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Managing Water in the West

Desalination and Water Purification Research and Development Program Report No. 84

New Ultrafiltration Capillary Membrane and Study of Fouling Parameters, Flux Restoration, and Pathogens Retention Using Membrane Sampling Device

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

November 3, 2000

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Please note that this version of the report is directly from the original author.

HYDRANAUTICS
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November 3, 2000

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Re: Final Report – Financial Assistant Agreement No. 98FC810060
"Development of New Ultrafiltration and Capillary Membrane and Study of Fouling Parameters, Flux Restoration and Pathogens Retention Using Membrane Sampling Device"

Dear Frank,

We are pleased to enclose our final report on the above subject. As you can see from the report, most of the work was accomplished at the University of Central Florida, our co-partner for this project.

We appreciate BuRec's continuous support to our research and development programs. The diskette copy (a Microsoft Word document) will be submitted once I hear from you with your comments.

Sincerely,

Mark Wilf, Ph.D.
Vice President, Applications Technology
and Product Development

cc: Diana Mulligan (w/o encl.)

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Development of New Ultrafiltration Capillary Membrane And Study of Fouling Parameters, Flux Restoration and Pathogens Retention Using Membrane Sampling Device

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Final Report

September 2000

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Bureau of Reclamation
Technical Service Center
Environmental Resources Team
Water Treatment Engineering and Research Group

Final Report

September 1, 2000

Wastewater Reclamation by a Newly Developed Ultrafiltration Capillary Membrane:

Effect of Operating Conditions on Fouling Behavior and Filtrate Water Quality

Submitted to

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1.0 INTRODUCTION

The use of UF membrane processes to treat secondary/tertiary wastewater for reuse are becoming common practice in the United States, as the depletion of fresh drinking water supplies continues. However, the performance of UF membranes can be affected by several factors such as feed water characteristics and operating conditions. Common operational conditions controlling UF membrane filtration include operating flux, backwash frequency, cross flow velocity and coagulant dose. Furthermore, membrane productivity can be significantly deteriorated by fouling, which results from solid, organic and microbial contaminants present in the feed water. The optimization of such conditions is essential to achieving the desired productivity and filtrate water quality during membrane filtration.

The purpose of this project is to assess the effect of various operating conditions on the performance of a newly developed small-scale HYDRAcap ultrafiltration pilot system designed for wastewater reclamation. More specifically, the objectives are:

- To evaluate the effectiveness of the UF Mini-HYDRcap Pilot Unit at determining the effect of operation flux on fouling.
- To evaluate UF membrane productivity and filtrate water quality under varying operating conditions.
- To measure the effect of the mass loading of solid, organic and microbial contaminants on membrane productivity.
- To develop a statistical model that correlates experimental operating conditions to membrane performance.

A series of pilot experiments were conducted using tertiary treated wastewater from the University of Central Florida's extended aeration wastewater plant located in Orlando, Florida. The effect of various operating conditions on membrane productivity was assessed by comparing the decline of the temperature corrected mass transfer coefficient (MTC) of water with respect to runtime. The operating conditions investigated were

operating flux, backwash frequency, cross flow velocity, and coagulant dose. In addition, the feed and filtrate concentrations of solid (turbidity and particle counting), organic (UV_{254} and TOC), and microbial (Total Coliform and Heterotrophic Plate Counts) parameters were measured to determine removal efficiency of the UF membrane under varying operating conditions. Lastly, a correlation between solid, organic and microbial loading to membrane system and membrane productivity was developed statistically using the experimental results obtained in this study. Based on the modeling results, process optimization and recommendation were discussed and delineated for future applications.

2.0 EXPERIMENTAL METHODS

The following chapter provides detailed information on the experimental methods used in this project. First, the source water and pilot unit used in this study are briefly presented. Next, the specific pilot operational procedures followed during the course of this project are provided. Lastly, information regarding the approach used to perform the water quality analysis including equipment, sampling techniques and analytical methods, is systematically documented.

2.1 Source Water

Source water for this project was tertiary treated wastewater obtained from the University of Central Florida (UCF)'s extended aeration wastewater treatment plant located at Orlando, FL. This one-mgd wastewater treatment plant began treating wastewater in 1968. In recent years, the facility has extended its service to provide treatment of wastewater generated from the nearby Research Park.

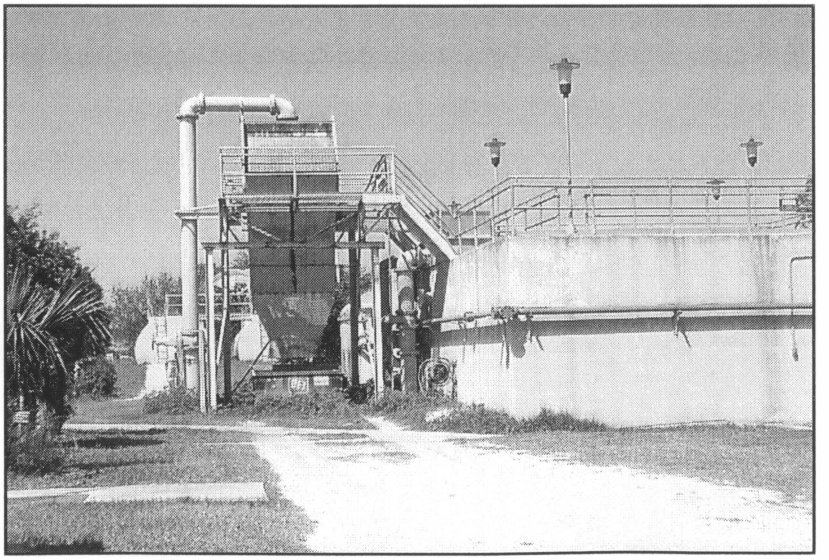
As shown in Figure 2-1, influent enters the plant through a 16" vitrified clay pipe and immediately passes through a bar screen to remove any large debris. Next, the water is pumped to an aeration tank, which contains bacteria and wastewater solids for waste

decomposition. The wastewater then enters settling tanks where it undergoes clarification. Supernatant from the clarification process is then collected in a wet well before entering sand filters for tertiary treatment. Such treatment removes any organic and solids not removed by the settling process. Lastly, the water is sent to a chlorine contact chamber for disinfection and discharged to a nearby evaporation percolation pond. Typical plant effluent water quality is provided in Table 2-1 (Eflin, 1999). The water quality presented is based on samples taken after chlorine contact during normal plant operation. It is important to note the water used in the current pilot study was routed to the pilot unit after sand filtration (*i.e.* before chlorination). Therefore, the feed coliform concentrations were much higher than presented in Table 2-1. In addition, frequent plant upsets during the course of the project elevated the particulate feed water quality.

Table 2-1 UCF WWTP Effluent Water Quality Reported by Plant

Parameter	Finished Water
Fecal Coliform (cfu/mL)	< 2
TSS (mg/L)	< 3
BOD (mg/L)	5-6

Figure 2-1: UCF Wastewater Treatment Plant, Orlando, Florida.



2.2 Mini-HYDRAcap Pilot System Description

2.2.1 General Description

A Mini-HYDRAcap™ Pilot Unit, developed by *Hydranautics* (Oceanside, CA), was used to perform all experiments conducted during the course of this project. Figure 2-2 is a front view of the pilot unit. As shown, the unit consists of six identical 4" diameter membrane modules arranged in parallel. Filtrate flow meters and pressure gages are placed just above each membrane module. This design makes it possible for simultaneous operation of the unit at six different filtrate flux rates. Each membrane module contains approximately 20 ft^2 of an identical polyether sulfone thin hollow fiber ultrafiltration membrane with inside-out configuration; that is feed water enters the center of the capillary tubes, filters through the wall, and is collected outside of the fibers. The unit is designed to be operated in a direct filtration or cross-flow mode and is capable of producing filtrate flows ranging from 0.3-1.1 gpm per membrane module.

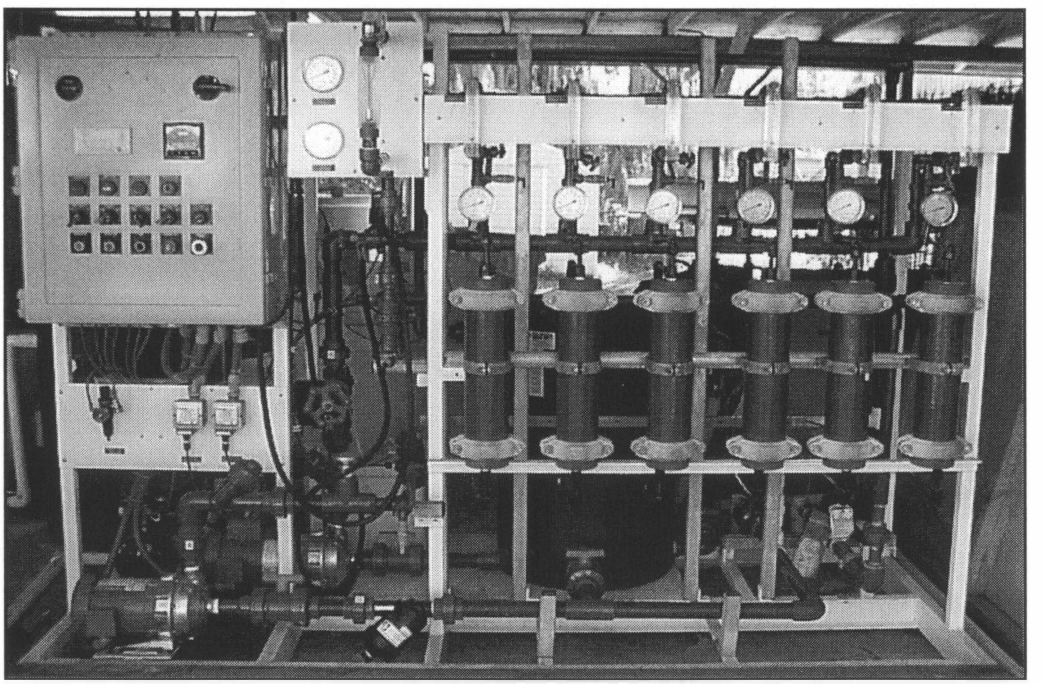
The HYDRAcap pilot unit features an automated backwashing system to remove foulants accumulated on the membrane surface during filtration. This system removes contaminants from the membrane surface through shear force by pumping filtrate water through the top and bottom of the membranes. In addition, the backwashing system is designed to inject chlorine into the backwash water to promote chemical breakdown of foulants present on the membrane surface. The backwashing cycle time and frequency can be changed through a programmable logic controller (PLC) equipped on the unit.

The unit is also designed to perform a semi-automated integrity test. The purpose of this feature is to identify any breaches in integrity of the membrane fibers. The test is a direct method in which pressure is applied to the inside of the membrane fibers. Final assessment of the integrity of the individual membranes is done by visual inspection of the filtrate flow meters. The presence of air bubbles in the meters indicates a degradation of membrane fibers.

2.2.2 Membrane Properties

As stated above, the Mini-HYDRAcap™ membrane modules contain thin hollow fiber UF membranes. Specifically, each module is comprised of approximately 2,000 fibers which have an inside diameter of approximately 0.8 mm and an average molecular weight cut of 150,000 Dalton. This particular membrane is designed for the treatment of surface water and secondary municipal wastewater effluent. Because of the poor feed water quality of source waters, the membranes were designed to withstand a wide pH range (2-13) and high chlorine exposure (100 ppm). Such characteristics allow for versatility in cleaning and backwashing procedures, respectively.

