and the underlying membrane polymers.

7.2.2.1 Mineral Fouling

The EDX spectra provided information on the extent of aluminum and silica fouling on both the project and the standard UF membranes. The results show differences in how mineral foulants were distributed on the membranes.

EDX spectra were collected at four locations on the project fiber examined. Table 11 and Table 12 summarize these results. Location Nos. 1 and 2 are characterized by high carbon and sulfur content, but low oxygen, aluminum and silicon content. The other two (Location Nos. 3 and 4) are characterized by low carbon and sulfur content, but high oxygen, aluminum, and silicon content. Figure 32 provides example SEM electron image and elemental intensity images for two of these locations (Nos. 1 and 3).

Table 11: EDX Results for Project Membrane Surface Atomic (%)

Element	No. 1	No. 2	No. 3	No. 4
C	78.7	76.22	32.6	28.1
O	16.5	18.56	50.9	47.5
S	4.0	4.27	1.0	1.2
Al	0.6	0.44	14	19.3
Si	0.3	0.52	1.5	3.9
Cl	--	--	--	--

Source: Kennedy/Jenks Consultants

Table 12: EDX Results for Project Membrane Surface Atomic Ratios

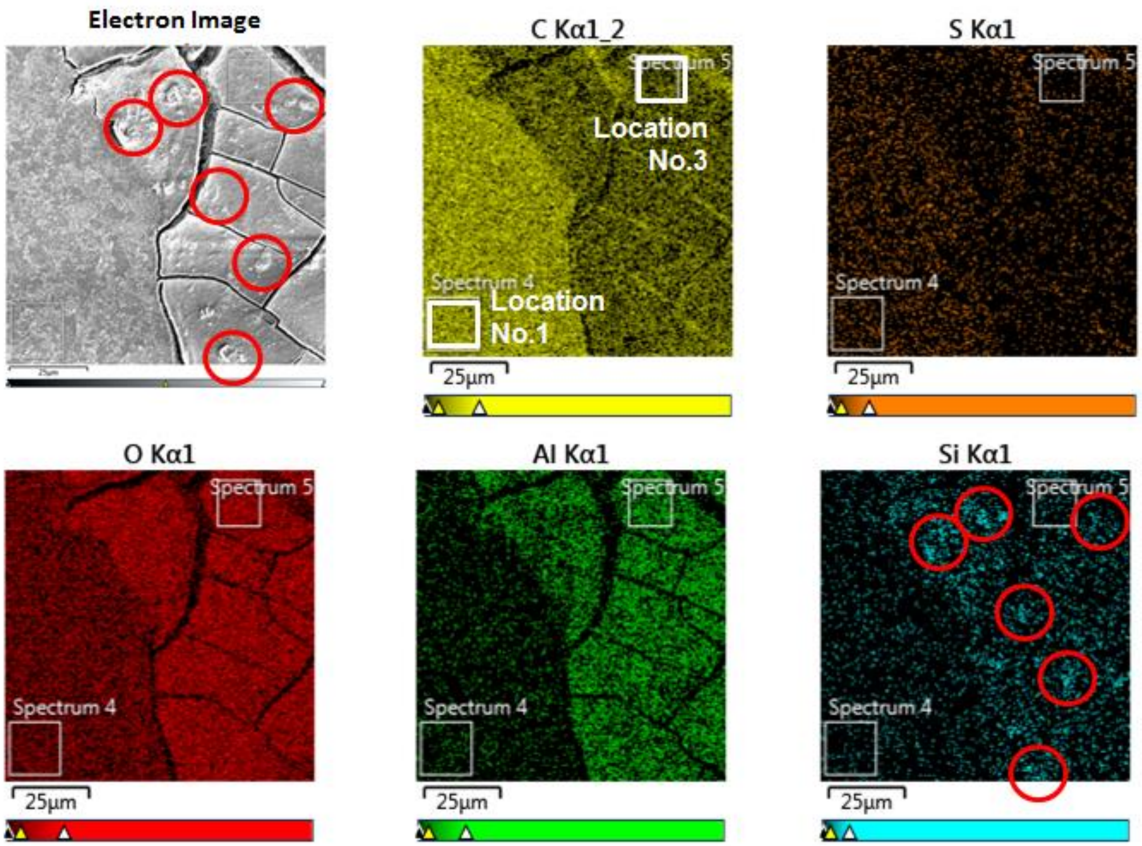
Element	No. 1	No. 2	No. 3	No. 4
C:S	19.7	17.9	32.6	23.4
O:S	4.1	4.3	50.9	39.6
C:O	4.8	4.1	0.6	0.6
O:Al	27.5	42.2	3.6	2.5
S:Si	13.3	8.2	0.7	0.3
Al:SI	2.0	0.84	9.3	4.9

Source: Kennedy/Jenks Consultants

The left side of the electron image in Figure 32 displays the relatively clean-looking lumen of the membrane fiber. This area is characterized by high carbon and sulfur content. In contrast, the scaled, cracked-looking portion on the right side of the electron image is characterized by lower carbon and sulfur content, but higher oxygen and aluminum content. Silicon intensity was also higher in this region; however, areas of higher silicon intensity occurred at specific locations rather than being evenly dispersed throughout the region (as was observed for aluminum and oxygen). Numerous red circles overlaying the electron image and the silicon intensity image demonstrate that many silica "hot spots" correspond to crystalline features visible in the electron image. Closer inspection of the electron image suggests that these are silica colloids that deposited on the membrane surface.

These results suggest that the fouled, cracked looking portions of the longitudinal fiber cross section visible in Figure 30 are the result of aluminum fouling. Closer inspection of Figure 30 also revealed that the crystalline deposits identified as silica are almost entirely co-located with aluminum fouling and rarely occurred in the cleaner portions of the fiber electron images. Note that the aluminum (Al)-to silicon (Si) ratio in the cleaner portion is 2.0, which is suggestive of colloidal clays.

Figure 32: SEM and EDX Element Intensity Plots for Project Membrane (Location Nos. 1 and 3)



Images Clockwise from Upper Left: SEM Electron Image, Carbon Intensity, Sulfur Intensity, Silica Intensity, Aluminum Intensity, and Oxygen Intensity. Specific location of spectra collection locations No. 1 and No. 3 are highlighted in the Carbon Intensity image plate. Red circles highlight some examples of silica colloids deposited in the membrane surface, as discussed in the accompanying text.

Source: Kennedy/Jenks Consultants

Table 13 provides a summary of the EDX spectra for five selected sampling locations on the standard membrane fiber. The locations are numbered in order of increasing atomic percent of aluminum. Figure 33 provides SEM electron image and elemental intensity images for two of these locations (Nos. 5 and 9), while Figure 34 provides those for location No. 7.

As was observed in the SEM-EDX electron image for the project fiber (Figure 32), areas of higher aluminum and oxygen intensity are associated with lower carbon intensity and vice versa. Figure 33, like Figure 34, also exhibits clear regions of higher carbon intensity (left side) and clear regions of higher aluminum and oxygen intensity (right side). The right side of the electron image of Figure 33 also has a more cracked, fouled appearance, but is not as extreme as that observed in Figure 32. In contrast, although there are areas of higher carbon or aluminum visible in the elemental intensity images of Figure 34, this location does not display visible areas of fouling, but instead displays the bumpier uneven appearance observed in the larger SEM image for the standard membrane fibers (Figure 31).

The Al:Si ratio ranged from 4.0 to 7.0, indicating a broader coverage of aluminum content on the standard membrane surface than generally observed on the project UF membrane (Table 11). However, the highest aluminum level observed on the standard membrane (9.1 percent) did not reach the higher aluminum levels of some areas of the project fiber (14 to 19.3 percent). This suggests that while there were no areas of extreme aluminum fouling on the standard UF membrane surface, on average the aluminum fouling on the standard membrane was more ubiquitous than on the project membrane. As observed for the project fiber, silica fouling on the standard membrane appears to be mainly associated with specific crystalline features in the SEM electron image and is likely due to colloid deposition.

The XPS results provided additional information on aluminum and silica fouling as well as fouling by calcium, manganese, and chloride. Table 14 summarizes the XPS elemental weight percentage results of the aged project and standard membranes. For comparison, the XPS results of a virgin project fiber are also presented. The virgin project fiber indicate the presence of sulfur, nitrogen, and silicon, which are all present in either the PES base polymer or the PSU-PEO-polysiloxane additive, but none of the other reported elements associated with mineral fouling (calcium, manganese, aluminum, or chloride).

Foulants were present on the surface of both the project and standard UF fibers, which result in lower weight percentages of sulfur and nitrogen on the aged fiber surfaces relative to the virgin project fiber. The S:N ratios for the virgin and aged project fibers were similar, suggesting that blinding of these elements by surface foulants is responsible for the reduced weight percentages of these elements in the aged fibers. The aluminum content on the standard membranes is higher than on the project membrane and the Al:Si ratios are also higher. These observations are consistent with previous observations with EDX.

The weight percent of silica on the aged project fibers was higher than the virgin fiber, even with the presence of other mineral foulants that act to dilute the relative contribution of this element to the total, indicating that silica fouling had occurred. In the aged project fiber the S:Si ratio was dramatically lower than the new fiber (2 as compared to 7), even though the weight percent of silicon in the aged fibers was slightly higher than in the new fiber. This is most probably due to blinding of the sulfur signal by surface foulants, as well as increased deposition of silica due to fouling. Significant silica presence was detected on the aged standard membrane fibers. This is solely due to silica fouling.

Calcium, manganese, and chloride scaling is often associated with chemical cleaning of membranes with alkaline solutions. The calcium and manganese percentages are similar for both the project and standard aged membranes, while lower chloride levels were detected on the standard UF membrane compared with the project UF membrane. Interestingly, during SEM-EDX analyses, chloride was only detected on the standard membrane (see Tables 11-14).

7.2.2.2 Organic Fouling

Carbon (C) and sulfur (S) in the samples can be attributed either to the membrane polymers themselves or, in the case of carbon, to organic fouling as well. An increase in the C:S atomic ratio can be attributed to organic fouling (Rabiller-Baudry, Gouttefangeas, Le Lannic, & Rabiller, 2012). However, without knowledge of the exact copolymer formulas or relative composition and without virgin fibers for comparison, it was not possible to determine a baseline C:S for comparison; however, if the membrane surface was purely PES or PSU, the C:S would be in the range of 12 to 27. For the project membrane fiber, the C:S ratios for location Nos. 1 and 2 fell within this range, while those for locations Nos. 3 and 4 are on the upper end or exceeded this range. This suggests that organic fouling as well as mineral fouling may be present at these latter locations.

The standard UF membrane is made up of modified PES (BASF, 2016). Without knowledge of the chemical nature of these modifications, it is not possible to state whether the observed C:S ratios for the aged fibers indicate widespread organic fouling or increased organic fouling relative to the project membrane. However, there was significant variation in the C:S ratio depending on the location sampled (with ratios ranging from 24 up to 48, Table 9). This suggests that areas of the membrane had increased carbon deposition relative to the underlying membrane polymers.

Table 13: EDX Results for Standard Membrane Surface Atomic (%)

Element	No. 5	No. 6	No. 7	No. 8	No. 9
C	78.8	63.7	58.7	68.0	39.5
O	16.4	29.3	34.4	24.4	48.2
S	3.1	2.1	1.2	2.8	--
Al	1.4	2.4	3.7	4.2	9.1
Si	0.2	0.6	0.6	0.6	2.2
Cl	0.8	1.3	1.1	--	--

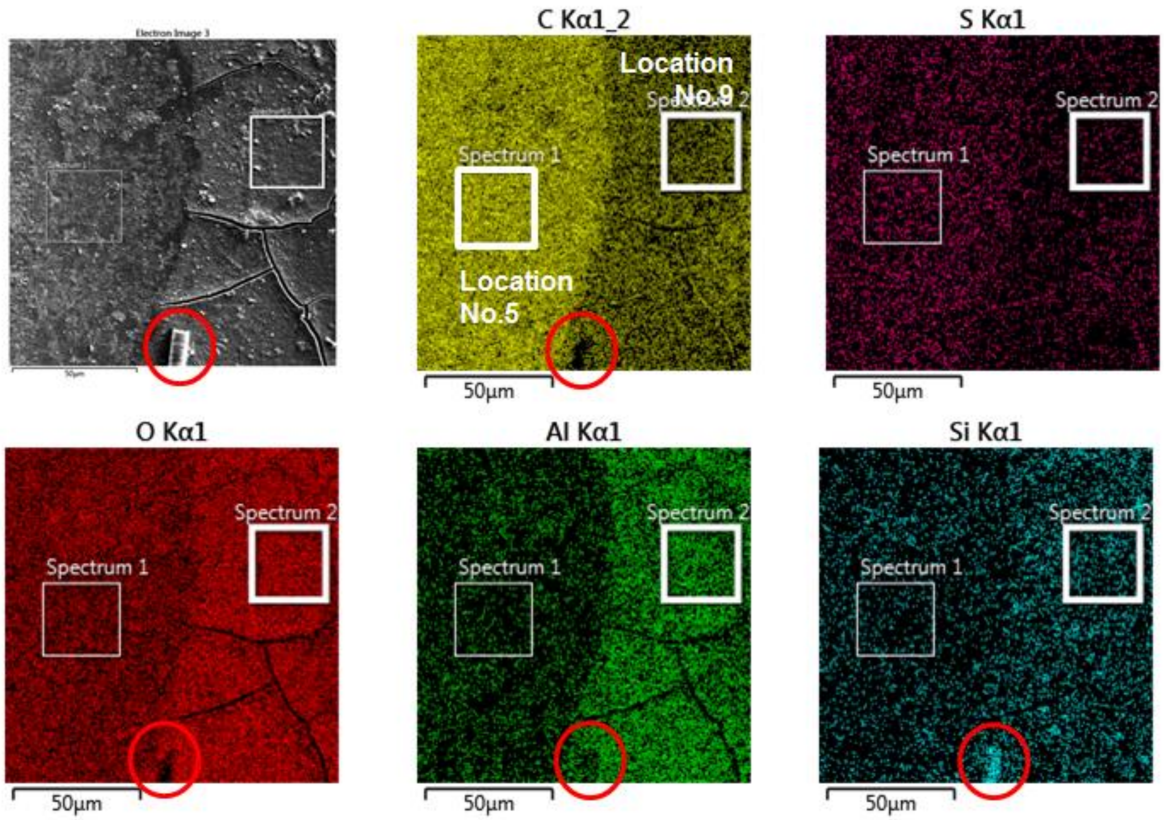
Source: Kennedy/Jenks Consultants

Table 14: EDX Results for Standard Membrane Surface Atomic Ratios

Element	No. 5	No. 6	No. 7	No. 8	No. 9
C:S	25.4	30.1	47.7	24.3	--
O:S	5.3	13.8	28.0	8.7	--
C:O	4.8	2.2	1.7	2.8	0.8
O:Al	11.7	12.1	9.4	5.8	5.3
S:Si	15.5	3.3	2.1	4.7	--
Al:Si	7.0	4.0	6.1	7.0	4.1