Figure 2-2: Mini-HYDRAcap Pilot Unit (Front View).



2.2.3 Process Flow

Figure 2-3 is a process flow diagram of the Mini-HYDRAcap pilot system. The diagram clearly identifies the main components of the system including tanks, pumps, valves, gages and meters. Specific details of these components are presented in Tables 2-2 to 2-5, respectively. A complete description of the process flow through the system is described below.

First, source water is gravity-fed from the nearby wastewater treatment facility to the feed tank. As shown, the tank includes a manual float valve to control flow to the tank. Next, the feed water is pumped from the feed tank (T1) to the unit by the feed pump (P2). The pilot is designed to provide optional ferric chloride pre-treatment of the water before membrane filtration. A specific dose is injected into the pipeline running from the feed tank to the unit by a LMI metering pump (P1). The feed water then passes through a 300 micron pre-filter before entering the bottom of each individual Mini-HYDRAcap module.

If the unit is operating in the direct flow mode, all filtrate water entering the membranes modules exits as product water and is stored in the filtrate tank (T4). As shown, an overflow drain line is attached to the topside of the tank to prevent overflow. If the unit is operating in the crossflow mode, water exits the membranes in two streams (concentrate and filtrate). Concentrate water is recycled back to the feed line (before the pre-filter), while the product water is stored in filtrate tank.

The recovery of the system during direct filtration is dependent on both the operating flux and the backwashing frequency. During direct filtration at 30 gfd (0.4 gpm), the system recovery ranges from 58-90 % for backwashing frequencies from 15-60 minutes, respectively. It should be noted increasing the operating flux under the same backwashing conditions would result in an increase in recovery. Because 100 % of the cross flow is recycled the above recovery values are also achieved during cross flow filtration.

Table 2-2: Pump Characteristics of Mini-HYDRAcap Pilot System

ID Number	MFG	Type	HP	Function
P1	LMI	Metering	n.a.	Injects ferric chloride into source water during pre-treatment
P2	Goulds	Centrifugal	¾	Pumps water from feed tank to membranes
P3	Goulds	Centrifugal	2	Backwashing pump
P4	LMI	Metering	n.a.	Injects chlorine into filtrate during backwashing

Table 2-3: Storage Tank Characteristics of Mini-HYDRAcap Pilot System

ID Number	Volume (gallons)	Description
T1	55	Feed Water Storage Tank
T2	50	Ferric Dose Storage
T3	7	Chlorine Storage Tank
T4	85	Filtrate Storage Tank

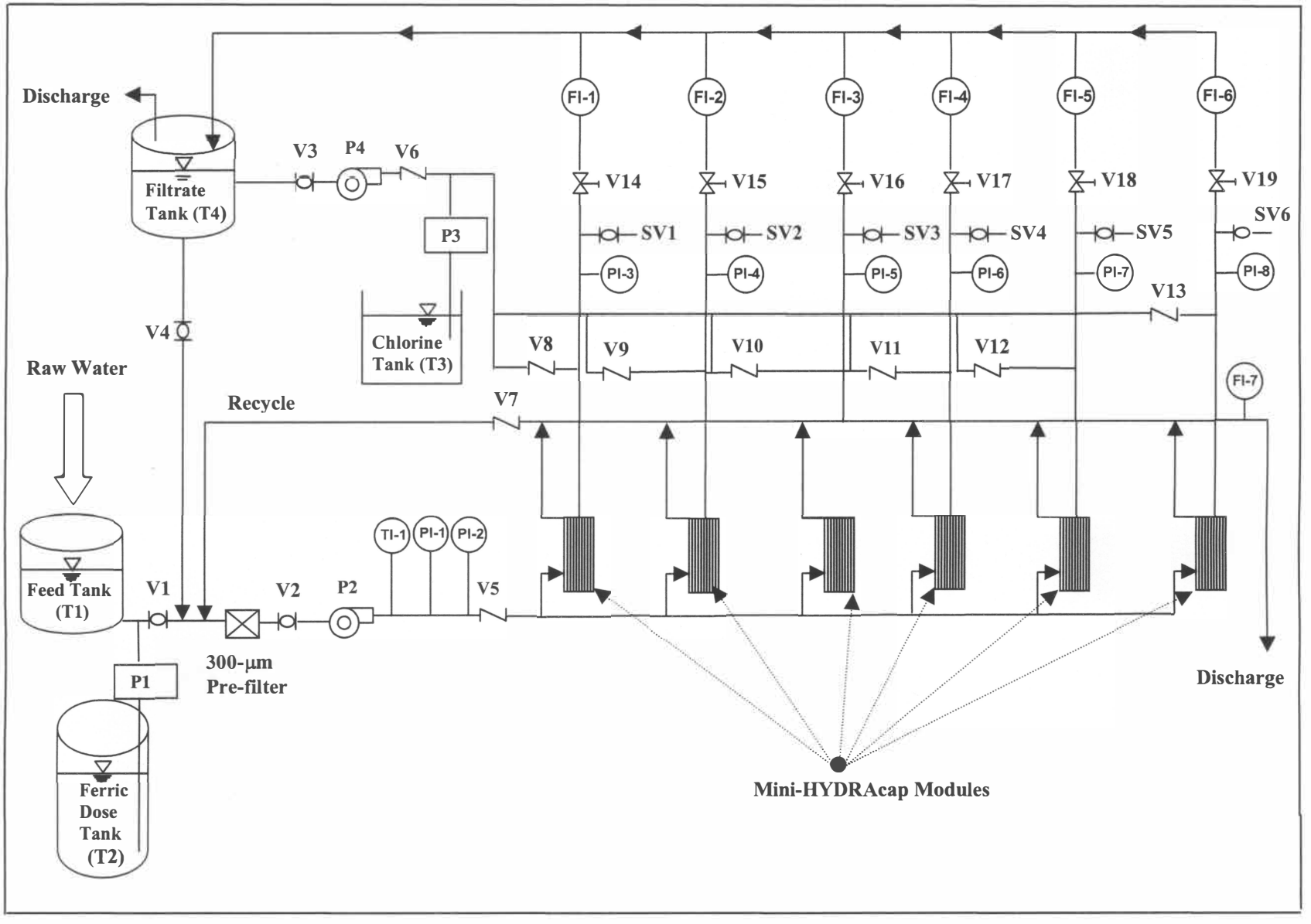
Table 2-4: Valve Characteristics of Mini-HYDRAcap Pilot System

ID No.	Quantity	Size (inches)	Valve Type
V1-V4	4	1-1/2"	True union ball
V5- V6	2	1-1/2"	Y pattern check
V7	1	1/4"	Check
V8-V13	6	1/2"	Ball-check
V14-V19	6	1/2"	Needle
SV1-SV6	7	1/4"	Solenoid

Table 2-5: Gage and Meters Characteristics of Mini-HYDRAcap Pilot System

ID Number	Measurement Range	Description
PI-1	(0-60) psi	Feed Pressure Gage
PI-2	(0-60) psi	Concentrate Pressure Gage
TI-1	(30-130) °F	Feed Water Temperature Gage
PI-(3-8)	(0-60) psi	Filtrate Pressure Gage
FI-(1-6)	(.2-2) gpm	Filtrate Flow Meters
FI-7	(1-10) gpm	Concentrate Flow Meter

Figure 2-3: Pilot Process Flow Diagram.



2.3 Pilot Operational Procedures

The general sequence of steps followed during experiments includes membrane cleaning, clean water flux analysis, membrane integrity testing, and setting of operational conditions. A detailed protocol of each step, based on information provided in the Mini HYDRAcap Users Manual (Separation Engineering Inc., 1999) is provided in thissection.

2.3.1 Membrane Cleaning

Prior to each experiment, the membranes were thoroughly cleaned using both high and low pH solutions. The high pH solution was prepared by dissolving approx. 5-lb citric acid in 30 gallons of potable water to achieve a pH ranging from 2 to 2.5. The low pH solution was prepared by mixing 750 ml of 50 % sodium hydroxide into 30 gallons of potable water to achieve a pH ranging from 12 to 12.5. Next, membrane cleaning was performed by completion of the steps shown below:

1. Close all valves on the filtrate tank.
2. Prepare low pH cleaning solution in the filtrate tank, mix thoroughly, and measure solution pH.
3. Open the valve at the bottom of the filtrate tank that controls the flow to feed pump.
4. Disconnect the discharge hose attached to the top of the filtrate tank and the discharge hose coming from the concentrate line.
5. Attach the hose from the concentrate discharge to the top of the filtrate tank.
6. Set the processing time to 53 minutes (maximum current setting).
7. Turn the flow selector switch to "cross flow" and press the start button.
8. Set concentrate flow to 6 gpm and close all filtrate valves.
9. Allow the cleaning solution to circulate via the concentrate line for 43 minutes.
10. Open each filtrate valve to 1 gpm and allow to circulate for 10 minutes.
11. Backwash the cleaning solution to drain.

12. Fill the filtrate storage tank with potable water and backwash to drain.
13. Repeat steps (2-12) using high pH cleaning solution.

2.3.2 Clean Water Flux Profile

To assess whether a given cleaning procedure adequately restored the flux capacity of each membrane, a clean water flux profile was developed. Profiles were generated by plotting operating flux versus transmembrane pressure (TMP) for each membrane. Specifically, the TMP was based on the pressure required to maintain filtrate flow rates of 1.2, 0.8, and 0.4 gpm for each membrane. The MTC values of each clean membrane was then determined through linear regression of flux on TMP. These values were then compared to the MTC values determined at the on set of the project (*i.e.* new membranes) to determine the percent recovery of the initial productivity. If the recovery was less than 75%, the cleaning procedure was repeated. The clean water flux profiles and percent recovery calculations after cleaning are provided for each pre-experimental condition in Appendix D. Detailed procedure for clean water filtration is provided below:

1. Drain, flush and fill filtrate storage tank with potable water.
2. Close all valves on the filtrate tank.
3. Set processing time to twenty minutes (direct flow).
4. Press the start button and adjust the feed pump speed to ~ 70% (feed pressure 20 psi-25 psi).
5. Adjust each filtrate flow to 1.2 gpm; allow flow stabilize for 5 minutes.
6. Record the feed water temperature, and filtrate pressure of each membrane.
7. Repeat steps 5 - 6 at filtrate flows of 0.8 gpm and 0.4 gpm.
8. Develop a plot of temperature corrected flux vs. transmembrane pressure.
9. Compare MTC values obtained from step 8 to the new membrane MTC values.

2.3.3 Membrane Integrity Test

Prior to beginning a given experiment, each membrane was also tested to assure membrane integrity using the semi-automated pressure hold test built into the Mini-HYDRAcap Pilot unit. The test is initiated by introducing approximately 20 psi of air to the feed side of each membrane. A damaged membrane would allow the air to escape through the membrane and therefore can be detected by the presence of air bubbles in the filtrate valve. The following steps summarize the procedure performed to conduct each pressure hold test:

1. Begin test in the soak (idle position).
2. Press the pressure hold button (ensure the pressure regulator on the compressor is set between 15 and 20 psi.).
3. Allow air to enter the membrane until the feed and concentrate pressure is 15<psi<20.
4. Visually inspect each filtrate flow meter for the presence of air bubbles for 2 minutes.
5. Isolate and pin the bottom and top of all damaged membranes (see Section 2.3.4).
6. Open the concentrate sample valve to remove air from the system.
7. Switch the system to crossflow and drain concentrate.
8. Readjust the pump frequency between 50-60%.
9. Press the system star button twice.

2.3.4 Damaged Capillary Repair

During the course of the project, there were no compromised fibers detected by the pressure hold test. In the event that air bubbles are detected in the filtrate valves, the procedure presented below is followed to repair the damage fibers:

1. Remove the membrane module containing the damaged capillary from the holder.
2. Fill the filtrate storage tank with approximately 20 gallons of potable water.
3. Connect the air hose to the center collection tube at one end of the membrane (adjust the pressure regulator to 1-2 psi).

4. Submerge the membrane vertically in the filtrate storage tank so that the end with the pressure fitting is on top and is under approximately six inches of water.
5. Observe which fiber is damaged, by detecting bubbles.
6. Once the damaged fiber is located place a small pin in the fiber top and bottom.
7. Repeat steps 3 - 5 to be sure the damaged membrane was correctly identified and pinned.
8. Reassemble the membrane to its original position.
9. Reset the pressure adjustment gage between 15 - 20 psi.

2.3.5 Ferric Chloride Dosing

In order to enhance UF membrane performance, feed water was dosed with ferric chloride prior to UF filtration during several experiments conducted in this project. The dose was injected into the source water at the beginning of the pipeline leading from the feed storage tank to the feed pump. This allowed for a mixing length of approximately. 15-ft prior to membrane filtration.

Experimental doses included 7-ppm and 14-ppm as ferric chloride. The ferric chloride used in dosing was 40% by weight and was purchased at the on set of the project. The following sample calculation illustrates the method used to determine the proper dilution volume and the required flow rate of ferric chloride to achieve a 7-ppm dose.

First, the ferric chloride stock concentration (mg/l) based on 40% by weight and specific gravity of 1.395 was determined:

$$Ferric\ Chloride\ Stock = (0.40) \times (1.395) \times (1000 mg/ml) \times (1000 ml/l) = 558{,}000\ \ mg/l \quad (2\text{-}1)$$

Next, the volume of stock ferric chloride required (V_r) based on a 100:1 dilution factor and mixing volume of 40 gallons was calculated:

$$V_r = (40gal.) \times (1/100) \times (3.785l/gal.) \times (1000ml/l) = 1514 \ ml \ FeCl_3 \quad (2\text{-}2)$$

Lastly, the desired injection flow rate to achieve a 7 ppm ferric dose based on a feed flow rate of 3.45 gallons per minute was evaluated:

$$\begin{aligned} \textit{Injection Flow Rate} &= \frac{(7mg/l) \times (3.45gal./\min) \times (3.785l/gal.) \times (1000ml/l)}{(558{,}000/100)mg/l} \\ &= 16.3 \ ml/\min. \ FeCl_3 \end{aligned} \quad (2\text{-}3)$$

2.3.6 Backwashing

Backwashing of the Mini-HYDRAcap membrane modules is performed through an automatic sequence of steps controlled by a programmable logic controller (PLC). The frequency of backwashing and the duration of each step can be altered using the Siemens interface screen included on the unit. The backwashing steps include forward flush, bottom backwash, top backwash, soak cycle, and final rinse. A description of each of the above steps as are summarized below.

Forward Flush – During this step, feed water is driven through the inside of the capillaries fibers to shear any foulants accumulated on the inner surface.

Bottom Backwash – In this step, filtrate water is pumped to the permeate side of the membrane by the backwash pump and exits at the bottom end of the membrane module. This is intended to concentrate cleaning on the bottom end of the membrane modules. In addition during this step, the chlorine pump is initiated and remains active until the *Soak*

Cycle (see below). The pump injects NaOCl to the backwash water to promote chemical degradation of foulants accumulated on the membrane.

Top Backwash – This step is identical to *Bottom Backwash* with the exception that backwash water exits the top of the membrane module. Accordingly, this step is intended to concentrate cleaning on the top portion of the membrane modules.

Soak Cycle – During this step, the system is paused and chlorine is permitted to react with foulants accumulated on the membrane.

Final Rinse – During this step both the bottom and top membrane modules are rinsed with backwash water. Accordingly backwash water is fed to the filtrate side of the membrane and exits to drain through the feed and concentrate lines.

Table 2-6 presents the experimental sequence times of the above steps used for all membrane backwashing events performed during the course of this project. In addition, the processing time in between backwashing (*i.e.* backwash frequency) ranged from 15-30 minutes. As shown, experimental sequence times used are within the manufactures recommend range.

Table 2-6: Backwashing Sequencing Times.

Unit Operation	Sequence Time	
	Recommended by MFG	Experimental
Soak	10-30 s	20 s
Final Rinse	5-15 s	12 s
Processing	20-60 min.	15-30 min
Forward Flush	5-10 s	9 s
Bottom Backwash	5-12 s	12 s
Top Backwash	5-12 s	12 s
Cycles between chlorine	1-4	1

As stated above chlorination was performed during *Bottom Backwash* and T*op Backwash* by the addition of NaOCl. A 5.25 % (by weight) NaOCl solution was dosed at 40ml/min into a total backwash flow of aprroximately 20 gpm. Accordingly, the conentration of Cl_2 in the backwash water is calculated as follows:

$$Cl_2(mg/l) = \frac{(5.25gNaOCl)(1gH_2O)(1000mg)(cm^3)(m^3)(71.0gCl_2)}{(100gH_2O)(cm^3)(g)(10^{-6}m^3)(1000L)(74.5NaOCl)} = 5.00\times10^4\, mg/l \quad (2\text{-}4)$$

$$Backwash(Cl_2) = \frac{(5.00\times10^4 gCl_2)*(40ml)(\text{min.}^2)(gal)(l\ )(0.4\text{min.})}{(l)(\text{min.})(0.4\text{min.})(20gal.)(3.785l)(1000ml)} = 26.4\ mg/l \quad (2\text{-}5)$$

2.3.7 Operation Mode (Direct versus Crossflow Filtration)

The Mini-HYDRAcap unit can operate in two filtration modes: direct and crossflow. As shown in Figure 2-3, to operate the unit in direct filtration mode the operator must first manually open valves V1 and V2 and close V4 and V7. This allows the feed pump to draw water from the feed storage tank to supply the membranes modules. Next, the operator must turn the unit on and select the "direct-flow" mode using the flow mode selector switch located on the control panel. Once the proper flow mode is selected, filtration is initiated. It is then necessary to adjust the variable speed pump (P2) between 60% to 70% of the maximum speed and open the filtrate valves to the desired flow rates. The steps necessary to operate in crossflow mode are similar to direct flow, however V7 is not closed which allows the concentrate to be recycled back to the feed line. In addition, the crossflow rate is set between 0 to 10 gpm. The 10 gpm maximum crossflow results in a 0.1 m/s cross flow velocity to the membrane surface as shown below:

$$\begin{aligned} Crossflow\ Velocity &= \frac{(10gpm)(1\text{min})(3780cm^3)(gal)(element)(m)}{(60s)(2000\,fibers)(\pi\times0.04^2cm^2)(100cm)(6\ elements)} \\ &= 0.10\ m/s \end{aligned} \quad (2\text{-}6)$$

It should be noted this calculation is based on 2000 capillary fibers per HYDRAcap element each consisting of a 0.4 mm inside radius.

2.3.8 Membrane Productivity Measurement

The MTC value of each HYDRAcap membrane was monitored under various experimental conditions to assess productivity. Specifically this was achieved by reading and logging gage and meter values on the pilot unit three times a day. As presented in Appendix B, specific readings included the run hour, feed water temperature, feed pressure, concentrate pressure, filtrate pressure, filtrate flow and concentrate flow (if operating in crossflow mode). The data was collected 5 minutes after a given back-washing event. Because the unit operated with a constant feed pressure, it was often necessary to readjust filtrate flow meters to their experimental values before taking a reading.

2.4 Water Quality Analysis

Solid, organic and microbial water quality parameters were measured in the feed and filtrate water to assess the water quality performance of the HYDRAcap membranes. In addition, feed water quality data was used to determine the mass loading effect of the above parameters on membrane productivity. Table 2-7 lists the specific water quality parameters measured along with the respective sampling frequency. Note that the sampling schedule is based on a ten-day processing time. Accordingly, the following section provides the sampling procedures and specific methods used in measuring solid, organic and microbial contaminants.

Table 2-7: Measured Water Quality Parameters and Sampling Frequency.

Parameter	Sample location						
	Feed	Filtrate 1	Filtrate 2	Filtrate 3	Filtrate 4	Filtrate 5	Filtrate 6
pH	Daily	Daily	Daily	Daily	Daily	Daily	Daily
Turbidity	Daily	Daily	Daily	Daily	Daily	Daily	Daily
Particle Counts	Daily	Daily	Daily	Daily	Daily	Daily	Daily
UV_{254}	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10
TOC	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10	Day 1,5,10
Total Coliforms	Day 1,10	Day 1,10	Day 1,10	Day 1,10	Day 1,10	Day 1,10	Day 1,10
*HPC	Day 1,10	Day 1,10	Day 1,10	Day 1,10	Day 1,10	Day 1,10	Day 1,10

***Heterotrophic Plate Count**

2.4.1 Sampling Procedure

All samples, excluding microbial parameters, were collected in 500-ml amber bottles. Sampling bottles were acid (1:1 HCL) and DI rinsed before each sampling event. To prevent contamination of foulants removed from backwashing, all samples were collected in a timely manner after 5 minutes of processing time following a backwash event. In addition, each sampling port valve was opened for 30 seconds prior to sampling to clear any contamination that may be present in the sampling lines. All samples were stored in a cooler and immediately transported to the nearby Environmental Systems Engineering Institute (ESEI) for water quality analysis.

Microbial samples were collected in 50 ml EPA sealed plastic containers. The following list of sampling instructions, as provided by the EPA for this particular container type, were followed in sampling.

1. Open container by pushing up on cap where indicated. (Do not use if arrow was broken before opening and do not take pill out of container.)
2. Fill container to "EPA Fill Line".
3. Close container by pressing cap from hinge side until it securely snaps shut.
4. Put tie through round hole on lid and pull through.

5. Complete information on sampling label.

2.4.2 pH Measurements

The pH measurement of samples was performed using the Standard 4500-H^+ B. Electrometric Method (19th Ed.). Reporting accuracy of this method is 0.01 pH units. The instrument used for pH measurements was a Corning 240 pH Meter. The pH meter was calibrated daily using Fisher Scientific Certified Standards. In addition, the potassium iodide (KI) level in the metering probe was maintained to the proper level throughout the course of the project.

2.4.3 Solids Measurement

2.4.3.1 Turbidity

Turbidity samples were measured within accordance to Standard 2130 B Nephelometric Method [19th Ed.]. The reporting limit for turbidity is 0.01 NTU. Measurements were made using a HACH Ratio Turbidimeter™ Model 18900 (Hach Company, Ames, IA). Stray light present during the Nephelometric turbidity measurement may reach the detector and be read as light scattered by the sample, leading to the largest source of error for low range turbidity measurements [0-2 NTU]. Accordingly, a stray light methanol standard was checked before each turbidity measurement. In each case, the standard was below 0.04 NTU and therefore deemed negligible. In addition, the calibration of the instrument was checked before each sample measurement by measuring turbidity standards of 1.57, 14.6 and 127 NTU. A deviation of ± 5% from the known turbidity value was accepted. At no time during the project was the instrument found to be outside the acceptable calibration range.