Source: Kennedy/Jenks Consultants

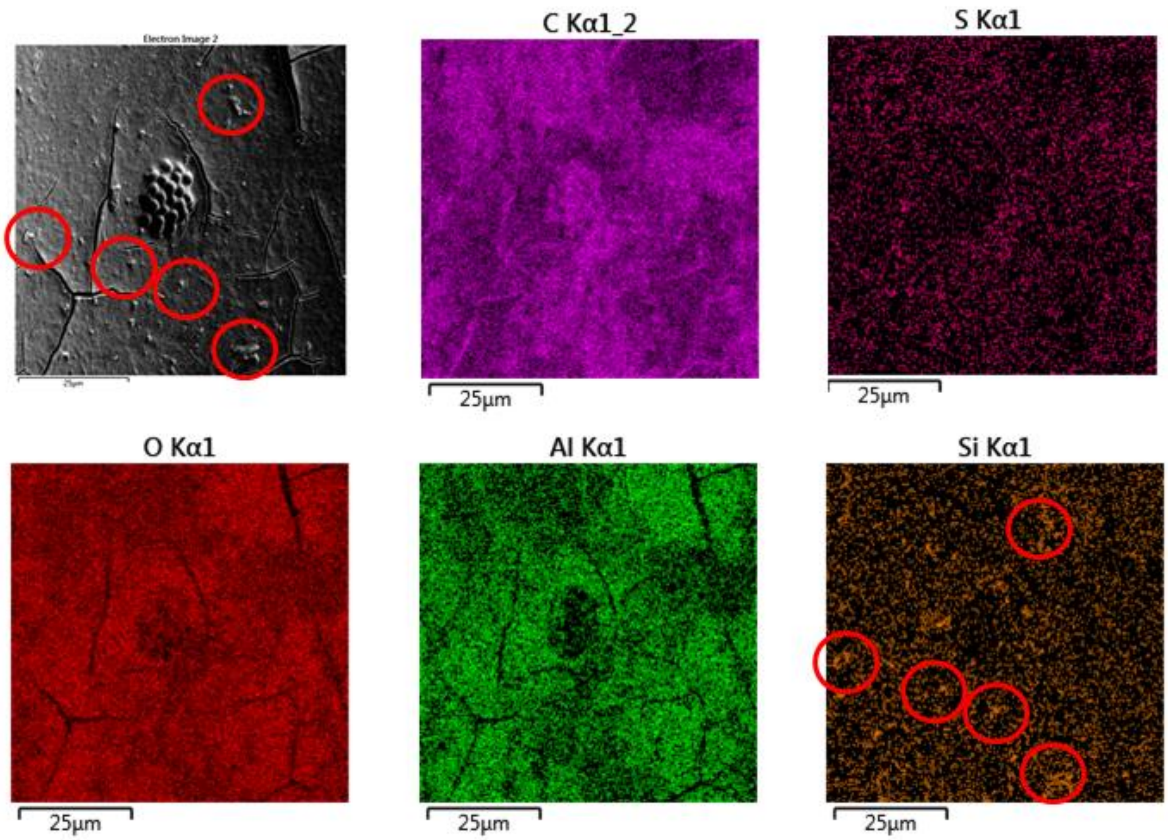
Figure 33: SEM and EDX Element Intensity Plots for Standard Membrane (Location Nos. 5 and 9)



Images Clockwise from Upper Left: SEM Electron Image, Carbon Intensity, Sulfur Intensity, Silica Intensity, Aluminum Intensity, and Oxygen Intensity. Specific location of spectra collection locations No. 5 and No. 9 are highlighted in the Carbon Intensity image plate. Red circle refers to a silica crystal deposited on the membrane surface.

Source: Kennedy/Jenks Consultants

Figure 34: SEM and EDX Element Intensity Plots for Standard Membrane (Location No. 7)



Images Clockwise from Upper Left: SEM Electron Image, Carbon Intensity, Sulfur Intensity, Silica Intensity, Aluminum Intensity, and Oxygen Intensity. Red circles highlight some examples of silica colloids deposited in the membrane surface.

Source: Kennedy/Jenks Consultants

Table 15: Membrane Characterization XPS Results (% By Weight)

Sample	S	N	Si	Ca	Mn	Al	Cl	S:N	S:Si	Al:Si
New Project UF	11.2	2.8	1.6	--	--	--	--	4.0	7.0	--
Aged Project UF	5.5	1.0	2.5	0.9	3.2	2.6	1.8	5.5	2.2	1.1
Aged Project UF	4.3	1.4	1.8	0.8	1.8	4.0	1.2	3.1	2.4	2.2
Aged std. UF	3.4	1.3	1.2	0.8	2.0	7.6	0.8	2.6	2.8	6.3
Aged std. UF	4.6	1.1	1.2	0.7	1.4	6.7	0.8	4.2	3.8	5.6

Source: Kennedy/Jenks Consultants

7.2.3 Project Membrane Stability

Proton NMR is used to characterize the organic chemical moieties present in the bulk membrane and their locations relative to each other the polymer molecules. For this project, NMR was used to determine the relative content of PSU and siloxane copolymers. Table 16 summarizes the proton NMR results for the aged membranes. For comparison, results for a virgin project fiber are also presented.

The virgin project fiber contained similar weight percentages of PSU and siloxane copolymers (3.9 and 3.8 percent, respectively). The PSU signal remained constant in both the new and aged project fiber, indicating this function group was intact in the aged fibers. The signal for the methyl group of the dimethylsiloxane functional group of the PSU -PEO -polysiloxane additive had completely disappeared in the aged project fiber. Siloxanes may be hydrolyzed under extremely acidic or alkaline conditions such as the chemically enhanced backwash and the clean-in-place operations used during pilot testing. Thus, hydrolyzation or some other chemical modification of the polysiloxane group in the project fiber is the most likely explanation for loss of this NMR signal in the aged fibers. This suggests that at some point during pilot testing, the membranes were exposed to chemical conditions that degraded the surface modifying groups of the project fiber. The destruction of polysiloxane moieties on the project membrane surface could potentially explain the change in relative performance of the project and standard UF modules observed after completion of CIP No. 3 during pilot testing of settled water (see chapter 4). That clean-in-place operation involved an extended overnight soaking in an acid solution.

There were no NMR signals for either PSU or siloxane in the standard fiber because this membrane is made of only PES and does not contain either of these copolymers.

Table 16: Membrane Characterization ^{1}H-NMR Results

Sample	PSU (% By Weight)	Siloxane (% By Weight)
New Project UF	3.9	3.8
Aged Project UF	3.9	0
Aged Project UF	4.0	0
Aged std. UF	0	0
Aged std. UF	0	0

Source: Kennedy/Jenks Consultants

7.6 Findings and Conclusions

7.6.1 Foulants

Both the project and UF membrane fibers exhibited evidence of mineral fouling. Most of this fouling was due to aluminum and silica, although evidence of calcium and manganese fouling, most likely as calcium carbonate and manganese dioxide, was also suggested. The most likely source aluminum foulants is the polyaluminum chloride coagulant used at Cal Water water’s treatment plant that forms aluminum hydroxide flocs. This coagulant is used to flocculate the raw water and residual aluminum was sometimes detected in the three source waters used for the pilot study. Naturally occurring silica was present in the pilot feed water, some of it possibly as colloidal silica or as an aluminosilicate clay.

EDX and XPS results suggest that aluminum is the major foulant on both the project and standard UF membrane. Spatially differentiated SEM-EDX results indicate that the project UF membrane fiber is susceptible to very significant levels of aluminum fouling, but this fouling is limited to only some areas of the fiber. Elsewhere aluminum levels are very low. In contrast, the standard UF membrane fibers were coated in lower aluminum concentrations, but fouling is spread more evenly across the membrane surface. These results were consistent with XPS results that found that although both fibers have evidence of aluminum fouling, the extent of aluminum fouling is higher on the standard UF membrane.

The second most prominent foulant was silica. From SEM-EDX results, silica fouling occurred due to colloidal deposition or, potentially due to growth of small crystals on the membrane surface. The extent of silica fouling was much lower than that of aluminum fouling. Interestingly, on the project fiber, silica deposits were mainly limited to areas with extensive aluminum fouling, suggesting the presence of colloidal clays. In contrast, although silica deposits were also found in areas of high aluminum fouling, as with aluminum fouling, they also occur more generally across the membrane surface of the standard membrane fiber.

These results suggest that, although the project membrane was not able to completely resist mineral foulant deposition, this fouling tended to occur in patches on the membrane surface, in contrast to the standard membrane where fouling was more widespread. This spatial difference in foulant deposition on the membrane surface is supportive of the initial study hypothesis that the presence of the PSU-PEO-polysiloxane additive in the project membrane significantly impacts the fouling behavior of this membrane relative to that of the standard PES membrane, at least with respect to mineral foulants. Insufficient information is available to assess if similar behavior occurred with organic foulants.

Heijnen et al. (2015), studying an earlier prototype of the project UF membrane, previously found that addition of the PSU-PEO-polysiloxane additive resulted in new structural features on the membrane surface. These researchers detected circular dots with diameters of 0.2 to 0.8 micrometer with atomic force microscopy (AFM) at relatively high densities across the modified membrane surface, but not on the reference PES membrane (Figure 2). It is possible that surface morphology differences, and not just differences in the chemical composition of the membrane surface, impact the fouling behavior of the project membrane.

Regardless of mechanism, the presence of the PSU-PEO-polysiloxane additive may have disrupted the development or adherence of foulant gel layers on the membrane surface. The observed differences in membrane surface fouling could have potentially interesting implications for the cleaning efficiency and/or performance of the project membrane over longer time frames than were evaluated during this pilot study. Further study would be required to properly assess what kind economic benefits, if any, could potentially be realized by this difference in fouling behavior.

7.6.2 Membrane Stability

NMR results indicate that at some point during pilot testing, the membranes were exposed to chemical conditions, possibly during a clean-in-place operation, that degraded the surface modifying polysiloxane groups of the project fiber. If the polysiloxane moieties on the project membrane surface were destroyed, this could be a potential explanation for the change in relative performance of the project and standard UF modules observed after completion of CIP

No. 3 during pilot testing of settled water (see chapter 4). Whether it was an acute or long-term chemical exposure that degraded the surface modifying additive, more study is required to determine the chemical compatibility of the project UF membrane with common membrane cleaning chemicals as well as to determine whether existing manufacturer cleaning protocols are acceptable for the project membrane or whether an entirely new set of protocols need to be developed. Until the chemical stability of the novel UF membrane under typical operating conditions can be assured, the product is not ready for commercialization.

CHAPTER 8: Measurement and Verification

This chapter provides a summary of third-party measurement and verification of potential electrical energy savings performed by BASE Energy, Inc. (BASE) during the pilot study. The full measurement and verification report is available as an appendix to this report.

8.1 Introduction

BASE developed a detailed measurement and verification plan to determine the energy savings of the project UF amphiphilic, anti-adhesive membrane compared with standard UF membranes.

The pilot unit consisted of two parallel ultrafiltration trains, one equipped with Standard UF membrane and the other equipped with BASF's project UF membrane. Power logging of feed water pumps for both Standard UF and proposed UF membrane systems were taken in parallel for three (3) distinct water quality conditions, settled water, organic-spiked water and backwash water. These three distinct tests were scheduled to be performed for 4 months each. Data logging and trends were scheduled to be taken for a minimum of 2 months per test (that is per water quality).

The following outlines the measurement details performed during the testing period of July 1, 2017 to October 31, 2018.