Turbidity samples were measured in 40-ml glass vials provided with the instrument. To minimize interference, the same vial was used for all turbidity measurements throughout the course of the project. The vial was rinsed with distilled water between each measurement. Excess water or condensation formed on the outside of the glass vial was removed prior to each measurement by wiping the vial with Kimwipes™ [Kimberly-Clark Corp., Roswelll, GA]. Next, the vial containing the sample was placed in the cylindrical holder located in the front of the instrument. The vial was oriented so the dot located on the top front was in alignment with a set mark on the instrument. Once the vial was properly positioned, it was covered with the provided cap. The turbidity was then measured by setting the instrument unit to the proper range; available ranges (NTU) are 0-2, 2-20, and 20-200. To assure precision, one duplicate measurement was made per sample set (*i.e.* 1 feed sample and 6 filtrate samples).

2.4.3.2 Particle Counting

Particle counting was performed using the Standard 2560 B. Electrical Sensing Zone Method [19th ed.]. The reporting limit for particle counts is 1/ml. The instruments used for all particle counts included a Hiaco/Royco 8000-A particle counter and CFC 800 sampler [Hiaco/Royco Company, Silver Spring, MY]. The following steps were performed for each particle count measurement:

1. Turn on counter (off/on switch located on back panel).
2. Press any key on counter screen until "start" option appears in lower left hand corner.
3. Fill 250 ml beaker with DI water obtained directly from the still.
4. Place beaker containing DI on the sampler platform; be sure it is secured by tightening screw.
5. Turn on sampler (off/on switch located on top right back panel).
6. Flush the sampler with DI @ 60 ml/min. until 50 ml remain in beaker (flow rate is adjusted using small knob bottom left hand corner of sample).

7. Refill beaker with DI.
8. Set flow rate of sampler to 60 ml/min.; stabilize for 15 s.
9. Press "start" on the counter screen.
10. After 30 s, shut off sampler.
11. Repeat steps 7 - 10 until DI particle counts (2 micron) are < 20.
12. Fill beaker with sample (note: to prevent cross contamination the feed sample, which contained the most particles, was sampled last).
13. Repeat steps 8 - 10.
14. After three consecutive sample measurements, repeat steps 7 - 11.

2.4.4 Organic Measurement

2.4.4.1 UV_{254} Absorbency

Samples were measured for UV_{254} within accordance to the Standard 5910 B. Ultraviolet Absorption Method [19th ed.]. The reporting limit for UV_{254} is 0.0001 AUFS. The instrument used for all measurements was a Hach DR/4000 U Spectrophotometer [Hach, Company Ames, IA]. Samples were filtered prior to measuring UV_{254} to remove any suspended organic matter present. As specified in SM 5910-B, the specific filter used was a Type A/E 0.47 μm glass fiber filter [Pall Corporation]. In addition, the pH was verified to be between 4-10. The following steps were performed in UV_{254} measurement.

1. Turn on spectrophotometer (off/on switch located on back panel).
2. Select the Organic UV_{254} users program.
3. Under the options menu change the cell size to 5-cm.
4. Allow sufficient time for the UV bulb to warm up (upon warm-up the flashing "UV-VIS" symbol upper right hand corner stops flashing).
5. Fill the 5-cm glass cell with DI from the still.

6. Remove excess water from the ends of the cell with *Kimwipes*™ (Kimberly-Clark Corp., Roswelll, GA).
7. Insert cell into holder (be sure the cell ends are orientated in the same direction for each sample measurement).
8. Close protective cover.
9. Zero the instrument using touch pad screen located on front of the instrument.
10. Filter sample with 0.47 μm glass fiber filter sample using a suction apparatus (rinse filter with DI to remove the presence of any organic matter prior to filtering).
11. Remove the cell containing DI, rinse and fill with sample.
12. Insert cell into holder.
13. Record the UV_{254} measurement (cm^{-1}).
14. Repeat steps 5 - 13 for each sample.

2.4.4.2 TOC (NPDOC)

Samples were measured for TOC in accordance to the Standard Persulfate Ultraviolet Oxidation Method 5310 C [19th ed.]. The reporting limit for dissolved organic matter (NPDOC) is 0.1 mg/L. The instrument used for TOC analysis was a Phoenix 8000 TOC Analyzer [Tekmar Dohrmann, Cincinnati, OH]. This unit is equipped with a Gilson auto-sampler (70-sample capacity) and stores data via a computer interface. The data is input and managed using TOC Talk Version 2.1 Software. Operation of the instrument was performed under the guidance of the User's guide to the use of the Phoenix 8000 Total Carbon Analyzer (Norris, 1997). The following steps were performed in operating the unit.

1. Prepare the following reagents in accordance to the User's Guide: DI water, Persulfate, gas supply and TOC Standards.
2. Select a calibration curve for the proper range of TOC concentrations.
3. Set up the sample run via the Sample set up screen.

4. Upon completion of the run save results.

In addition, quality assurance and quality control procedures established by ESEI were followed during the measurement of TOC. Accordingly one duplicate and spiked sample was prepared and measured for every seven samples measured. This frequency was established because each sampling event consisted of one feed water and six filtrate samples, for a total of 7 samples. For this project the percent recovery was determined for each spiked sample. A percent recovery ranging from 85 - 115% was deemed acceptable. Because the TOC in the source water ranges between 6 - 10 mg/l all measurements of accuracy were performed by spiking with 4 mg/l TOC.

2.4.5 Microbial Measurement

2.4.5.1 Total Coliform (TC)

Total Coliform analysis was performed in the Department of Molecular Biology and Microbiology at the University of Central Florida by Claudia Romero under the supervision of Dr. Saleh A. Naser. All measurements were conducted in accordance to Standard Method (SM) 9222 B. Total Coliform Membrane Filter Procedure (19th Ed.). The Total Coliform Membrane Filter Technique measures coliform groups as facultative anaerobic, gram negative, non-spore forming, or rod shaped bacteria that develop red colonies with a metallic golden sheen under specific conditions. Specifically the sheen is developed for 24 hours at 35°C on an endo type medium containing lactose. As presented in SM 9222 B., results of the coliform determinations were reported by the following equation:

$$Total\ Coliforms\ /\ 100\ ml = \frac{coliform\ colonies\ counted}{ml\ sample\ filtered} \times 100 \qquad (2\text{-}7)$$

In addition, when the total number of bacterial colonies (coliform and non-coliform) exceeds 200 per membrane or the if the colonies are not distinct enough for counting, it is reported as *to numerous to count* (TNTC).

2.4.5.2 Heterotrophic plate count (HPC)

Heterotrophic plate count measurements were also performed in the Department of Molecular biology and Microbiology at the University of Central Florida by Claudia Romero under the supervision of Dr. Saleh A. Naser. All measurements were conducted using the Standard 9215 B. Pour Plate Method [19th ed.]. The HPC (formerly known as standard plate count procedure) estimates the number of all live heterotrophic bacteria in water samples. As stated in the SM 9215 B., the combination of the procedure and medium, which produces the largest of number colonies, should be chosen. In addition all HPC samples were immediately analyzed to prevent changes in bacterial population. Samples were incubated in R2A agar and incubated for 48 hours at 35°C. Also all counts were performed immediately after incubation. As indicated in SM 9215 B, HPC colonies can arise in many forms including pairs, chains, clusters, or single cells. Therefore, HPC results are reported in CFU/ml as presented below:

$$CFU / ml = \frac{colonies\ counted}{actual\ volume\ of\ sample\ in\ dish} \qquad (2\text{-}8)$$

Furthermore as outlined in the SM 9215 B., when reporting results it is proper to include the method, incubation temperature and time, and the medium: for example, CFU/ ml, pour plate method, 35 °C/ 48 hr, plate count agar.

3.0 Results and Discussion

The following chapter presents results of pilot experiments conducted on the Mini-HYDRAcap unit. Specifically, the chapter is divided into the following four sections:

3.1 Theoretical Background

3.2 Effect of Operating Conditions on Membrane Productivity

3.3 Effect of Operating Conditions on Membrane Filtrate Water Quality

3.4 Statistical Model Development

Section 3.1 provides theory and background information utilized in assessing the results presented in subsequent sections. Section 3.2 presents a comparison of K_w decline as a function of operation time for selected experiments which were performed to isolate the effect of a specific operating condition on membrane productivity. Section 3.3 discusses results of the water quality analysis and includes the performance of HYDRAcap membranes at rejecting solid, organic and microbial contaminants under various operating conditions. Section 3.4 describes model development used to determine the effect of mass loading on membrane productivity.

3.1 Theoretical Background

In this section, the method involving pilot data analysis, including the determination of water mass transfer coefficient of water (K_w) and runtime is presented. In addition, background information on the resistance model describing productivity decline is provided.

3.1.1 Mass Transfer Coefficient of Water (K_w)

Membrane productivity is often described by the temperature corrected water mass transfer coefficient (MTC), also often referred to as specific flux. The procedure of estimating MTC values is briefly explained as follows.

Net driving force (NDF) is the amount of energy supplied to produce filtrate and evaluated by the following equation:

$$NDF = (\Delta P - \Delta \Pi) \tag{3-1}$$

Where: NDF = net driving force

ΔP = pressure gradient

$\Delta \Pi$ = osmotic pressure gradient

In the case of UF and MF processes, the osmotic pressure is negligible and the net driving force is simply equal to pressure gradient. The pressure gradient is described as the transmembrane pressure (TMP) and is determined by the average pressure difference across the membrane as shown in Equation 3-2.

$$\Delta P = \left(\frac{P_f + P_c}{2} \right) - P_p \tag{3-2}$$

Where: P_f = feed stream pressure

P_c = concentrate stream pressure

P_p = filtrate stream pressure

The amount of water passing through the membrane is termed the filtrate flux and is calculated by:

$$F_w = \frac{Q_p}{A} \tag{3-3}$$

Where: F_w = water flux

Q_p = filtrate stream flow

A = membrane area

The water flux across a membrane changes with temperature. Thus, the flux is generally normalized at a temperature of 20°C as follows:

$$F_{W20} = \frac{F_w}{2.72^{0.019(T-20^\circ C)}} \tag{3-4}$$

Where: F_w = water flux

T = temperature (°C)

F_{w20} = flux normalized to 20°C

It should be noted the temperature correction factor of 0.019 used in Equation 3-4 was provided by Hydranautics and used throughout the course of the project to correct K_w for feed water temperature variations.

Finally, the temperature corrected mass transfer coefficient (MTC) of water (K_w) is obtained by normalizing filtrate flux with respect to net driving force (*i.e.*, transmembrane pressure, ΔP):

$$K_w = \frac{F_{w20}}{NDF} = \frac{F_{w20}}{\Delta P} \tag{3-5}$$

3.1.2 Runtime Determination

An alternative method of evaluating UF membrane productivity is the determination of runtime. The runtime is often defined as the filtration time between cleaning events and represents the time at which the maximum tolerable transmembrane pressure is achieved.

The runtime can be determined using the linear normalized MTC decline rate as shown in Equation 3-6. As shown the runtime (days) is calculated by subtracting the initial and final normalized MTC values and dividing by the corresponding normalized MTC decline rate. The MTC_f value is determined by dividing the operating flux by the maximum TMP, which is membrane specific. In addition, MTC_i and the normalized MTC decline rate, $\Delta(MTC/MTC_i)/\Delta t$, can be determined from experimental MTC decline data.

$$Runtime = \frac{\left(MTC_f / MTC_i\right) - \left(MTC_i / MTC_i\right)}{\frac{\Delta(MTC/MTC_i)}{\Delta t}} \times (CF) \qquad (3\text{-}6)$$

Where: MTC_f = final value of MTC (gfd/psi)

MTC_i = initial value of MTC (gfd/psi)

$\Delta(MTC/MTC_i)/\Delta t$ = normalized MTC decline rate (1/hour)

CF = conversion factor (day/hour)

3.1.3 Resistance Model

A common method of modeling the decline of productivity during MF and UF membrane filtration is through the resistance model. In this model, the filtrate flux through the membrane (F_w) is expressed as a function of the total resistance encountered during filtration:

$$F_w = \frac{\Delta P}{\mu R_t} \qquad (3\text{-}7)$$

Where: ΔP = transmembrane pressure

μ = viscosity of water

R_T = total hydraulic resistance to filtrate flow

The mass transfer coefficient (MTC) of water (K_w) can then be related to total resistance by dividing both sides of Equation 3-7 by ΔP:

$$K_w = \frac{1}{\mu R_t} \tag{3-8}$$

The total resistance is often expressed as a series of hydraulic resistances caused by the membrane, and solid, organic, and microbial foulants present in the feed water:

$$R_t = R_m + R_{solid} + R_{organic} + R_{microbial} + R_{coagulated\ solids} \tag{3-9}$$

Where: R_m = membrane resistance

R_{solid} = resistance due to mass loading of solids

$R_{organic}$ = resistance due to mass loading of organics

$R_{microbial}$ = resistance due to mass loading of microorganisms

$R_{coagulated\ solids}$ = resistance due to mass loading of coagulant dose

As indicated in Equation 3-9, a resistance term can also included to account for the mass loading of coagulated solids resulting from the addition of coagulant pretreatment prior to membrane filtration. During dead end filtration, the resistance terms associated with the above mass loading terms can be simply related to filtrate volume ($F_w \times t$) and foulant concentrations present in the feed water as follows:

$$R_i = X_i\ F_w C_i t \tag{3-10}$$

Where: R_i = membrane resistance due to mass loading of foulant, *I*

F_w = operating flux

X_i = statistical coefficient (change of resistance with respect to mass loading of foulant, *i*)

C_i = feed concentration of foulant, *i*

t = filtration time

The individual mass loading resistance terms included in Equation 3-9 can be determined from various aggregate water quality parameters such as turbidity or particle counts for solid loading, UV_{254} or TOC for organic loading, and HPC or TC for microbial loading.

3.2 Membrane Productivity

The following section provides experimental results describing the effect of temperature, operating flux, backwash frequency, coagulant dose and crossflow velocity, on membrane productivity. The influence of feed water temperature on membrane productivity was first assessed by determining the temperature correction factor based on pilot operational data. Membrane productivity was then evaluated under the operating parameters listed above by monitoring K_w with respect to operation time during experiments that differed by a single operating parameter. The effect of operating flux on membrane fouling was further investigated by using the normalized MTC decline rates to calculate runtime, based on the maximum tolerable TMP of the HYDRAcap membranes. It should be noted that the productivity of the HYDRAcap membranes varied. Specifically, average K_w values for membranes one through six measured during filtration of clean water after cleaning were 13.3, 15.7, 21.5, 15.8, 19.2, and 15.7 gfd/psi, respectively (refer to Appendix D). The K_w values used to assess membrane productivity as presented in this section were estimated based on average values determined from

elements one, two, four, and six. As indicated, the measured productivity data of membranes three and five were excluded from the average because they were inconsistent with documented HYDRAcap productivity and varied significantly during filtration experiments (refer to Appendix D).

3.2.1 Effect of Temperature

As stated in Section 3.1.1, all measured MTC values were corrected for temperature by applying the following relationship:

$$Kw_T = Kw_{20°C} e^{0.019(T-20°C)} \qquad \text{(3-4 repeated for } K_w\text{)}$$

The temperature correction factor of 0.019 presented in Equation 3-4 was verified using actual pilot operational data. First, the equation was linearized by taking the natural log of both sides as follows:

$$Ln(Kw_T) = Ln(Kw_{min}) + \theta(T - T_{min}) \qquad (3\text{-}11)$$

Where: T_{min} = minimum temperature of pilot operational data

Kw_T = MTC values at a recorded operational temperature, T

Kw_{min} = MTC value determined at T_{min}

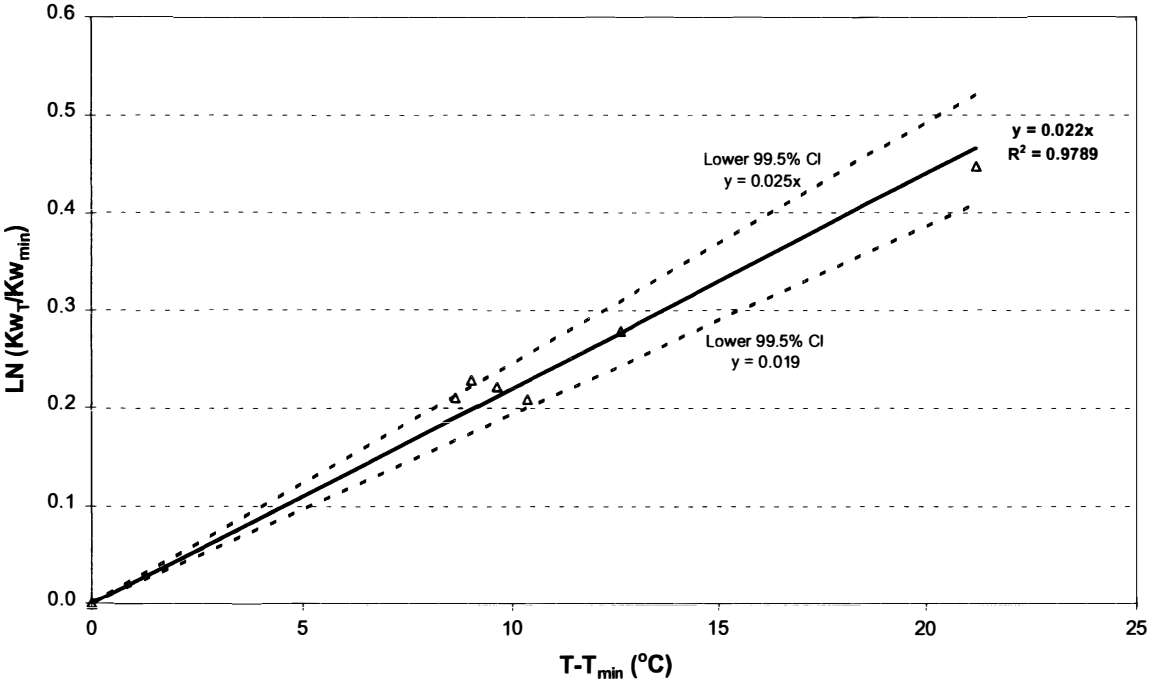
θ = temperature correction factor

Rearranging Equation 3-11

$$Ln\left(\frac{Kw_T}{Kw_{T\,min}}\right) = \theta(T - T_{min}) \qquad (3\text{-}12)$$

Next, θ was determined by plotting the right side of Equation 3-12 vs. ($T-T_{min}$). This plot was developed from pilot operational data and is presented in Figure 3-1. The y-values used in the plot were determined by averaging the MTC (non-temperature corrected) values of the six membrane elements after a given cleaning event. As shown in Table E-1 located in Appendix E, the effectiveness of cleaning events varied among the experiments. Therefore only K_w values determined from clean water flux profiles in which the average % recovery was within 5% were used to develop the plot. This corresponded to experiments A, E, F, G, I, M and O which represent a feed water temperature range of 12°C to 33°C. As indicated, the slope of line (θ) is 0.022 with a 99.5% confidence interval of ± 0.003. The positive values associated with this range indicate the slope is indeed positive and that the Ln (K_w/Kw_{Tmin}) increases with increasing temperature. Furthermore the interval contains the temperature correction factor of 0.019, provided by Hydranautics. It should be noted the broad range of this interval is due to the small number of data points used to develop the plot. The observed increase in productivity for increasing feed water temperature is due to the temperature dependency of water viscosity. As a result, a high temperature would have a lower viscosity and be subject to less frictional resistance passing through the membrane (Cheryan, 1998).

Figure 3-1: Temperature Correction Factor Determination for HYDRAcap UF Membranes Based on Operational Data. K_w values based on clean water flux profiles conducted prior to experiments A, E, F, G, M and O. K_w values measured at feed water temperatures ranging from 12 to 33 °C. Confidence intervals (CI) shown are based on linear regression analysis.



3.2.2 Effect of Operating Flux

The effect of operating flux on HYDRAcap productivity is systematically documented in this section. The results presented are based on data from experiments conducted at 20, 30, 44 and 60 gfd which have been identified as experiments B, F, E and C, respectively (Table A-1). As indicated in Table A-2, each of the above experiments were conducted under the following operating conditions: Backwash Frequency = 20 min, Ferric Chloride Dose = 0 ppm and Cross Flow = 0 gpm (*i.e.* dead-end filtration). A comparison of the temperature corrected MTC (K_w) decline as function of operation time for each of the above experiments is provided below.

Figure 3-2 presents K_w versus operation time for experiments conducted at 20, 30, 44, and 60 gfd. The trend lines were developed by regression analysis based on linear least squares fit. The R^2 values of trend lines (*i.e.* 0.70 for 30 gfd, 0.80 for 44 gfd, and 0.97 for 60 gfd) suggest that experimental data were relatively well described by the linear relationship, with an exception of the 20 gfd experiment (R^2=0.43). The linear regression trend lines also show that the slopes (dK_w/dt) were all negative values, indicating that K_w decreased with time for all of the operating fluxes tested under a given time period and experimental conditions. In addition, the magnitude of the K_w decline rates steadily increased as operating flux increased as shown in Figure 3-2. The K_w decline rates for 20, 30, 44, and 60 gfd were estimated at 0.0176, 0.0356, 0.0692, and 0.1718 gfd/psi/hour, respectively.

Also shown in Figure 3-2, the y-intercepts of the regression lines, representing the initial K_w values, ranged from 10.0 to 14.9 gfd/psi. This variation may be due to insufficient membrane cleaning between experiments, limitations of the filtrate pressure gage sensitivity, and performance variation among six membrane elements. In order to account for the variations in initial K_w (MTC_i), the values were normalized with respect

to the K_{w0} determined by the linear regression, and their decline rates, $d(K_w/K_{w0})/dt$, were plotted versus operation flux as presented in Figure 3-3. As shown, the decline rates of the normalized MTC values clearly increased with increasing operating flux. Figure 3-4 further illustrates the influence of flux on productivity by presenting the estimated runtimes, which can be achieved during operation at 20, 30, 44 and 60 gfd. The runtimes shown were determined using Equation 3-6 and represent the filtration time, which could be achieved prior to reaching a TMP of 17.5 psi. This pressure value is within the manufacturers maximum recommended range of 15-20 psi (Separation Engineering Inc., 1999). As shown in Figure 3-4, runtimes range from 25 to 1.6 days for operating flux values ranging from 20 to 60 gfd, respectively. This decrease of runtime associated with higher operating flux is attributed to an increased rate of mass loading, which causes irreversible fouling to occur much faster.