BASE performed the following measurements:

- Current logging of the feed water pump #1 (project UF membrane)
- Current logging of the feed water pump #2 (Standard UF membrane)
- Current logging of the backwash pump
- Spot power measurement of the above equipment

The project team provided BASE with the following information:

- Project plans, piping and instrumentation (P&ID) line diagrams
- Design drawings of demonstration pilot unit with equipment specifications
- Pilot unit inlet water flow with the best available resolution for the duration of measurement
- Flow through each membrane module/filter for the duration of measurement
- Turbidity of the influent water for duration of the measurement
- Conductivity of the influent water for duration of the measurement
- pH level of the influent water for duration of the measurement
- Turbidity of the combined effluent for duration of the measurement
- Conductivity of the membrane backwash for duration of the measurement

BASE performed the following analyses based on the measurements collected:

- Obtained and analyzed pilot unit trend data to determine water flow through the Standard UF and project UF membranes for each water quality.
- Compared backwash pump power consumption between Standard UF and project UF membranes for each water quality
- Performed power measurements for feed pumps and backwash pumps
- Determined energy intensity (ratio of pump power draw to flow) for feed water pumps and backwash pumps for Standard UF and project UF membranes systems

8.2 Results

8.2.1 Filter Energy Consumption

The Standard UF and project UF membranes were tested for three water qualities. The specific power for each filter was calculated as follows:

Specific Power = (Average Feed Pump Power) / (Flowrate through Filter)

Tables 17-20 show the average feed pump and backwash pump flowrates through each of the filters as well as the average power measured from the main feed. The flowrate through the filter was measured for the same period and provided to BASE for analysis.

Table 17:Flowrate and Power of Pilot Filter Feedwater Pumps Module Set #1

UF Filter	**Average Feed Pump Flow Rate** (gpm)	**Average Feed Pump Power Draw** (kW)	**Specific Feed Pump Power** (kW/gpm)	**Feed Pump Project UF Energy Improvement** (%)
Pilot Test #1 – Surface Water				
Project UF Membrane (Line 1)	35.11	0.71	0.0046	**7.3%**
Standard UF Membrane (Line 2)	34.93	0.76	0.0050	**7.3%**
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
Project UF Membrane (Line 1)	15.93	0.18	0.0025	**7.7%**
Standard UF Membrane (Line 2)	15.89	0.19	0.0027	**7.7%**
Pilot Test #3 – Backwash water				
Backwash water was not tested during Pre Line 1 Failure Period [(a)]				

(a) A fiber breakage on Line1 (project module) occurred in April 2018. Both the project and Standard UF membrane module were replace in June 2018

Source: Kennedy/Jenks Consultants

Table 18:Flowrate and Power of Pilot Filter Feedwater Pumps Module Set #2

UF Filter	**Average Feed Pump Flow Rate** (gpm)	**Average Feed Pump Power Draw** (kW)	**Specific Feed Pump Power** (kW/gpm)	**Feed Pump Project UF Energy Improvement** (%)
Pilot Test #1 – Surface Water				
Project UF Membrane (Line 1)	36.00	0.68	0.0043	**10.0%**
Standard UF Membrane (Line 2)	36.01	0.76	0.0048	**10.0%**
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
Not enough data to analyze performance during Post Line 1 failure period [(a)]				
Pilot Test #3 – Backwash water				
Project UF Membrane (Line 1)	14.66	0.28	0.0044	**3.8%**
Standard UF Membrane (Line 2)	14.71	0.29	0.0045	**3.8%**

(b) A fiber breakage on Line1 (project module) occurred in April 2018. Both the project and Standard UF membrane module were replace in June 2018

Source: Kennedy/Jenks Consultants

Table 19: Flowrate and Power of Pilot Filter Backwash Pump Module Set #1

UF Filter	Average Backwash Pump Flow Rate (gpm)	Average Backwash Pump Power Draw (kW)	Specific Backwash Pump Power (kW/gpm)	Backwash Pump Project UF Energy Improvement (%)
Pilot Test #1 – Surface Water				
Project UF Membrane (Line 1)	67.89	3.42	0.0114	**8.6%**
Standard UF Membrane (Line 2)	67.27	3.71	0.0125	**8.6%**
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
Project UF Membrane (Line 1)	59.44	3.34	0.0128	**2.7%**
Standard UF Membrane (Line 2)	61.91	3.57	0.0131	**2.7%**
Pilot Test #3 – Backwash water				
Backwash water was not tested during Pre Line 1 Failure Period [(a)]				

(a) A fiber breakage on Line1 (project module) occurred in April 2018. Both the project and Standard UF membrane module were replace in June 2018

Source: Kennedy/Jenks Consultants

Table 20: Flowrate and Power of Pilot Filter Backwash Pump Module Set #2

UF Filter	Average Backwash Pump Flow Rate (gpm)	Average Backwash Pump Power Draw (kW)	Specific Backwash Pump Power (kW/gpm)	Backwash Pump Project UF Energy Improvement (%)
Pilot Test #1 – Surface Water				
Project UF Membrane (Line 1)	62.77	2.59	0.0094	**2.0%**
Standard UF Membrane (Line 2)	62.78	2.65	0.0096	**2.0%**
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
Not enough data to analyze performance during Post Line 1 failure period [(a)]				
Pilot Test #3 – Backwash water				
Project UF Membrane (Line 1)	58.21	3.54	0.0138	**7.7%**
Standard UF Membrane (Line 2)	57.77	3.81	0.0150	**7.7%**

(a) A fiber breakage on Line1 (project module) occurred in April 2018. Both the project and Standard UF membrane module were replace in June 2018

Source: Kennedy/Jenks Consultants

8.2.2 Comparison of Filter Energy Consumption

In the previous section, the average flow and power draw per filter type for a given water quality was presented. Of the two UF membrane filter types tested (Standard UF membrane and project UF membrane), the project UF membrane had the lowest energy consumption per average flow rate. Across all three water quality tests, the project UF feedwater pump showed better energy performance than the Standard UF feedwater pump. Additionally, the backwash frequency for each module was based on timer/schedule. The data shows that the backwash pumping energy consumption for the project unit was less than the Standard Unit most likely due to the less fouling of the project unit's membranes.

Table 21 shows the specific energy consumption for each filter type during the logged filtration periods. The specific energy consumption values for the UF pumps are presented in terms of kWh of electricity consumed per million gallons (MG) of treated water. The specific energy consumption values presented in Table 19 include the combined feed pump and backwash pump energy consumption for a given volume of treated water.

Based on the pilot unit's SCADA trends and logged pump data:

- For each UF membrane, the backwash pump runtime is 25 percent of the feed pump runtime
- In the case where the membrane filters are continuously operating, the feed pump runtime would be 80% and the backwash pump runtime would be 20 percent (25 percent of 80 percent).

The specific energy consumption values presented in Table 21 are based on these different pump runtimes as well as the pump performance data shown in Tables 17-20.

Table 21:- Specific Power per Water Quality Test

Standard UF Membrane (kWh/MG)	**Project UF Membrane** (kWh/MG)	**Standard UF Membrane** (kWh/MG)	**Project UF Membrane Energy Improvement**
Pilot Test #1 – Surface Water	449.6	415.6	7.6%
Pilot Test #2 – Surface Water with Organics Added	354.2	336.6	5.0%
Pilot Test #3 – Backwash water	487.7	460.6	5.6%

Source: Kennedy/Jenks Consultants

Table 22:- Specific Power per Filter Type

Filter	**Feedwater Pump Specific Energy Consumption‡** (kWh/MG)	**Backwash Pump Specific Energy Consumption‡** (kWh/MG)	**Overall Pumping Specific Energy Consumption‡** (kWh/MG)
Standard UF Membrane	249.4	185.8	435.3
Project UF membrane	231.5	175.6	407.1
Savings	**17.9 kWh/MG**	**10.3 kW/MG**	**28.2 kW/MG**
% Savings	**7.2%**	**5.5%**	**6.5%**

Based on average results for all test conditions

Source: Kennedy/Jenks Consultants

CHAPTER 9: Projected Benefits Evaluation

This chapter presents the benefits evaluation for substituting the project UF membrane for standard UF membranes in existing MF/UF treatment processes.

9.1 Approach and Assumptions

The projected benefits have been broken into four categories:

- Energy conservation
- Water savings
- Reduced chemical use
- Reduced membrane replacement cost

A survey by the American Membrane Technologies Association (AMTA) regarding membrane filtration plants in California[5] was used to extrapolate the performance data collected in this report in order to estimate the potential statewide benefits of substituting the project UF membrane for the standard UF membrane. Nearly 90 percent of the flow is treated by MF/UF systems with or without downstream RO treatment. Preliminary estimates indicate that, on a treatment volume-basis, approximately 51 percent of the membrane facilities is located in SCE service area, about 46 percent in PG&E service are and 1.5 percent in SDG&E service area. This estimate does not include energy conservation in industrial membrane processes or membrane bioreactors used in wastewater treatment. Additionally, this evaluation only applies to the MF/UF treatment process itself and does not consider impacts on downstream processes, such as Reverse Osmosis membrane treatment[6].

[5] www.AMTAOrg.Com. Accessed in December, 2014.

[6] Based on the results of side by side RO bench-scale testing (Chapter 6) there are no anticipated benefits on downstream RO processes by use of the project UF membrane compared with the standard UF membrane.

Table 23 summarizes additional assumptions that were utilized in this benefits evaluation.

Table 23: System Assumptions Used for Economic Evaluation of Project Ultrafiltration Membrane Benefits Projections

Assumption	Value	Notes
Statewide MF/UF Flowrate	400 MGD	See footnote 6
Average energy consumption for MF/UF filtration	800 kWh/million gallons	See footnote 6
Energy cost	0.1175 $/kWh	CEC, 2015
Greenhouse gas emission factor	0.000331 metric tons/kWh	CEC, 2015
Chemical O&M Cost for MF/UF filtration	$0.25/1000 gallons	See footnote 6
Chemical O&M Cost associated with CIP cleanings	20 percent	Estimate based on pilot performance
Number of MF/UF membrane modules	510 modules /10 MGD	See footnote 6
Price of standard UF module	2080 $/module	BASF communication
Price of project UF module	2400 $/module	BASF communication
Baseline UF membrane lifetime	5 years	See footnote 6

Source: Kennedy/Jenks Consultants

9.2 Summary of Projected Benefits of Project UF Relative to Standard UF Membrane

The anticipated potential benefits of substituting the project UF for the standard UF in the membrane treatment process are summarized in Table 24 for each of the water sources tested. For the purpose of this benefits evaluation, the average anticipated savings for all waters was used. In no instance did the project UF membrane underperform the standard UF membrane. Therefore, the project UF membrane provides similar or better operational costs than the standard UF membrane, regardless of water quality.

Energy savings will reduce the required cost of electricity purchased, as well as reduce the related greenhouse gas production. The energy savings were previously presented in Chapter 8 (M&V).

No significant water savings are anticipated for the project UF membrane, based on the results of this project. Although a slight increase in water yield was demonstrated during testing of settled water, due to the performance of the project module during testing of organic-spiked water and backwash water, no water savings could be demonstrated for these more challenging waters.

CIP frequency reduction will reduce chemical costs for treatment. The values for were previously reported in Chapters 4 to 6 for settled water, organic-spiked water and backwash water respectively. In addition, chemical usage from daily CEB was accounted for in calculating projected chemical costs savings.

Increased membrane lifetime will reduce the rate, and therefore the cost, of membrane replacement. During membrane treatment, the membrane elements are periodically replaced due to loss of capacity caused by irreversible fouling. CIP effectiveness is a way of assessing irreversible foulant build up. The values in Table 20 were previously reported in Chapters 4 to 6 for settled water, organic-spiked water and backwash water respectively. Due to the large variation observed in irreversible fouling for the different water sources, for the purpose of these benefit calculations it was estimated that, with further refinement of the chemical resistance and chemical cleaning procedures for the project UF membrane, the membrane life of the would be increased by 39 percent.

Table 24: Anticipated O&M Benefits Achieved by Substituting Project Ultrafiltration for Standard Ultrafiltration

Source Water	Energy Savings	Water Savings	CIP Frequency Reduction	Reduction in Irreversible Fouling
Settled Water	7.6%	0.4%	74.4%	0.0%
Organic-Spiked Water	5.0%	0.0%	5.3%	94.0%
Backwash Water	5.6%	0.0%	0.0%	22.8%
Average	**6.1%**	**0.1%**	**26.5%**	**38.9%**

Source: Kennedy/Jenks Consultants

9.3 Estimated Energy Conservation

Major power usage in the membrane process comes from the membrane feed and backwash pumps. Per chapter 8, energy savings are anticipated from both feed and backwash pumping due to usage of the project UF membrane. Overall energy savings resulting from substituting the project UF membrane for the standard UF membrane in a typical MF/UF treatment process are 6.1 percent, regardless of water type.

A survey by AMTA indicate that there are approximately 100 microfiltration/ultrafiltration treatment plants with a total design capacity of approximately 400 MGD, eight nanofiltration facilities (30 MGD), and over 100 RO facilities (400 MGD) in California[7]. Depending on the water quality characteristics, energy requirements for treating about 1 million gallons of water may range from 600 to 800 kW for MF/UF membranes. Table 25 shows the estimated energy savings and reduction in greenhouse gas emission due to the implementation of the proposed technology.

Assuming a 50 percent market penetration, the proposed technology can reduce the energy use for MF/UF treatment by 3,545 MWh per year for an anticipated cost savings of approximately $416,600 per year.

[7] www.AMTAOrg.Com. Accessed in December 2014.