Specifically, the drastic increase of the normalized K_w decline rate was observed with 60 gfd experiment, compared to low operating fluxes. A similar trend has been observed by numerous investigations including a study by Laine *et al.* (1991) who utilized hollow fiber UF membranes for the treatment of Boise River water. The authors reported that severe fouling occurred at an operating flux of 60 gfd, while at 46.5 gfd no fouling was observed. However, it should be noted that, in our study, fouling occurred even at low operating fluxes (*e.g.* 20 and 30 gfd), probably due to poor feed water quality.

Enhanced membrane fouling at higher operating flux may be explained simply by the increase of mass loading of foulants to the membrane system. For example, direct membrane filtration of water at 60 gfd would filter three times the amount of water as a membrane operating at 20 gfd for the same time period. Assuming steady feed water quality, this would result in three times the mass loading of foulants to the membrane surface operating at 60 gfd. However, as shown in Appendix C, feed water characteristics varied during the course of the project, primarily due to frequent

disruptions of wastewater plant operation. Therefore to accurately correlate particle loading to the K_w decline rates, cumulative particle mass loading was calculated based on particle counts and then plotted against K_w, as presented in Figure 3-5. With the exception of the 20 gfd run, the results generally show the trend of declining K_w with increasing operating flux. Both 30 and 44 gfd experiments showed similar slopes (*i.e.* 1E-5), as expected for identical particle mass loading to the membrane. However, the slope of 60 gfd run slightly increased from 1E-5 to 3E-5 gfd/psi per unit particle mass loading (gal-counts/ft^2-ml). This finding is attributed to the difference in the structure of fouling layers formed at different operating fluxes. The cake layer could be more compressed under the operation at high flux due to the stronger drag force induced by filtrate flow. As a result, the fouling layer becomes more compact and causes larger hydraulic resistance (per a given particle loading) to filtrate flow. It is also expected that the removal of foulants by backwashing becomes more difficult as foulants are more densely packed.

Similar to Figure 3-5, cumulative organic loading to membrane system was evaluated based on feed UV_{254} and was plotted against K_w values measured at various operating fluxes. The results shown in Figure 3-6 indicated that K_w declined linearly with increasing organic loading. It was also found that the K_w decline rate increased with increasing operating flux. Similar results were documented by Robert (1999) who determined the mass loading of organic foulants, measured from NPDOC, was a significant fouling parameter responsible for productivity decline during MF/UF pilot studies. Even though significant portions of organic matter passed through the HYDRAcap UF membranes (refer to Section 3.3.2), organic substances seem to play an important role in membrane fouling during wastewater reclamation. High molecular weight organic matter could cause significant productivity loss through plugging membrane pores. The organics may also enhance biological activities in the membrane system, causing severe biofouling. Lastly, organic matter could act as a cohesive in the formation of irreversible particle fouling layer. The importance of organic matter in

fouling of UF/MF membranes has been pointed out by several investigators. Mallevialle *et al.* (1989) characterized the fouling layer formed during MF and UF membrane filtration of natural waters. They reported that the fouling layer was composed mostly of clay (kaolinite) and organic matter. Furthermore, the organic matter was found to be packed under the inorganic fouling layer, forming a gel-like organic matrix. The study of Bersillon (1988) on ultrafiltration of natural waters also confirmed that organic matter played a critical role in cohesion of the formed fouling layer, resulting in long-term flux decline.

Figure 3-2: K_w vs. Operation Time for Various Operating Flux (20-60 gfd). Experimental Conditions: Backwash Frequency = 20 min., Ferric Dose = 0 ppm, and Cross Flow = 0 gpm. Regression lines are based on linear least squares fit.

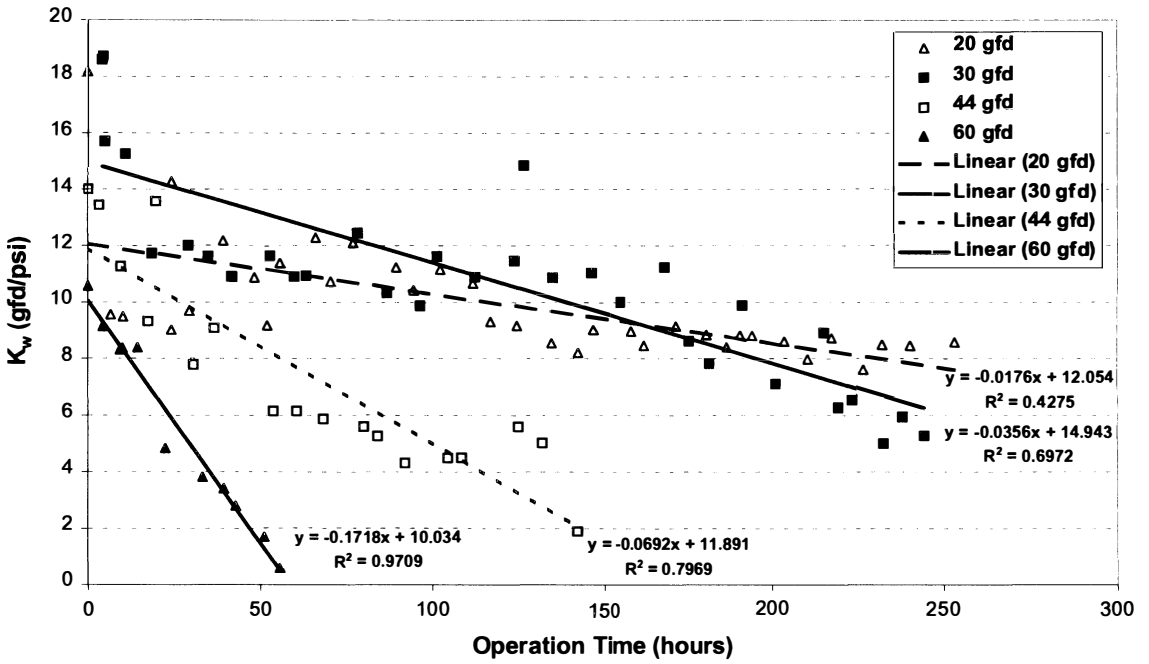


Figure 3-3: Normalized Productivity Decline Rate ($(dK_w/K_{w0})/dt$) versus Operating Flux. Experimental Conditions: Backwash Frequency = 20 min., Ferric Dose = 0 ppm, and Cross Flow = 0 gpm.

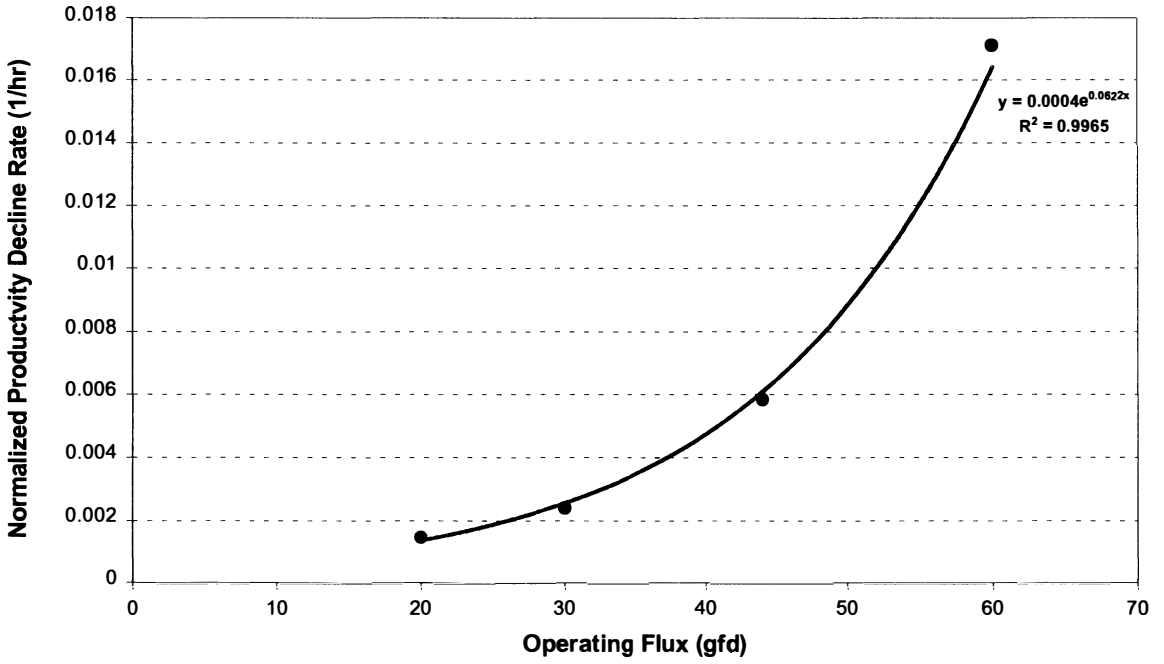


Figure 3-4: Runtime vs. Operation Flux. Experimental Conditions: Backwash Frequency = 20 min., Ferric Dose = 0 ppm, and Cross Flow = 0 gpm. Runtimes represent the filtration time before the transmembrane pressure reaches 17.5 psi. Runtimes were calculated using the normalized MTC decline rates determined from linear regression analysis.

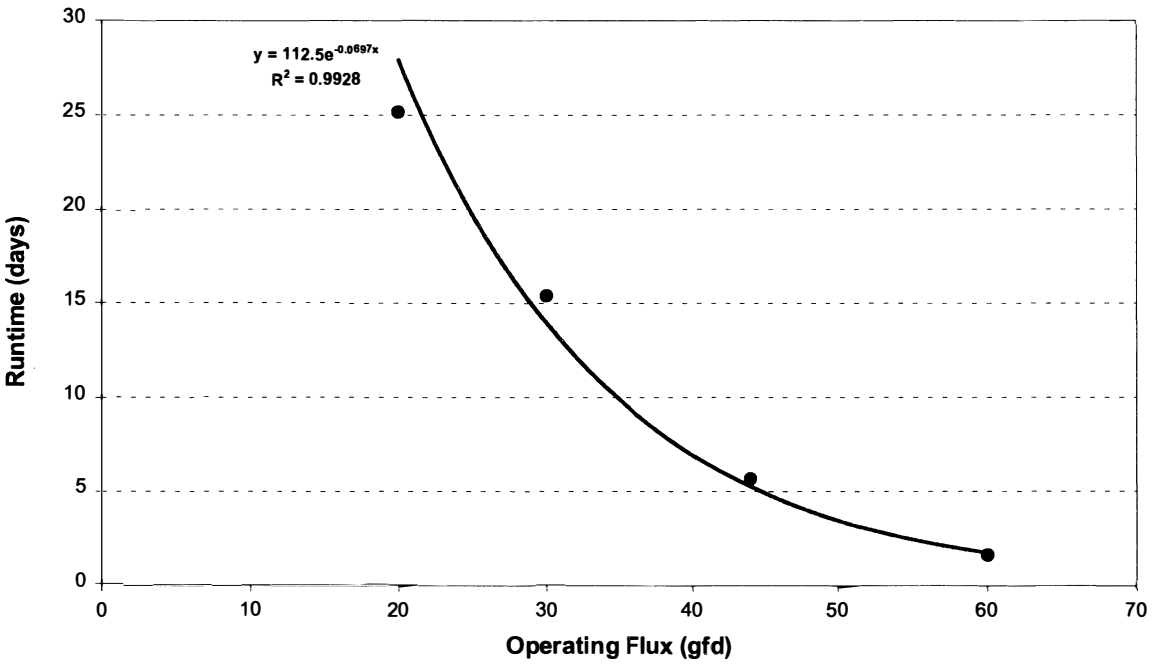


Figure 3-5: K_w vs. Particle Mass Loading Based on Particle Counts for Various Operating Flux (20 – 60 gfd). Experimental Conditions: Backwash Frequency = 20 min., Ferric Dose = 0 ppm, and Cross Flow = 0 GPM. Particle loading is estimated by particle counts (counts/ml) × filtrate volume per unit membrane surface area (gal/ft^2). Regression lines are based on linear least squares fit.