Table 25: Estimated Electricity and Electrical Cost Savings due to the Implementation of the Proposed Technology in California

% CA MF/UF Market Penetration	10% CA Market	25% CA Market	50% CA Market	100% CA Market
Flow Rate for MF/UF (MGD)	40	100	200	400
Energy Use for MF/UF (kWh/Year)	11,688,000	29,220,000	58,440,000	116,880,000
% Savings With project UF	6.1%	6.1%	6.1%	6.1%
Energy Savings With project (kWh/Year)	709,072	1,772,680	3,545,360	7,090,720
Total MF/UF Energy Cost ($/Year)	$1,373,340	$3,433,350	$6,866,700	$13,733,400
Savings in Electricity Cost With project ($/Year)	**$83,316**	**$208,290**	**$416,580**	**$833,160**

Source: Kennedy/Jenks Consultants

9.4 Estimated Water Savings (that is Increase in Water Yield)

Per manufacturer recommendations, the two membrane modules were operated at the same backwash frequencies (and therefore the same water yields) during most of pilot testing. The ability of the project membrane to provide increased water yield was tested for a particular source water only if it had been previously demonstrated that the permeability performance of the project membrane was sufficiently better than the standard UF membrane and that the backwash frequency of the project membrane could be reduced without causing the performance of the project membrane to otherwise decline to below that of the standard membrane. Although some small water savings were demonstrated during testing of settled water, no water savings could be shown during testing of organic-spiked or backwash water. No significant water savings through the proposed technology have been demonstrated at this time.

9.5 Estimated Reduction in Use of Membrane Cleaning Chemicals

The proposed technology minimizes fouling of membranes by repelling organic and inorganic foulants. This, in turn, can extend the time interval between membrane cleaning and lower the amount of chemicals needed for cleaning. Chemical requirement estimates range from $0.15 to $0.25 per 1000 gallons of water treated during MF/UF treatment. Costs for chemical cleaning come from daily CEBas well as less frequent CIP procedures. During this project, chemical usage due to CIP procedures made up approximately 20 percent of total cleaning chemical use. The proposed technology has the potential to lower the chemical cost of CIP procedures by 26.4 percent, but would not lower the chemical cost of daily CEB (since both the standard and the project membranes are subjected to CEB at the same frequency). Accordingly, savings in chemical cost using project membranes was estimated assuming a total cost of chemical cleaning of $0.25/1000 gallons, 20 percent of the savings resulting from CIP procedure, a 26.5 percent savings resulting from the use of project membrane and no estimated savings in the CIP procedure. Table 26 shows the estimated chemical savings due to implementation of the proposed technology.

Assuming a market penetration of 50 percent, the estimated reduction in chemical cost is approximately $945,000 per year for California ratepayers.

Table 26: Estimated Chemical Savings and Chemical Cost Savings due to the Implementation of the Proposed Technology in California

% CA MF/UF Market Penetration	10% CA Market	25% CA Market	50% CA Market	100% CA Market
Flow Rate for MF/UF (MGD)	40	100	200	400
Overall Chemical Cost ($/year)	$3,652,500	$9,131,250	$18,262,500	$36,525,000
% Savings in Chemicals for Cleaning with Project Membrane (CEB)	0.0%	0.0%	0.0%	0.0%
% Savings in Chemicals for Cleaning with Project Membrane (CIP)	26.5%	26.5%	26.5%	26.5%
% Savings in Overall Chemicals for Cleaning with Project Membrane	5.2%	5.2%	5.2%	5.2%
Savings in Chemical Cost with Project Membrane ($/yr)	**$189,033**	**$472,582**	**$945,164**	**$1,890,329**

Source: Kennedy/Jenks Consultants

9.6 Estimated Reduction in Membrane Replacement Cost

During membrane treatment, the membrane elements are periodically replaced due to loss of capacity caused by irreversible fouling. MF/UF membranes have a typical service life of 5 to 7 years. Since the proposed technology lowers the potential for irreversible fouling, the frequency of membrane replacement will be reduced. Assuming a 39 percent increase in the typical five-year membrane life, the estimated membrane lifetime for the proposed replacement technology would be seven years.

A 10 MGD plant typically has about 510 modules, and assuming an annual membrane replacement rate of 20 percent (equivalent to an operating lifetime of 5 years), about 102 modules require replacement each year. Assuming an operating lifetime of approximately 7 years, only 68 modules of the proposed membrane would require replacement each year. Representative costs for the two modules are $2,080 per module for conventional membrane and $2,400 per module for the proposed membrane. Table 27 shows the membrane cost savings due to the implementation of the proposed technology.

Assuming a 50 percent market penetration, the potential savings in membrane replacement cost is approximately $980,000 per year.

Table 27: Estimated Membrane Cost Savings due to the Implementation of the Proposed Technology in California

% CA MF/UF Market Penetration	10% CA Market	25% CA Market	50% CA Market	100% CA Market
Flow Rate for MF (MGD)	40	100	200	400
Project Membrane Life (years)	7	7	7	7
Project Replacement Frequency (modules/10 MGD/yr)	73	73	73	73
Cost for Standard Membrane Replacement ($/yr)	$848,640	$2,121,600	$4,243,200	$8,486,400
Cost for Project Membrane Replacement ($/yr)	$700,800	$1,752,000	$3,504,000	$7,008,000
Savings in Membrane Replacement Cost ($/yr)	**$147,840**	**$369,600**	**$739,200**	**$1,478,400**

Source: Kennedy/Jenks Consultants

9.7 Projected Benefits

Table 28 summarizes the combined cost savings due to the implementation of the proposed technology.

Table 28: Summary of Total Estimated Cost Savings due to the Implementation of the Proposed Technology in California

% CA MF/UF Market Penetration	10% CA Market	25% CA Market	50% CA Market	100% CA Market
Savings in Electricity Cost ($/Year)	$83,316	$208,290	$416,580	$833,160
Savings in Chemical Cost ($/Year)	$189,033	$472,582	$945,164	$1,890,329
Savings in Membrane Replacement Cost ($/Year)	$147,840	$369,600	$739,200	$1,478,400
Total Estimated Savings ($/Year)	**$420,189**	**$1,050,472**	**$2,100,944**	**$4,201,889**

Source: Kennedy/Jenks Consultants

The following are the estimated benefits over the next twenty-five years, assuming 50 percent market penetration:

- Estimated Energy Conservation: 88,600 MWh
- Reduction in Chemical Use: $24 Million (present worth)
- Reduction in Membrane Replacement Cost: $18 Million (present worth)
- Reduction in greenhouse gas emissions: 29,300 metric tons CO_2[8]
- Water savings (that is increase in water yield): 0 Million Gallons

9.8 Market Segment and Penetration

A key benefit of the proposed membrane is that no capital investment is required for the incorporation of the proposed membrane in an existing membrane treatment facility. It simply involves replacing the conventional membrane with the proposed membrane unit during the next change out cycle.

In no instance did the project UF membrane underperform the standard UF membrane. Therefore, the project UF membrane is anticipated to provide similar or better operational costs than the standard UF membrane, regardless of water quality. Given the performance and the projected cost savings above, it is reasonable to assume a 50 percent market penetration for the proposed technology.

9.9 Qualitative Benefits to Ratepayers

Through supporting deployment and eventual adoption of the proposed technology, California IOU ratepayers will experience other qualitative benefits, including: 1) improved environmental sustainability through reduced energy demand and associated carbon footprint, and 2) greater availability of a locally available water resource through higher water recycling. In order to obtain these results, first, the membrane formulations must be improved to rectify the problems identified in the earlier sections. Subsequently, reduction in the backwash frequency resulting from lower fouling potential can result in reduced energy demand and higher recycled water yield.

9.10 Cost-to-Benefit Analysis

As described in Section 9.6 and 9.7 above, the proposed membrane can lower the cost of treatment through savings in energy, chemical and membrane replacement costs. Approximately 20, 45 and 35 percent of the savings result from savings in electricity, chemical and membrane replacement cost, respectively. The project membrane is expected to be approximately 15 percent more expensive than the standard membrane. For a 40 MGD plant, the first year of replacing standard membrane with the project membrane will cost approximately $127,000 more. However, the annual savings in electricity and chemical costs are approximately $83,000 and $189,000, respectively. Hence, the return on investment for the proposed technology is less than one year for most membrane treatment facilities.

[8] (CEC, 2015)

CHAPTER 10: Technology Transfer Activities

The following technology transfer activities were performed regarding this project:

- Presentation of preliminary findings to Kennedy/Jenks staff in February 2018, and
- Acceptance for presentation at the California-Nevada Chapter of the American Water Works Association --- Fall Conference, 2018

The details of these are presented below:

Presentation of preliminary findings to Kennedy/Jenks Staff (2-20-2018)

This presentation was made to Kennedy Jenks staff on 20th February 2018 with an intent to discuss initial findings, and to disseminate the details of the technology to our clients (that is water and wastewater treatment facilities). The slides from this presentation are included in Appendix B.

California-Nevada American Water Works Association Fall Conference, 2018, Rancho Mirage, CA

An abstract submitted using the initial findings of the study for California-Nevada American Water Works Association Fall Conference, 2018 was accepted for podium presentation. However, a presentation was not made in the conference due to the challenges (described in Chapter 4 and elsewhere) encountered with the membrane performance after the first several CIP cycles. The abstract is included in Appendix B.

CHAPTER 11: Product Readiness Plan

In general, several vendors market membrane systems for water and wastewater treatment. The pathways for commercialization of membrane systems are reasonably well established. After laboratory proof of concept, field studies are often performed to optimize membrane characteristics and technology demonstration. Tests are performed in coordination with California State Water Resources Control Board for Title 22 certification. Testing should be conducted under representative hydraulic conditions, at a designated maximum flux and TMP. To comply with Surface Water Treatment Rules requirements and DDW's water treatment approval process, a technology demonstration study should consist of 1) pathogen challenge testing and 2) an assessment of turbidity removal performance. Similarly, appropriate performance requirements need to be met for recycle water use certification. These tests typically take about three to six months. Upon receiving the certification, the membrane is marketed using various methods including targeted client presentation, conference presentations, and side-by-side pilot testing. Once, a water/recycle water agency decides to use the new membrane, the revised operational plan (that is use of new membranes) must be approved for appropriate uses (drinking water or recycled water) by the permitting agency.

The project membrane tested in this study contained a PSU- PEO- polysiloxane surface-modifying additive to mitigate organic and inorganic fouling of membranes. In various bench scale studies and limited pilot studies performed prior to this project, the membrane was very effective in resisting organic and inorganic fouling and maintaining a significantly higher flux rate than conventional UF membranes. However, in the long-term pilot testing performed under this study the initial superior performance observed for the project membrane could not be sustained after a few CIP cycles. The performance of project and the standard conventional membrane were comparable after this initial period. An autopsy performed on the project membrane indicated that the polysiloxane functionality has been chemical degraded during testing. The vendor is currently investigating this issue. It is anticipated that, based on the findings of the investigation, appropriate changes will be incorporated in the membrane composition, production process and/or recommended operating and cleaning procedures. The membrane will likely be commercialized upon successful demonstration of the modified membrane through long-term field demonstration like the current study. The timeline for commercialization and the economics of the modified membrane will be developed after the field demonstration.

Finally, in this pilot test, the performance of the project UF membrane was tested using a surface water source and an organic spiked surface water (to represent recycled water). Additional tests using secondary/tertiary effluent will be required to obtain Title 22 certification for use of this membrane for recycle water treatment. Title 22 stipulates the filtered effluent turbidity during treatment using the membrane must not exceed (1) 2 NTU on average over 24-hour period, (2) 5 NTU for more than 5 percent of the time over 24-hour period, and (3) 10 NTU any time. Typically, tests are done over a period of three to six months to demonstrate the membrane performance. Upon successful demonstration, the membranes can be marketed for recycled water treatment.

CHAPTER 12: Summary and Conclusions

This chapter summarizes the findings of this project, presents conclusions on the utility of the proposed technology to provide energy and water savings to California ratepayers, and estimates the readiness of this product for commercialization. Suggested further work to improve the technology's readiness for market is also presented.

12.1 Summary of Findings

The project UF membrane, with its novel, surface-modifying PSU-PEO-polysiloxane copolymer, was tested in parallel with a standard PES UF membrane. Other than this modification, the two UF membrane modules were identical. Long-term pilot tests were performed over a period of 20 months at the Cal Water Northeast Water Treatment Plant in Bakersfield, California. Three different feed water sources were utilized: settled (that is coagulated, flocculated, and settled) surface water, settled surface water spiked with humic acid, and backwash water produced during cleaning of the full-scale microfiltration treatment process.

The performance of the proposed project UF membrane was mixed. Initial testing with settled water indicated that the novel membrane consistently outperformed the standard membrane, reducing the pressure required to pump water through the membrane by an average of 20 percent. An increased water yield using the project UF membrane was demonstrated during initial testing, but was, in part, limited by the already high baseline water recovery of the standard membrane treatment process with this source water. Also related to the reduced pressure requirements for the project membrane, energy usage for both feed and backwash pumping was reduced (6.6 percent) as was the predicted cleaning frequency (74 percent); however, the cleaning efficiency of both membranes was similar. The performance improvement relative to the standard membrane was consistent and observed for a period of 5 months (including pilot testing periods for flux optimization and steady-state operation). However, towards the end of pilot testing with settled water, the performance improvement disappeared. This may have resulted from a chemical cleaning that was performed around that time period. When both membrane modules were replaced the next year, the previous performance of the project membrane treating settled water could not be replicated. This lack of reproducibility may have been at least partially attributable to changes in water quality (lower turbidity, higher water temperature) that resulted in a source water less challenging to treatment, minimizing performance difference between the two membranes.

Testing with organic-spiked water (settled water spiked with 3 mg/L of humic acid) did not demonstrate the same process improvements for the project membrane that were observed during settled water testing. When testing organic-spiked water, no improvement was observed in the pressure required to pump through the membrane, although the measured energy usage for feed and backwash pumping was reduced 3.5 percent). No improvement in water yield could be demonstrated. The predicted frequency of required cleanings was improved slightly (5 percent); however, the effectiveness of those cleanings was dramatically improved for the project membrane relative to the standard membrane. The recovery in membrane performance following a CIP for the project membrane was almost complete, while that of the standard membrane was negligible.