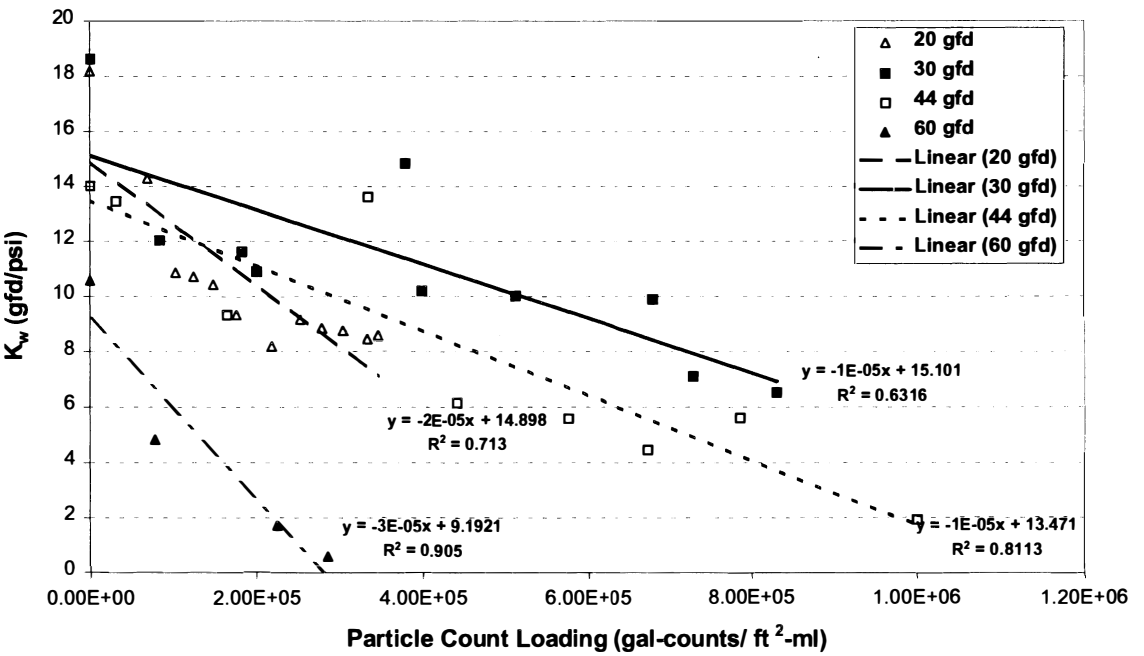
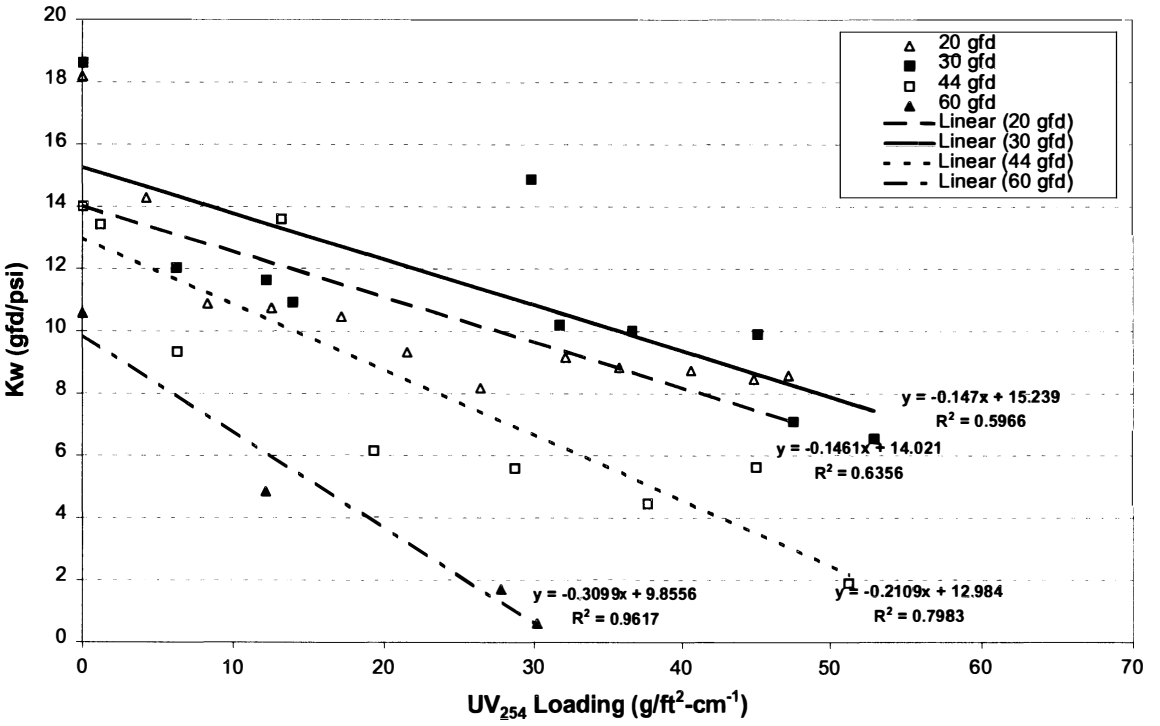


Figure 3-6: K_w vs. Organic Mass Loading Based on UV_{254} for Various Operating Flux (20 – 60 gfd). Experimental Conditions: Backwash Frequency = 20 min., Ferric Dose = 0 ppm, and Cross Flow = 0 GPM. Organic loading is estimated by UV_{254} (cm^{-1}) × filtrate volume per unit membrane surface area (gal/ft^2). Regression lines are based on linear least squares fit.



3.2.3 Effect of Backwash Frequency

The backwashing frequency (BWF) is one of the primary factors affecting UF/MF membrane performance. Particularly, in dead-end filtration, backwashing by air and/or water is the only means to remove foulants from the system. In this section, HYDRAcap productivity data is presented for experiments conducted at 15, 20, and 30 minute BWFs, identified as experiments G, F and H, receptively (Table A-2). Each experiment was conducted under the following operating conditions: Flux = 30 gfd, Ferric Chloride Dose = 0 ppm and Cross Flow = 0 gpm (*i.e.* dead-end filtration). The time associated with a given backwashing frequency corresponds to the filtration time before a backwashing event occurs (*i.e.* time interval between backwashing events). Accordingly, operating at a BWF of 30 minutes would result in two backwashing events per hour while operating at a BWF of 15 minutes would result in four backwashing events per hour. A comparison of K_w decline as a function of operation time for each of the above experiments is provided in the following section.

The importance of backwashing frequency is demonstrated in Figure 3-7 which presents K_w versus operation time for experiments conducted at 15, 20, and 30 minute BWFs. The trend lines developed from linear regression clearly indicated that K_w declined much faster as backwashing frequency increased. As shown in Figure 3-7, the slopes (dK_w/dt) of the linear regression lines for the 30 and 20 min BWFs were estimated at -0.0605 and -0.0356 gfd/psi/hour, respectively. However, the trend line of K_w observed during operation at the 15 min BWF was almost flat or slightly increased (0.0042) with respect to runtime, indicating that no fouling occurred within the given experimental duration. This observation suggested that decreasing the time between backwashing significantly improved UF membrane productivity. Lastly, the y-intercepts of the linear regression lines (K_{w0}) for the 30, 20, and 15 min. BWFs were found to be 15.9, 14.9, and 10.2 gfd/psi, respectively. The low K_{w0} value associated with 15 min. BWF is probably a

result of insufficient cleaning before the experiment, which may partially explain the slight increase of K_w observed during operation.

When assessing the optimal backwash frequency, it is also necessary to consider the effect of backwashing on system recovery. Figure 3-8 presents recovery values for backwashing frequencies ranging from 15-60 minutes; these values were calculated for a backwash flow of 20 gpm, backwash duration of 45 seconds and an operating flux of 30 gfd. As shown in Equation 3-13, the system recovery, during direct filtration, is simply one minus the ratio of total backwash volume to the total filtrate volume produced.

$$\text{Recovery} = 1 - \frac{Q_{backwash} \times t_{backwash}}{BWF \times F_w} \times (CF) \qquad (3\text{-}13)$$

Where: $Q_{backwash}$ = backwash flow (gpm)

$t_{backwash}$ = backwash duration (minutes)

BWF = backwash frequency (minutes)

F_w = filtrate flux (gfd)

CF = conversion factor (minutes/day)

As shown in Figure 3-8, increasing the backwash frequency from 15 to 30 minutes raises the system recovery by 36% (*i.e.* 58 to 79%). Therefore when determining the optimal backwash frequency, it is important to compare the increase of productivity associated with system recovery (*i.e.* higher backwash frequency) to the increase in productivity due to the reduction of K_w decline (*i.e.* low backwash frequency). Another consideration when increasing backwashing is the added chemical cost associated with chlorine addition.

The elimination of UF fouling observed with operation at the 15 minute BWF is consistent with previous studies Robert (1999) in which the author reported a significant

increase in runtime for backwash frequencies of 15 minute or less. These observations of increased productivity may be explained by several flux restoration mechanisms associated with backwashing. Such mechanisms include convection, oxidation, and biofouling control. Solid foulants, which block the membrane pores and/or accumulate on the surface of the membrane, are removed by convection, which results from the reverse flow of filtrate water through membrane. The chlorine present in the backwash water oxidizes or destroys organic adsorbed or accumulated on the membrane surface. In addition, the chlorine represses microbial growth, which would inhibit biofilm formation on the membrane surface. The effectiveness of chlorination for backwashing has been evaluated by several previous studies (Laine *et al.*, 1991; van der Graff *et al.,* 1999).

Further investigation of the effect of backwash frequency was conducted by developing a plot of K_w versus cumulative backwash volume as presented in Figure 3-9. This figure allows a direct comparison of the effectiveness of backwashing for various backwashing frequencies. As shown flux enhancement per unit backwashing water volume decreased with increasing backwash frequency. Specifically, the decline rates of K_w with respect to cumulative backwash volume for 30, 20, and 15 min. BWFs were estimated at 0.0018, 0.0012, and 0.0001 gfd/psi/gallons, respectively. This result clearly demonstrated that the efficiency of backwashing was dependent on backwashing frequency. It is expected that increasing time in between backwashing events allows the formation of thicker fouling layer that is not easy to remove, and thus leads to irreversible fouling. In addition, microbial growth on the membrane surface would be greatly enhanced with increasing time interval between chlorine injections by backwashing.