Performance of the project membrane when treating backwash water was intermediate to that observed for settled water and organic-spiked water, but were also highly variable. The pressures required to push water through the membrane ranged between 7 and 21 percent lower with the project membrane than with the standard membrane. As with previous settled water testing, this variability in performance may have been inversely related to changes in water quality, specifically turbidity. Overall, energy usage for feed and backwash pumping was reduced by 6.8 percent (a similar energy savings to that reported for treatment of settled water). No improvement in water yield could be demonstrated. No improvement in cleaning frequency for the project membrane with this water is predicted; however, a 23 percent improvement in cleaning effectiveness was observed.

An evaluation of any benefits on downstream RO treatment processes was also performed. The two UF membranes treated backwash water and the filtrate produced by each UF membrane was in turn used as the feed water to two bench-scale RO membrane test cells. Permeability (specific flux) decline of the RO membrane cells with each filtrate water was monitored. No performance improvement by use of the project membrane was observed. This result was consistent with trends in filtrate water quality previously observed during this pilot testing. During earlier testing of settled water, organic-spiked water and backwash water, levels of foulants or foulant surrogates (that is turbidity, total organic carbon and specific ultraviolet absorbance at 254 nm (SUVA-254)) in the filtrate water produced by both UF membranes were consistently similar. Since the filtrate, water produced by the two UF membranes is the same, there would be little anticipated benefit on downstream processes.

After testing the UF membranes with settled water and organic-spiked water (but not backwash water), the membrane modules were replaced. Membrane fibers were collected from the used modules and analyzed for the presence of foulants, as well as the presence of the surface modifying copolymers PSU and polysiloxane. Testing indicated that while the percentage of PSU present in the project membrane remained at levels identical with that in virgin project membrane fibers, no polysiloxane remained. This result suggests that the polysiloxane had been chemically transformed or degraded, most likely due to daily CEB or the less frequent, but harsher CIP procedures. It was not possible to determine when or at what rate the loss of polysiloxane occurred but could possibly be tied a CIP performed near the end of settled water testing. This CIP used significantly longer exposure times during acid and alkaline cleanings as well as introduction of a new cleaning chemical, citric acid. Immediately preceding cleaning, the project membrane had consistently outperformed the standard membrane, and after cleaning, the performance of the two membranes was similar.

Also examined on the aged membrane fibers was the presence and distribution of foulants. Both the project and standard UF membrane fibers showed the same general foulants, mostly aluminum and silica; however, there was also some evidence of carbon fouling that may have been due to organic matter deposition. While organic carbon and silica are natural water quality constituents in the raw surface water used for testing, the presence of aluminum was due to use of polyaluminum chloride coagulant upstream of the membrane pilot unit at the water treatment plant. Although the basic nature of the foulants did not differ, the distribution of those foulants on the membrane surfaces was different. On the standard membrane, foulants were more evenly distributed across the membrane surface while on the project membrane, fouling occurred in patches, with the rest of the membrane surface remaining, to all appearances, clean of major fouling. These observations supported one of the initial project hypotheses that deposition of foulants on the membrane surfaces was affected by the amphiphilic surface modifying polymers in project membrane. The observed distributions foulants on the project membrane could potentially have implications for maintaining better performance or better recovery after cleaning cycles over longer operating lifetimes than were tested as part of this project.

12.2 Conclusions

The results of the pilot testing performed in this project suggest that the project UF membrane module is not market ready. The chemical degradation of the project membrane surface observed during testing indicates that further work may be needed on the part of the manufacturer to evaluate special chemical resistance specifications and cleaning protocols that may differ from their other membrane offerings.

Based on membrane characterization results, aluminum in the water was the major scalant on both the project and standard membranes. To the authors' knowledge, previous bench and pilot-scaling testing of the project membrane was not performed on coagulated water. Although not definitively established, the presence of aluminum in the source water may have partially contributed to the somewhat decreased performance of the project membrane observed during this pilot test as compared with previous pilot testing.

Although this product is not market ready, it does have potential for both energy and water savings. Even given the variable performance observed during these pilot tests, the project membrane was verified to provide an average of 6 percent energy savings. Membrane characterization results indicated different patterns on scale build-up, suggesting that the project membrane did perform differently than the standard membrane. In addition, definite benefits were seen with regard to energy savings and ease of cleaning, which impact the frequency of cleaning and the effectiveness of these cleanings (which in turn impacts membrane lifetime). Even using a possibly impaired project module during some testing, this project demonstrated energy and chemicals savings, as well as some evidence to support, with refined manufacturer cleaning procedures, lower membrane replacement costs.

At no time during the pilot study did the project UF membrane underperform the standard membrane with regards to either quality of water produced, or energy, water yield, or chemical costs. Therefore, although this novel membrane is not yet ready for commercialization, based on the results observed in this pilot test, with further refinement this membrane is anticipated to be of benefit to California water suppliers, customers and ratepayers in the future.

12.3 Suggested Further Work

Prior to full commercialization, it is recommended that further bench and/or pilot testing be performed with the project membrane to better assess the chemical compatibility of the amphiphilic membrane chemistry. Appropriate changes should be incorporated in the membrane formulation to better resist fouling and/or damage to the surface chemistry while treating different types of water. In addition, compatibility with various water quality standards anticipated for target treatment applications should be addressed, including water treatment chemicals used in those treatment processes such as coagulants and cleaning chemicals. In particular, the acceptable range of conditions and rigorousness of chemical cleanings, including the nature, the concentration and the exposure time of cleaning chemicals used must be better evaluated to ensure that the membrane surface of the proposal technology will not be damaged during future routine treatment operation.

GLOSSARY AND ACRONYMS

Term	Definition
AFM	Atomic force microscopy
AFY	Acre-feet per year
Al	aluminum
AMTA	American Membrane Technologies Association
Bar	A unit of pressure. 1 bar is equivalent to 14.50377 psi.
BASE	BASE Energy, Inc.
C	Carbon
Cal Water	California Water Services
CEB	Chemically enhanced backwash
CEC	California Energy Commission
CIP	Clean-in-place
COD	Chemical oxygen demand
DDW	California Division of Drinking Water
DOC	Dissolved organic carbon
EDX	Energy dispersive X-ray spectroscopy
ft^2	Square foot
GFD	Gallons per foot-squared per day (a unit of membrane flux)
GHG	Greenhouse gases
GWh/yr	Gigawatt hours per year
H-NMR	Photon nuclear magnetic resonance
IOU	Investor-owned utility
IPMVP	International performance measurement and verification protocol
ISO	International Organization for Standardization
KWH	Kilowatt hour
LMH	Liters per meter squared per hour (a unit of membrane flux). 1 LMH is equivalent to 0.588 GFD.
LPMF	Low-pressure membrane filtration
m^2	Square meter

Term	Definition
M&V	Measurement and verification
mbar	millibar
Membrane Flux	$$J = \frac{Q_p}{A_m}$$ Where: J = membrane flux (LMH) Q_p= filtrate flow rate (LPH) A_m= membrane surface area (m^2)
Membrane Permeability	Also see Specific Flux $$M = \frac{J}{TMP}$$ Where: M = membrane permeability $\left(\frac{LMH}{bar}\right)$-- also called specific flux J = membrane flux (LMH) TMP= transmembrane pressure (bar)
MF	Microfiltration
mg	Milligram
mg/L	Milligrams per liter
MG	Million gallons
MGD	Million gallons per day
MH	Liters per meter squared per hour
µm	Micrometer
µS/cm	Microsiemens per centimeter
MT/yr	Metric tons per year
MWH	Megawatt hour
nm	Nanometer
NOM	Natural organic matter
NSF	National Sanitation Foundation
NTU	Nephelometric turbidity unit
P&ID	Piping and instrumentation diagram
PEG	Polyethylene glycol
PEO	Polyethyleneoxide
PES	Polyethersulfone

Term	Definition
PG&E	Pacific Gas & Electric
psi	Pounds per square inch (a unit of pressure)
PSU	Polysulfone
pvc	Polyvinyl chloride
RO	Reverse osmosis
S	Sulfer
SCADA	Supervisory control and data acquisition
SEM	Scanning electron microscope
SEM-EDX	Scanning electron microscopy with dispersive x-ray spectroscopy
Si	silicon
Specific Flux	See Membrane Permeability
SUVA	Specific ultraviolet absorbance, or ultraviolet absorbance at a particular wavelength divided by the total organic carbon concentration
$SUVA_{254}$	Specific ultraviolet absorbance at 254 nm
TDS	Total dissolved solids
TMP	Transmembrane pressure
Transmembrane Pressure	$$TMP = P_f - P_p$$ Where: TMP= transmembrane pressure (bar) P_f= feed pressure (bar) P_p= filtrate pressure (bar)
TOC	Total organic carbon
TSS	Total suspended solids
UF	Ultrafiltration
VFD	Variable frequency drive
Water Recovery	$$R = \frac{Q_{p,net}}{Q_f}$$ Where: R= Recovery (%) $Q_{p,net}$= net filtrate flow rate (LPH) after correcting for any losses due to backwash, etc. Q_f= total feed flow rate (LPH)
WTP	Water treatment plant

Term	Definition
XPS	X-ray photoelectron spectroscopy

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APPENDIX A:
Energy Measurement and Verification Report for BASF New Anti-Adhesive Membrane Technology at Cal Water Bakersfield, CA

Energy Measurement and Verification (M&V) Report for BASF New Anti-Adhesive Membrane Technology at Cal Water Bakersfield, CA

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Table of Contents

1 INTRODUCTION

BASE Energy, Inc. was contracted by Kennedy Jenks Consultants to provide third party measurement and verification of the potential electrical energy savings resulting from the use of R&D ultrafiltration (UF) amphiphilic, anti-adhesive membrane. The operation, measurements and testing of the pilot demonstration water treatment unit occurred at California Water Services Company, Bakersfield, CA.

The ultrafiltration membrane filters used in this pilot can be used to remove bacteria, viruses, particles and suspended solids from drinking water, process water, sea water and waste water. The R&D UF membrane compared to a standard membrane filter will require less pressure and pumping energy due to a reduction of membrane fouling. The patented Mutibore® membrane and dizzer ® modules have been developed by inge GmbH which is a subsidiary of BASF.

In 2017-2018, Kennedy Jenks conducted this Pilot Study at the California Water Services Company in Bakersfield, CA to assess the energy savings potential for R&D UF membrane filter. Under sponsorship of the California Energy Commission, Kennedy Jenks set-up a pilot scale plant to test this concept. The Ultrafiltration Pilot set-up included two filtration systems to run in parallel. Water filtration tests were performed for surface water, surface water with organics added and backwash water.

The objective of this project is to evaluate the electrical energy savings resulting from reduced pump discharge pressure and therefore less pumping power for the R&D membrane compared to the Standard UF membrane system.

Two BASF UF modules, a high efficiency unit and standard efficiency unit, were run in parallel during pilot testing. The parallel units are referred to as R&D UF (high efficiency) and Standard UF (standard efficiency). Please refer to the table below for details:

Table 1-1 – Pilot Study Ultrafiltration Membranes

UF Module	Description	Common Characteristics
R&D UF Module	The inge® R&D UF module is the amphiphilic, anti-adhesive UF BASF membrane contained in a BASF Dizzer® PoLoFlo module. This R&D amphiphilic membrane has anti-adhesive PEO polysiloxane functional groups in a polysulfone (PS) membrane matrix.	The R&D and Standard UF membranes used in this study had a nominal pore size of 0.02 µm and combined seven individual fibers in a single capillary reinforced within a strong support structure. The membranes were bundled together in a plastic housing (module). Each module was approximately 66-inches long, and 10 inches in diameter. The membrane surface area in each module was approximately 80 m^2.
Standard UF Module	The Standard UF module is a conventional UF BASF membrane contained in a BASF Dizzer® XL 0.9 MB 80 WT membrane module. The membrane material used in the Standard UF module was polyethersulfone (PES).	

Measurements were performed for the following tests. These three distinct tests were performed for 4 months each. Data logging and trends were taken for a minimum of 2 months per test (i.e. per water quality).

Table 1-2 – Water Quality Tests

Water Quality	Description
Surface Water	Pre-treated Membrane Feed Water – Kern River water
Backwash Water	Reject water stream generated during treatment process
Surface Water with Organics Added	Kern River water spiked with humic acid to replicate reclaimed water

Section 2 of this report provides details on the description of the UF water treatment system. Section 3 provides the measurement and verification plan protocol. The results of the measurement and verification are presented in Section 3 and the discussion of the results is presented in Section 5.

2 DESCRIPTION OF FILTRATION SYSTEM

The Ultrafiltration demonstration system was set up at the California Water Services Company plant in Bakersfield, CA. This pilot demonstration unit is designed for a desired inlet feed flow of 30 GPM per module and a minimum inlet pressure of 30 psi; however, the unit was operated at flows up to 36gpm per module during some testing periods. A photo of the demonstration system is shown in Figure 2-1 below.

The Cal Water Bakersfield plant is designed to treat 22 MGD of surface water drawn from the Kern River through coagulation-flocculation, sedimentation and microfiltration. After water passes through the coagulation-flocculation and sedimentation process, the water was directed to the pilot unit. Water then flowed in parallel to the standard and R&D UF membrane modules. The pilot unit considered in this study only treated a small fraction of the total water processed at the 22 MGD plant.

Figure 2-1 Photo of Pilot Unit

Figure 2-2 shows the flow schematics of the pilot system.

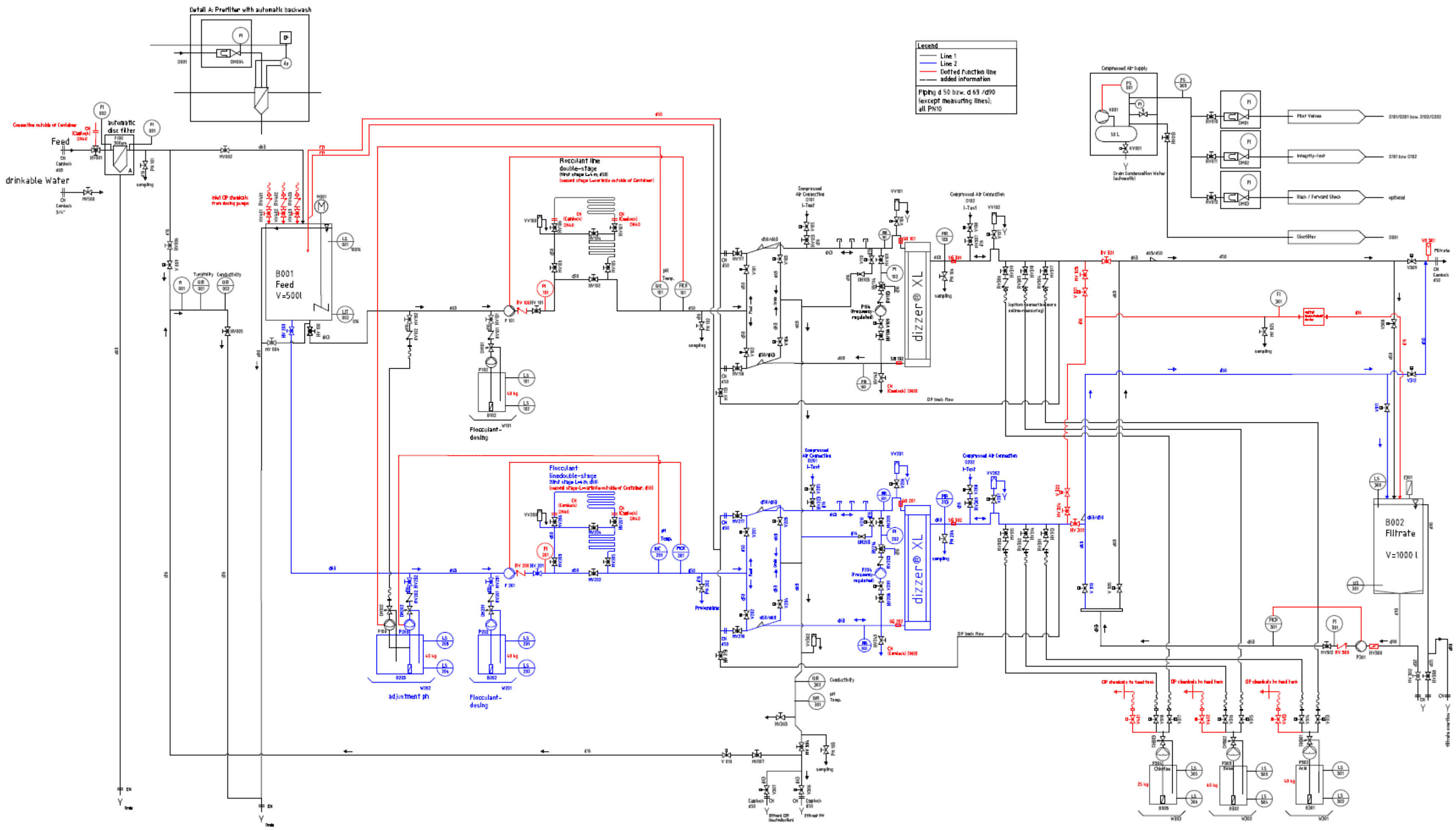


Figure 2-2 P&ID and Flow Schematic of Pilot Unit

Figures 2-3 and 2-4 show pictures of the R&D UF and Standard UF membrane modules. Figure 2-5 shows a picture of the pilot unit pumps. Table 2-1 shows the major energy consuming equipment associated with the pilot project. Please refer to Table 1-1 for some details regarding R&D UF and Standard UF module specifications.

Figure 2-3 Photo of R&D UF Membrane Module (foreground)

Figure 2-4 Photo of Standard UF Membrane

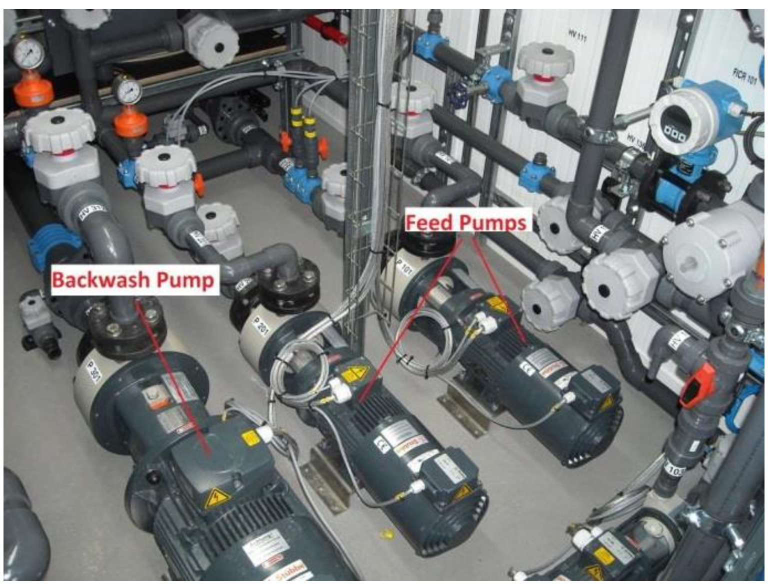


Figure 2-5 Photo of Pilot Unit Pumps

Table 2-1 shows the energy consuming equipment considered in this project.

Table 2-1 – Equipment Considered

Equipment	Motor Size*	Function
Feed Pump #1	3.45 kW	Water Supply Pump for R&D UF Membrane (Variable Speed)
Feed Pump #2	3.45 kW	Water Supply Pump for Standard UF Membrane (Variable Speed)
Backwash Pump	6.3 kW	Backwash Pump (Variable Speed)

*Motor Nameplate Data

3 MEASUREMENTS AND VERIFICATION PLAN

BASE developed a detailed measurement and verification plan to determine the energy savings of the inge® R&D UF amphiphilic, anti-adhesive membrane compared to standard UF membranes. For the baseline system (Standard UF membrane), the influent water was pumped from the common feed tank to the Standard UF membrane module with a variable speed pump. For the demonstration system (R&D UF anti-adhesive membrane), the influent water was pumped from the common feed tank to the R&D UF membrane module with a variable speed pump. Tests were to be performed for three distinct water qualities (surface water, backwash water and surface water with organics added) for a period of four months per water quality. Table 3-1 shows the measurement and verification (M&V) plan for determining energy consumption of the baseline and proposed ultrafiltration feed water pumps. The table also summarizes the data to be collected by BASE and the facility. IPMVP M&V Option B – Retrofit Isolation with All Parameter Measurement will be used for determining the energy savings.

Table 3-1 shows the M&V Plan developed for this project. The project objective was to pilot test the efficiency of BASF's innovative membrane technology which minimizes fouling on membrane surfaces for water and wastewater treatment and therefore reduces the feed water pumping energy requirement compared to Standard UF membrane technologies. The pilot unit consisted of two ultrafiltration trains – one membrane module equipped with Standard UF membranes and one membrane module equipped with BASF's innovative membrane technology – which treated water in parallel. Power logging of feed water pumps for both Standard UF and proposed membrane systems were taken in parallel for three (3) distinct water quality conditions. These three distinct tests were scheduled to be performed for 4 months each. Data logging and trends were scheduled to be taken for a minimum of 2 months per test (i.e. per water quality).

The following outlines the measurement details performed during the testing period of 7/1/2017 to 10/31/2018.

Measurements performed by BASE included:

- Current logging of the feed water pump #1 (R&D UF membrane)
- Current logging of the feed water pump #2 (Standard UF membrane)
- Current logging of the backwash pump
- Spot power measurement of the above equipment

The following information was provided to BASE:

- Project plans P&ID line diagrams
- Design drawings of demonstration pilot unit with equipment specifications
- Pilot unit inlet water flow with the best available resolution for the duration of measurement
- Flow through each membrane module/filter for the duration of measurement
- Turbidity of the influent water for duration of the measurement
- Conductivity of the influent water for duration of the measurement

- pH level of the influent water for duration of the measurement
- Turbidity of the effluent for duration of the measurement
- Conductivity of the effluent for duration of the measurement
- pH level of the effluent for duration of the measurement

Table 3-1 - Measurement and Verification Plan: M&V Parameters

Equipment	Rating	Parameter Measured	Instruments	Source	Duration	Interval[1]
Pilot Test #1 – Surface Water						
UF Membrane Module with Standard UF Membrane	3.45 kW	Power Draw of Feed Water Pump	Spot Power Measurement and Data Logger	BASE Energy	2-4 months[†]	10 sec
	-	**Surface Water** Flow Through Module with Standard UF Membrane (gpm)	SCADA	Kennedy Jenks	2-4 months[†]	1 min
UF Membrane Module with Proposed Membrane	3.45 kW	Power Draw of Feed Water Pump	Spot Power Measurement and Data Logger	BASE Energy	2-4 months[†]	10 sec
	-	**Surface Water** Flow Through Module with Proposed Membrane (gpm)	SCADA	Kennedy Jenks	2-4 months[†]	1 min
Backwash Pump (serves both Membrane Modules)	6.3 kW	Power Draw of Backwash Pump	Spot Power Measurement and Data Logger	BASE Energy	2-4 months[†]	10 sec
	-	Backwash Water Flow (gpm)	SCADA	Kennedy Jenks	2-4 months[†]	10 sec
Pilot Test #2 – Surface Water with Organics Added						
UF Membrane Module with Standard UF Membrane	3.45 kW	Power Draw of Feed Water Pump	Spot Power Measurement and Data Logger	BASE Energy	2-4 months[†]	10 sec
	-	**Surface Water (with Organics Added)** Flow Through Module with Standard UF Membrane (gpm)	SCADA	Kennedy Jenks	2-4 months[†]	1 min
UF Membrane Module with Proposed Membrane	3.45 kW	Power Draw of Feed Water Pump	Spot Power Measurement and Data Logger	BASE Energy	2-4 months[†]	10 sec
	-	**Surface Water (with Organics Added)** Flow Through Module with Proposed Membrane (gpm)	SCADA	Kennedy Jenks	2-4 months[†]	1 min
	6.3 kW	Power Draw of Backwash Pump	Data Logger	BASE Energy	2-4 months[†]	10 sec

[1] Trend data interval should be best available resolution from the facility's SCADA

Table 3-1 - Measurement and Verification Plan: M&V Parameters						
Equipment	**Rating**	**Parameter Measured**	**Instruments**	**Source**	**Duration**	**Interval[1]**
Backwash Pump (serves both Membrane Modules)	-	Backwash Water Flow (gpm)	SCADA	Kennedy Jenks	2-4 months†	10 sec
Pilot Test #3 – Backwash Water						
UF Membrane Module with Standard UF Membrane	3.45 kW	Power Draw of Feed Water Pump	Spot Power Measurement and Data Logger	BASE Energy	2-4 months†	10 sec
	-	**Backwash Water** Flow Through Module with Standard UF Membrane (gpm)	SCADA	Kennedy Jenks	2-4 months†	1 min
UF Membrane Module with Proposed Membrane	3.45 kW	Power Draw of Feed Water Pump	Spot Power Measurement and Data Logger	BASE Energy	2-4 months†	10 sec
	-	**Backwash Water** Flow Through Module with Proposed Membrane (gpm)	SCADA	Kennedy Jenks	2-4 months†	1 min
Backwash Pump (serves both Membrane Modules)	6.3 kW	Power Draw of Backwash Pump	Data Logger	BASE Energy	2-4 months†	10 sec
	-	Backwash Water Flow (gpm)	SCADA	Kennedy Jenks	2-4 months†	10 sec

Table 3-2 – Measurement Devices	
Spot Power Meter	• True RMS Power Meter Hioki 3286-20
Electrical Current Data Logger & Current Transducer	• Onset 4 –Channel Analog Data Logger UX120-006M • Onset 20 Amp Split Core AC Current Transducer
Pilot Unit Instrumentation and Controls	• Control Panel with Programmable Logic Controller • Industrial Computer • Magnetic flow transmitter • pH probes • temperature probes • pressure transmitters

	• conductivity analyzers

4 ANALYSIS OF MEASUREMENT DATA

BASE performed the following analyses based on the measurements performed in Section 3:

- Obtained and analyzed pilot unit trend data to determine water flow through the Standard UF and R&D UF membranes for each water quality.
- Compared backwash pump power consumption between Standard UF and R&D UF membranes for each water quality
- Performed power measurements for feed pumps and backwash pumps
- Determined energy intensity (ratio of pump power draw to flow) for feed water pumps and backwash pumps for Standard UF and R&D UF membranes systems

During the measurement period (7/1/2017 through 10/31/2018), the pilot demonstration unit experienced extended periods of "downtime", during which the unit needed repairs or was being commissioned and/or re-commissioned. For example, in April 2018 the R&D UF membrane (Line 1) experienced a fiber breakage and required replacement. Both the R&D UF and Standard UF modules were replaced simultaneously to ensure consistent operational runtimes. Data was not available for approximately two months until the new modules were installed and the system was operational. Based on these maintenance issues, the testing periods did not follow the expected testing schedule. Table 4-1 below shows the periods of "usable" data for each testing period (pre and post module replacement in April 2018), as supplied by Kennedy Jenks personnel. In Table 4-1 below, Module Set #1 refers to the first set of modules prior to line #1 fiber breakage. Module #2 refers to the new set of modules installed in April 2018.

Table 4-1 – Actual Testing Periods for Each Water Quality

Start Date	End Date
MODULE SET #1	
Pilot Test #1 – Surface Water	
9/15/17	10/16/17
11/5/2017	11/27/2017
11/29/2017	12/4/2017
1/8/2018	1/23/2018
3/14/2018	3/19/2018
3/27/2018	3/28/2018
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)	
2/21/2018	2/26/2018
3/8/2018	3/14/2018
MODULE SET #2	
Pilot Test #1 – Surface Water	
6/25/2018	7/8/2018
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)	
7/9/2018 12:26pm	7/10/2018 6:00pm
7/13/18 3:00am	7/13/18 8:00am
Pilot Test #3 – Backwash Water	
8/2/2018	8/23/18

8/31/2018	9/10/2018
9/14/2018	10/16/2018

Table 4-2 below shows the spot power measurements performed on the Feed Pumps and Backwash pump motors. The motor power factor and voltage obtained from the spot power measurements along with the logged pump electrical amperage was used to calculate the pump power draw during the logging period.

Table 4-2 – Spot Power Measurements					
Equipment	**Measurements**				
	Volts	**Amps**	**Power Factor**	**Power Draw,** kW	**Motor Speed**
Feed Pump #1	459	0.74	0.60	0.355	31 Hz
Feed Pump #2	459	0.85	0.62	0.416	33 Hz
Backwash Pump	459	6.13	0.82	3.999	55 Hz

The following describes the measurement set-up for the baseline and R&D UF membrane systems.

<u>Baseline System (Standard UF)</u>

Baseline is defined as operation of the skid unit with Standard UF membrane filters. To establish the baseline, both flow and pump (feed pump #2 and backwash pump) energy consumption was monitored to determine the energy performance. The pilot unit's SCADA system was setup to distinctly identify and monitor backwash pump operation for both the R&D and Standard modules. The measurement periods for the baseline system are the same as the R&D UF membrane system, since both membrane modules operated in parallel.

<u>R&D UF Membrane System</u>

This study aims to evaluate the claimed reduction of pumping energy consumption of the R&D UF membrane system filter compared to a Standard UF membrane system The R&D UF membrane system filters in a similar manner as the Standard UF membrane system; however, the R&D UF membrane compared to a Standard UF membrane filter is claimed to require less pressure and pumping energy due to a reduction of membrane fouling. Both flow and pump (feed pump #1 and backwash pump) energy consumption was monitored to determine the energy performance. The pilot unit's SCADA system was setup to distinctly identify and monitor backwash pump operation for both the R&D and Standard modules. The measurement periods for the R&D UF membrane system are the same as the baseline membrane system, since both membrane modules operated in parallel.

<u>Measured Parameters</u>

As an example, Figures 4-1 and 4-2 show the parameters logged or provided by facility personnel including the module feed pump flowrate, backwash pump flowrate and logged pump amperage for a sample period. The flowrates for both the R&D Unit (Line 1) and Standard UF Unit (Line 2) are similar, however, the pump electrical amp draw is greater for the Standard UF Unit (Line 2) compared to the R&D Unit pump (Line 1). The similar feedwater pump flowrates can be seen in Figure 4-1. The difference in power amp draw for feedwater pumps and backwash pumping cycles can be seen in Figure 4-2.

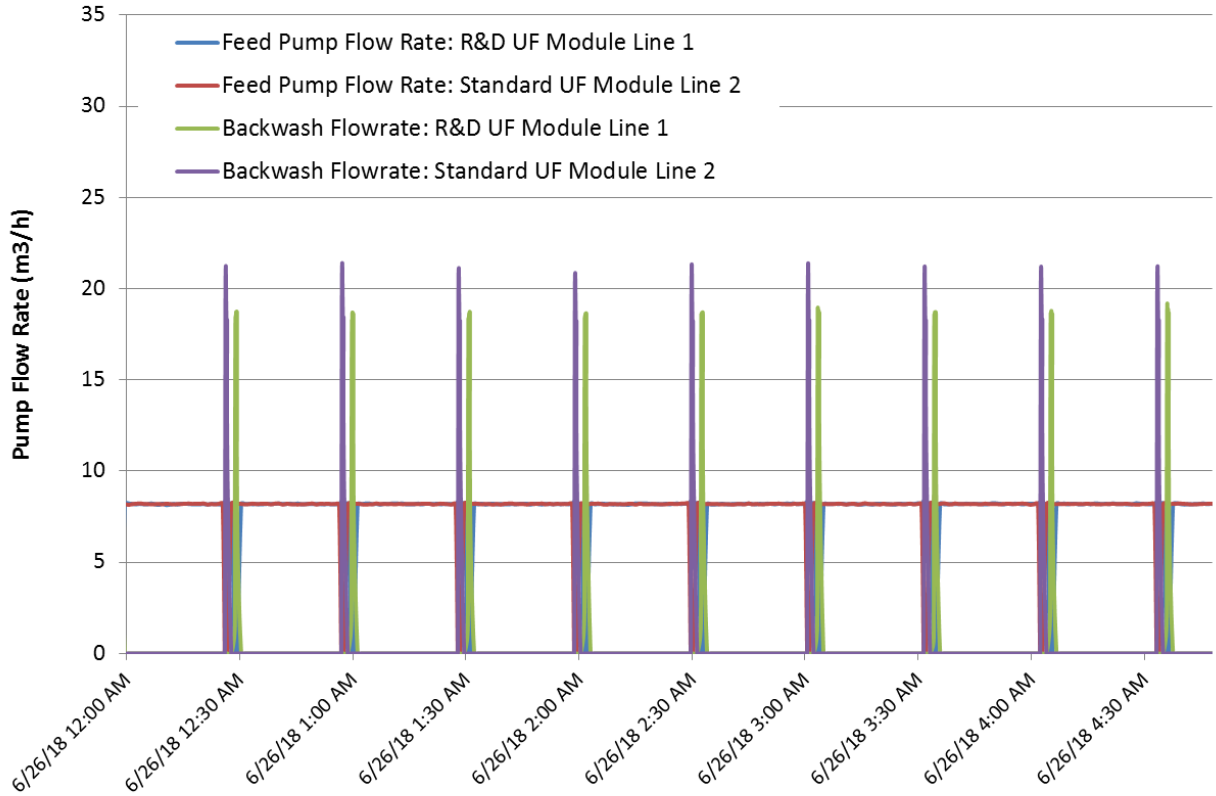


Figure 4-1 Trended Data

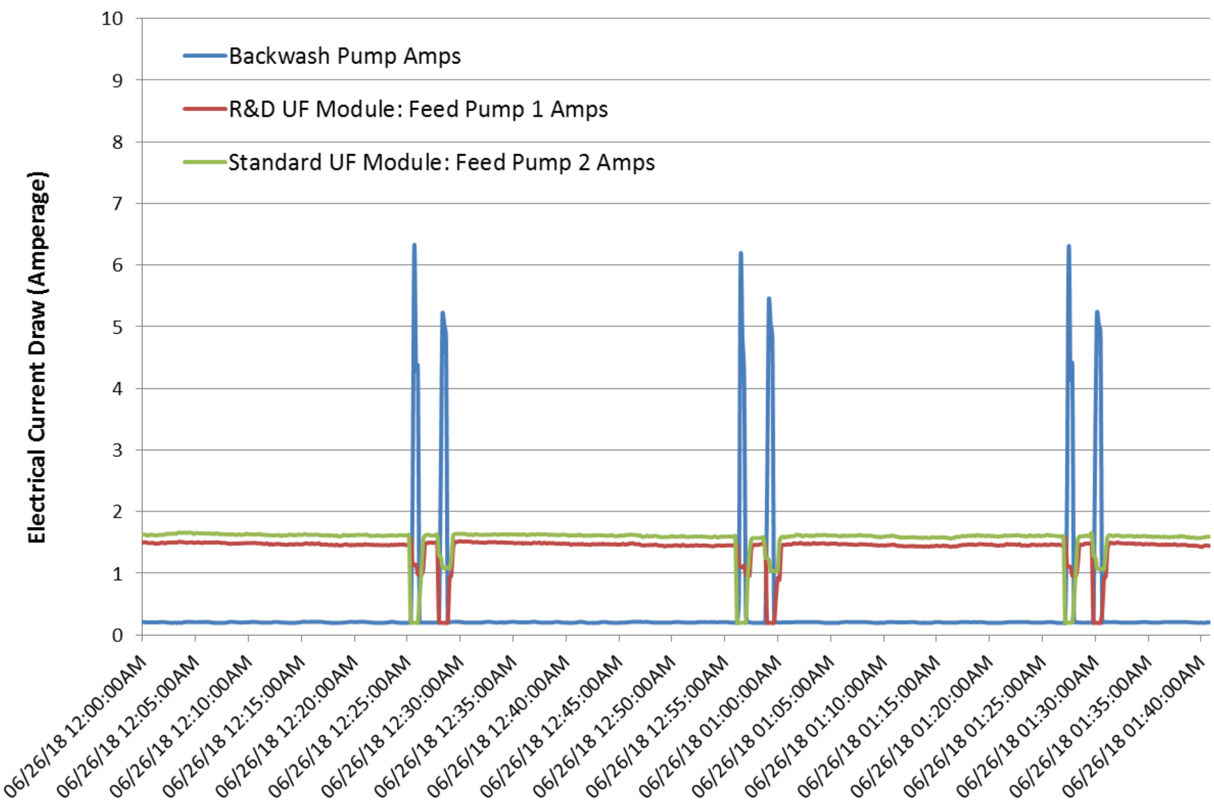


Figure4-2 Logged Data

<u>Feed Pump and Backwash Pump Energy Consumption</u>

The Standard UF and R&D UF membrane filters were tested for three water qualities. The feed pump power for each membrane module was measured and recorded for the periods shown in Table 4-3. The backwash pump power for each membrane module was measured and recorded for the periods shown in Table 4-4. The specific power for each filter was calculated as follows:

Specific Power = (Average Feed Pump Power) / (Flowrate through Filter)

Tables 4-3 and 4-4 show the average feed pump and backwash pump flowrates through each of the filters as well as the average power measured from the main feed. The flowrate through the filter was measured for the same period and provided to BASE for analysis.

Tables 5-1 and 5-2 in the following section present the overall performance and energy savings for the Standard UF and R&D UF membrane filters which consider the combined energy consumption of the feed and backwash pumps.

Table 4-3 – Flowrate and Power of Filter Feedwater Pumps				
UF Filter	**Average Feed Pump Flow Rate** (gpm)	**Average Feed Pump Power Draw** (kW)	**Specific Feed Pump Power** (kW/gpm)	**Feed Pump R&D UF Energy Improvement** (%)
MODULE SET #1				
Pilot Test #1 – Surface Water				
R&D UF Membrane (Line 1)	35.11	0.71	0.0202	**7.3%**
Standard UF Membrane (Line 2)	34.93	0.76	0.0218	
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
R&D UF Membrane (Line 1)	15.93	0.18	0.0111	**7.7%**
Standard UF Membrane (Line 2)	15.89	0.19	0.0120	
Pilot Test #3 – Backwash water				
Backwash water was not tested during Pre Line 1 Failure Period				
MODULE SET #2				
Pilot Test #1 – Surface Water				
R&D UF Membrane (Line 1)	36.00	0.68	0.0189	**10.0%**
Standard UF Membrane (Line 2)	36.01	0.76	0.0210	
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
Not enough data to analyze performance during Post Line 1 failure period				
Pilot Test #3 – Backwash water				
R&D UF Membrane (Line 1)	14.66	0.28	0.0192	**3.8%**
Standard UF Membrane (Line 2)	14.71	0.29	0.0199	

Table 4-4 – Flowrate and Power of Filter Backwash Pump				
UF Filter	**Average Backwash Pump Flow Rate** (gpm)	**Average Backwash Pump Power Draw** (kW)	**Specific Backwash Pump Power** (kW/gpm)	**Backwash Pump R&D UF Energy Improvement** (%)
MODULE SET #1				
Pilot Test #1 – Surface Water				
R&D UF Membrane (Line 1)	67.89	3.42	0.0504	**8.6%**
Standard UF Membrane (Line 2)	67.27	3.71	0.0551	
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
R&D UF Membrane (Line 1)	59.44	3.34	0.0562	**2.7%**
Standard UF Membrane (Line 2)	61.91	3.57	0.0577	
Pilot Test #3 – Backwash water				
Backwash water was not tested during Pre Line 1 Failure Period				
MODULE SET #2				
Pilot Test #1 – Surface Water				
R&D UF Membrane (Line 1)	62.77	2.59	0.0413	**2.0%**

Standard UF Membrane (Line 2)	62.78	2.65	0.0422	
Pilot Test #2 – Surface Water with Organics Added (3 ppm Humic Acids)				
Not enough data to analyze performance during Post Line 1 failure period				
Pilot Test #3 – Backwash water				
R&D UF Membrane (Line 1)	58.21	3.54	0.0608	**7.7%**
Standard UF Membrane (Line 2)	57.77	3.81	0.0659	

5 DISCUSSION OF RESULTS

Comparison of Filter Energy Consumption

In the previous section, the average flow and power draw per filter type for a given water quality was presented. Of the two UF membrane filter types tested (Standard UF membrane and inge ® R&D UF membrane), the inge ® R&D UF membrane had the lowest energy consumption per average flow rate. Across all three water quality tests, the R&D UF feedwater pump showed better energy performance than the Standard UF feedwater pump. Additionally, the backwash frequency for each module was based on timer/schedule. The data shows that the backwash pumping energy consumption for the R&D unit was less than the Standard Unit most likely due to the less fouling of the R&D unit's membranes.

Table 5-1 shows the specific energy consumption for each filter type during the logged filtration periods. The specific energy consumption values for the UF pumps are presented in terms of energy consumption (kWh) per volume of treated water (million gallons, MG). The specific energy consumption values presented in Table 5-1 include the combined feed pump and backwash pump energy consumption for a given volume of treated water.

Based on the pilot unit's SCADA trends and logged pump data:

- For each UF membrane, the backwash pump runtime is 25% of the feed pump runtime
- In the case where the membrane filters are continuously operating, the feed pump runtime would be 80% and the backwash pump runtime would be 20% (25% of 80%).

The specific energy consumption values presented in Table 5-1 are based on these different pump runtimes as well as the pump performance data shown in Tables 4-3 and 4-4.

Table 5-1 – Filter Specific Energy Consumption per Water Quality Test

Water Quality Test	**Standard UF Membrane** (kWh/MG)	**R&D UF Membrane** (kWh/MG)	**R&D UF Membrane Energy Improvement**
Pilot Test #1 – Surface Water	449.6	415.6	7.6%
Pilot Test #2 – Surface Water with Organics Added	354.2	336.6	5.0%
Pilot Test #3 – Backwash water	487.7	460.6	5.6%

Table 5-2 - Specific Energy Consumption per Filter Type

Filter	**Feedwater Pump Specific Energy Consumption‡** (kWh/MG)	**Backwash Pump Specific Energy Consumption‡** (kWh/MG)	**Overall Pumping Specific Energy Consumption‡** (kWh/MG)
Standard UF Membrane	249.4	185.8	435.3
inge ® R&D UF membrane	231.5	175.6	407.1
Savings	**17.9 kWh/MG**	**10.3 kW/MG**	**28.2 kW/MG**
% Savings	**7.2%**	**5.5%**	**6.5%**

‡Based on average results for all test conditions

APPENDIX B:
Technology Transfer Activities

This appendix includes the following technology transfer activities performed regarding this project:

- PowerPoint Presentation of preliminary findings to Kennedy/Jenks staff in February 2018.
- Acceptance for presentation at the CA NV AWWA --- Fall Conference, 2018.

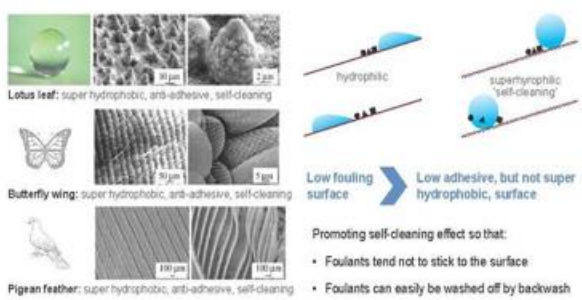
Novel Amphiphilic, Anti-adhesive Membrane to Improve Energy Efficiency and Increase Water Yield during Membrane Treatment

Pilot Testing Progress

February 20, 2018

California Energy Commision
California Water Services
BASF/inge
Kennedy/Jenks Consultants

Reducing UF Membrane Fouling



UF Pilot Unit

- Side-by-side comparison
  - BASF/inge's PoLoFlo (new anti-adhesive coating)
  - Standard BASF/inge dizzer module (dizzer® XL 0.9 MB 80 WT)
- 80 m^2 membrane surface area
- Inside-out filtration mode
- Flux fixed, TMP variable

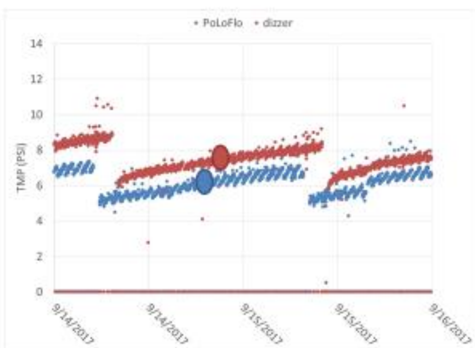
Testing Location

- Cal Water's Northeast Bakersfield Water Treatment Plant
- Source = Kern River
- Treatment train =
  - Permanganate, coagulation, sedimentation,
    Pall MF,
    free chlorine disinfection

Testing Overview

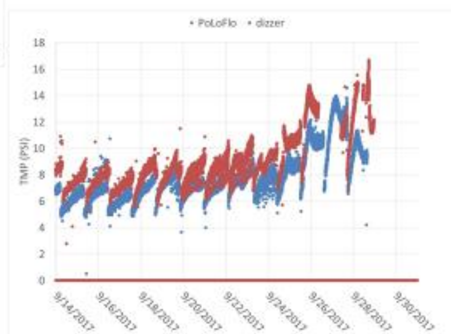
- <u>3 Water Quality Types:</u>
  - Settled surface water (i.e. typical MF/UF feed water)
  - Settled surface water spiked with organic foulants
  - MF backwash water (higher turbidity, foulants)
- <u>Measurements:</u>
  - Performance: Flux, pressure
  - Water Quality
    - Turbidity (performance)
    - Foulants (TOC, Ca, TDS, etc)
  - Energy

Trans-membrane Pressure

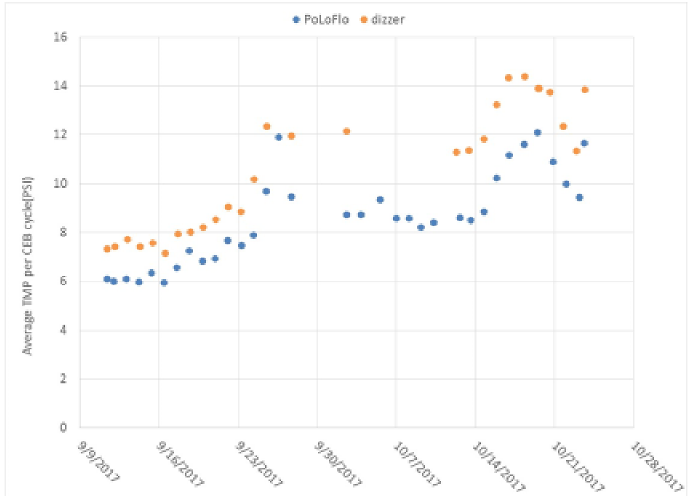


- Flux fixed at 102 LMH (60 GFD), TMP allowed to vary
- Backwash with filtered water every 30 m
- Chemically enhanced backwash (CEB) every 24 h

- Over long term, foulants build up and daily flux maintenance less effective

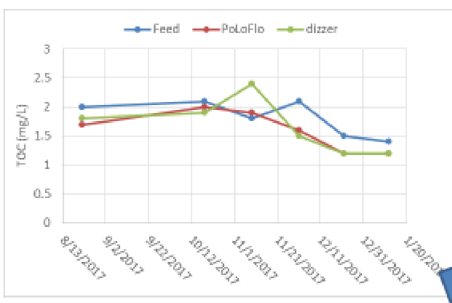


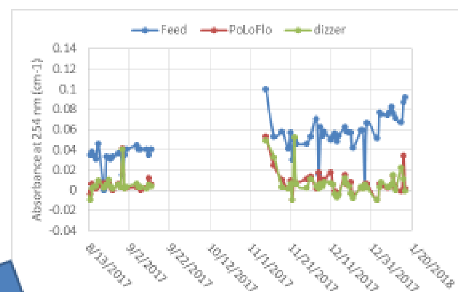
Performance Comparison



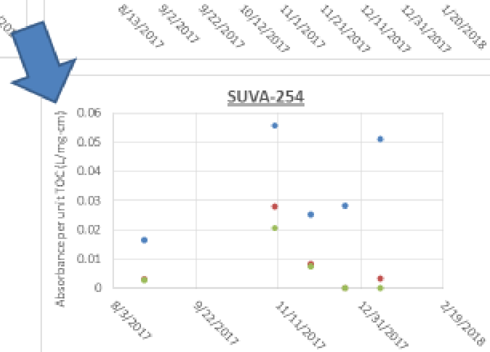
- PoLoFlo TMP is 19.3 ± 4.0 % lower than dizzer
- Current measurement on feed pumps PoLoFlo is 5 -20 % lower than dizzer

Organic Foulants



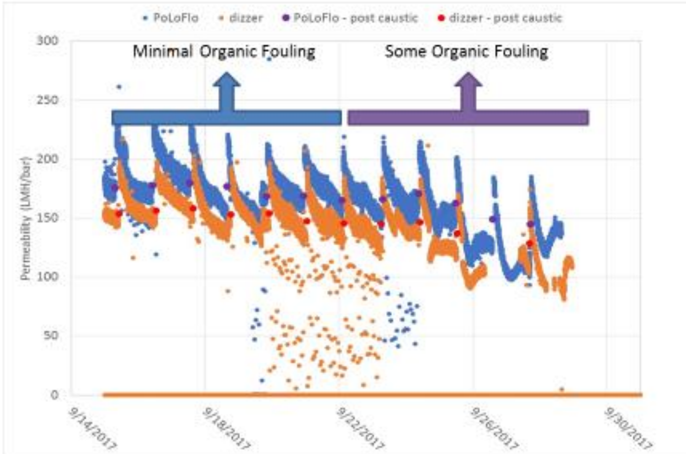


- Minor TOC removal, but high aromaticity removal
  - High SUVA removal
  - Aliphatic TOC (small MW?) not a foulant
- Removal by both membranes is the same
  - No difference in how the organic foulant sticks to the surface
  - Does surface chemistry impact cleaning efficiency?

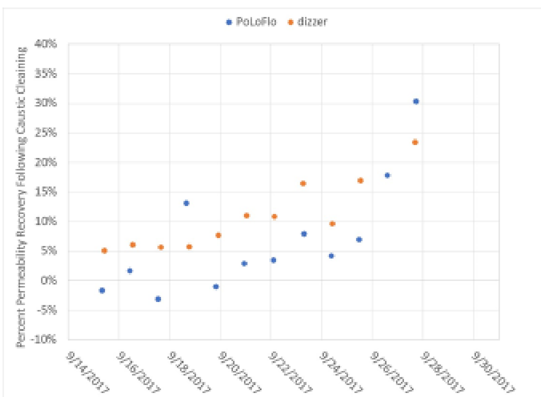


CEB Performance Recovery

- Daily chemically enhanced backwash (CEB)
  - Caustic (pH 11.5-12.0) → Removes Organic Foulants
  - Sulfuric Acid (pH 2.0-2.5) → Removes Mineral Foulants



Impact of Organic Fouling



Post-Caustic Permeability Increase (%)*	PoLoFlo	dizzer
Min	-4.05%	0.05%
Max	684.91%	24.63%
Median	**1.67%**	**5.69%**

* Total Permeability Increase after full CEB is ~ 20-25%

- Caustic clean more effective on dizzer than PoLoFlo
  - More organics depositing on dizzer surface
- Trend in Caustic CEB Importance matches SUVA trend
- Mineral fouling WAY more important for this water source
  - 80% of permeability recovery due to acid cleaning

Abstract Accepted for Presentation at CA NA AWWA Fall Conference, 2018, Rancho Mirage, CA

Title: **Demonstration of a Novel Amphiphilic Ultrafiltration Membrane for Improved Energy Efficiency of Membrane Treatment**

Participants in this section will learn about a recent field demonstration of an innovative amphiphilic, anti-adhesive ultrafiltration (UF) membrane to increase the water yield and reduce the energy demand for water treatment and reclamation.

Abstract:

During water treatment using microfiltration (MF) and ultrafiltration (UF) membranes, organic and inorganic foulants deposit on the membrane surface and pores, increasing the transmembrane pressure (TMP) and thereby increasing the energy demand. Current techniques to minimize fouling primarily involve incorporation of hydrophilic compounds to repel deposition of organic foulants. However, the types of foulants in the feed water are complex in nature and include organic, inorganic and microbial constituents. The limitation in the current approach is by only creating a hydrophilic surface the major organic components can be repulsed initially from the surface, but others (for example inorganic foulants) can still attach to the membranes. This, in turn, can facilitate eventual deposition of both organic and inorganic materials, thereby increasing the energy demand. This project evaluated the efficiency of a novel UF membrane that has amphiphilic (that is both hydrophilic and hydrophobic) functionality as well as anti-adhesive characteristics that retard deposition of both organic and inorganic foulants.

A one-year field demonstration of this amphiphilic UF membrane was performed at a surface water treatment facility. The treatment process at this facility consisted of coagulation-flocculation and sedimentation followed by microfiltration (MF) to remove turbidity, waterborne pathogens and other contaminants. A pilot unit used in the demonstration study consisted of two UF trains, which allowed for simultaneous side-by-side testing of anti-adhesive and conventional UF membranes. Initially, the feed water to the existing MF membranes was used for the UF pilot study. Subsequently, pilot testing was also conducted using organic spiked surface water as a surrogate for recycled water, as well as backwash water generated from the full-scale membrane process. In addition, a bench scale study was performed with RO test cells to evaluate the benefits of the novel UF membrane on downstream RO treatment often used for water reclamation.

The increase in TMP for the amphiphilic membrane was observed to be much lower (~20%) compared to the standard membrane. Additionally, compared to the standard membrane, higher water yield could be obtained with the amphiphilic membrane due to the decreased backwash frequency required. The lower fouling potential (hence, lower energy demand) and increased water yield observed for this novel membrane could help to reduce the costs associated with membrane treatment.