Figure 3-7: K_w vs. Operation Time for Backwash Frequencies (15 – 30 minutes). Experimental Conditions: Flux = 30 gfd, Ferric Dose = 0 ppm and Cross Flow = 0 gpm. Backwashing was performed for 65 seconds including 25 ppm NaOCl addition for 24 seconds. Regression lines are based on linear least squares fit.

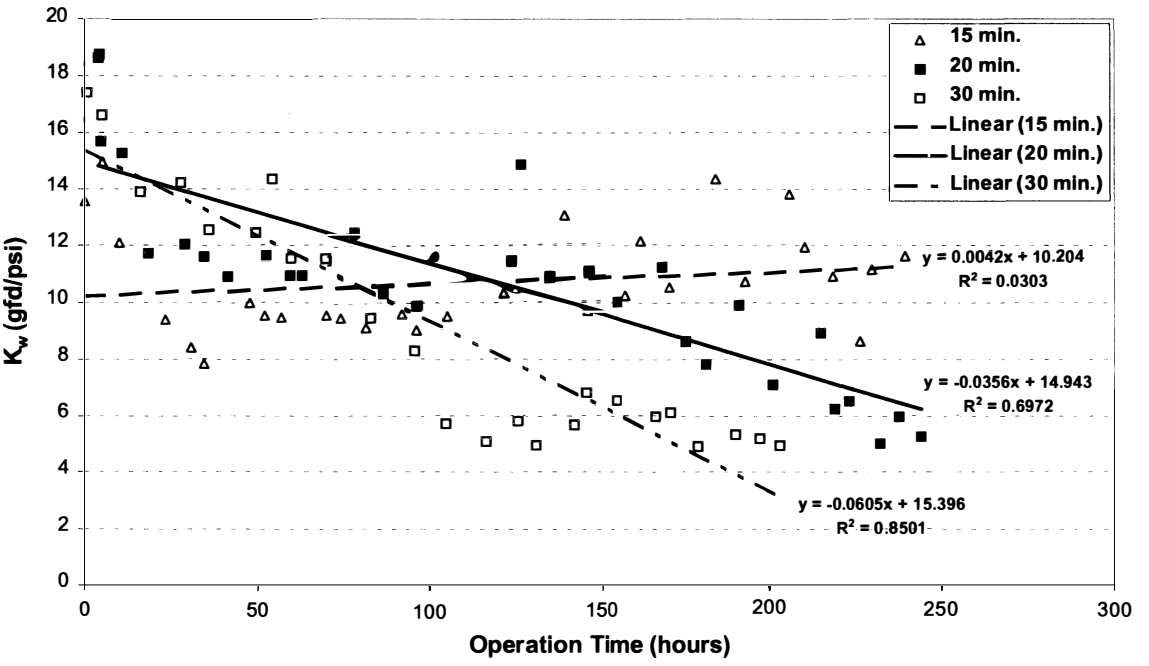


Figure 3-8: Recovery vs. Backwashing Frequency (15 – 60 minutes). Recovery values based on system performing direct filtration at 30 gfd (0.4 gpm) with a 20 gpm backwash flow for a 45 second backwash duration.

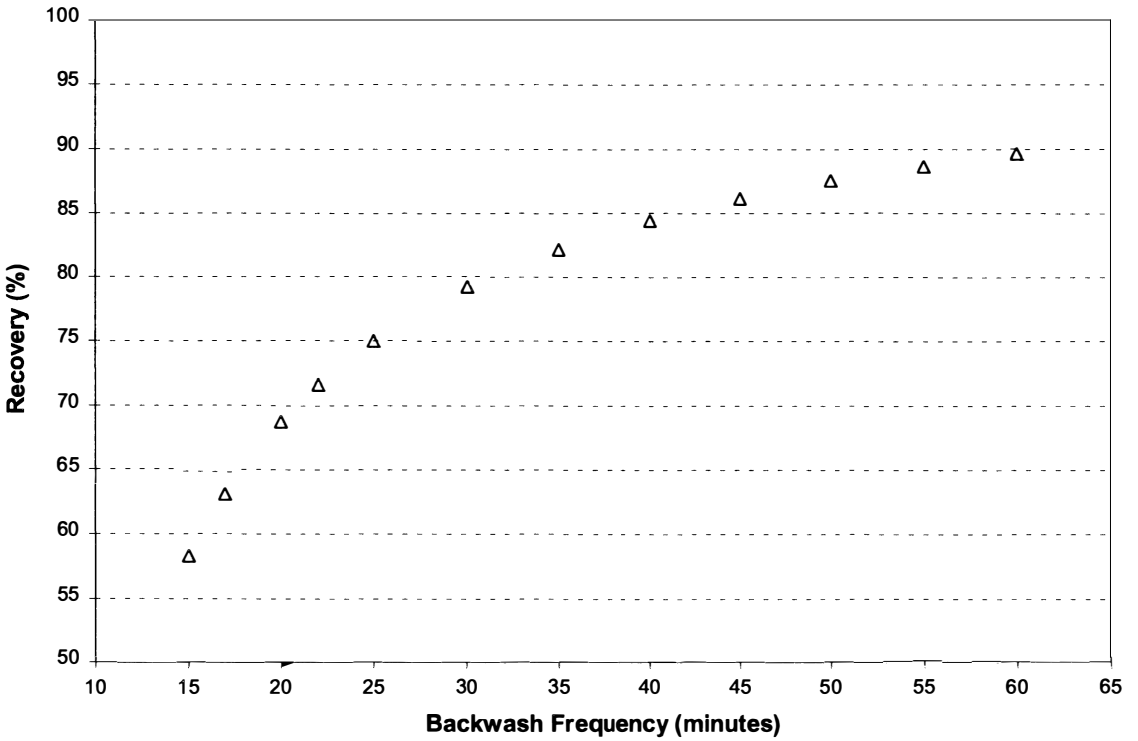
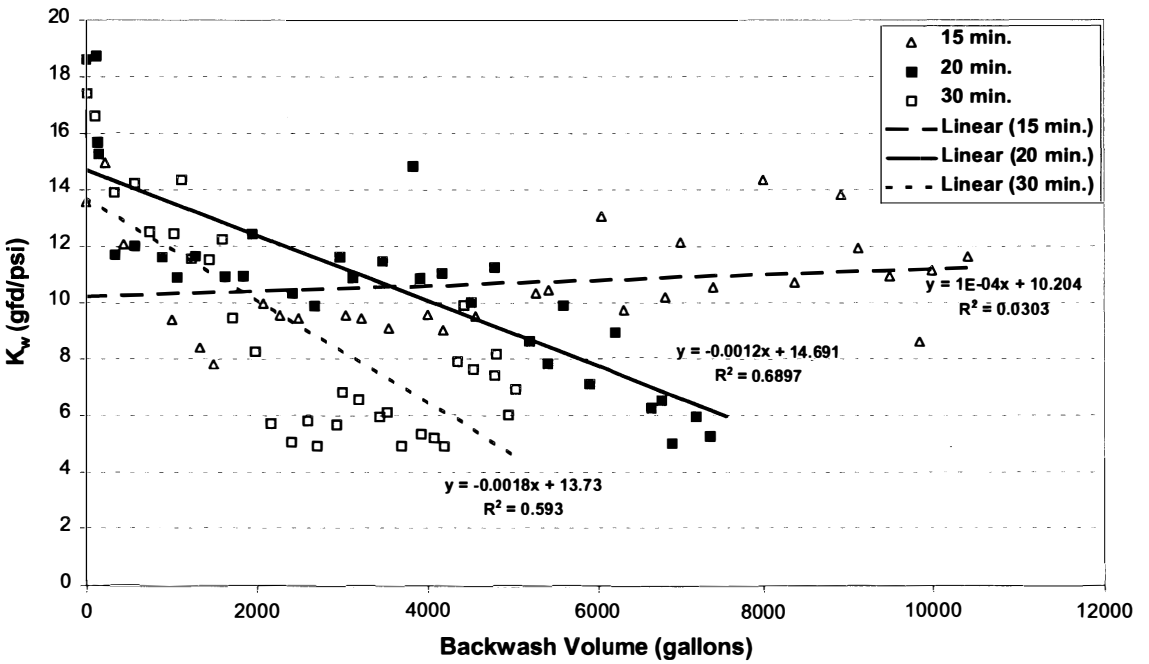


Figure 3-9: K_w vs. Backwash Volume for Various Backwash Frequencies (15 – 30 min). Experimental Conditions: Flux = 30 gfd, Ferric Dose = 0 ppm and Cross Flow = 0 gpm. Backwashing was performed for 65 seconds including 25 ppm NaOCl addition for 24 seconds. Regression lines are based on linear least squares fit. Backwash Volume is based on average recovery values (%) of 55, 68 and 79 corresponding to backwash frequencies (min.) of 15, 20 and 30, respectively. Regression lines are based on linear least squares fit.



3.2.4 Effect of Ferric Chloride Pretreatment

The pretreatment of feed water by coagulation is common practice to control fouling during membrane filtration. However, direct addition of coagulants to the membrane system (*i.e.* in-line coagulation) has not been thoroughly studied. The following section presents the effect of ferric chloride pretreatment on membrane productivity. The results shown were obtained from two sets of experiments, which differ only in operating flux and ferric dose. The first set consisting of experiments A and O (Table A-2) were conducted with 0-ppm and 7-ppm ferric chloride pretreatment, respectively. Both experiments were conducted under the following operating conditions: Flux = Varied among membranes one through six (32 – 52 gfd), BWF = 20 min., and Cross Flow = 0 gpm. The latter set of experiments comprised of E and J were conducted by applying 0-ppm and 14-ppm ferric chloride pretreatment. Similarly, both experiments were conducted under the following operating conditions: Flux = 30 gfd, BWF = 20 min., and Cross Flow = 0 gpm. To isolate the effect of ferric chloride pretreatment on membrane productivity, comparison of K_w decline for the sets of experiments described above is presented.

Figure 3-10 presents average K_w versus operating time for experiments conducted with 0-ppm and 7-ppm ferric chloride pretreatment, respectively. As shown, with 7-ppm ferric chloride, no flux decline was observed after a slight initial drop of K_w to 10.0 gfd/psi within the first 14.2 hours of operation. In comparison, operation with no ferric chloride dose resulted in a faster decline of K_w and the membranes were severely fouled after just 80 hours of runtime. Accordingly the slopes of the linear regression lines are -0.0311 and -0.1652 gfd/psi/hour, respectively, indicating the decline in K_w with respect to time was much greater with no ferric chloride pretreatment.

Additional results of the effect of coagulant dose on membrane productivity are shown in Figure 3-11. Similarly, K_w as a function of operation time for experiments conducted with 0-ppm and 14-ppm ferric chloride is presented. As shown, the K_w values associated with the application of a 14-ppm dose decreased moderately during the first 37 hours of operation, but showed no further decline or a slight increase thereafter. However, operation with no ferric dose indicated a drastic decrease of K_w and resulted in severe fouling after 250 hours of runtime. The slopes associated with 0-ppm and 14-ppm dose were found to be -0.0356 and 0.0019 gfd/psi/hour, respectively. This data was consistent with the previous comparison shown in Figure 3-10, in which 7-ppm ferric chloride coagulation significantly enhanced membrane productivity. Reiss *et al.* (1999); Lahoussine-Turcaud *et al.* (1990) also demonstrated that coagulant pretreatment reduced or eliminated fouling during UF filtration. In addition, the authors concluded the specific coagulant used effected the degree of flux enhancement. Braghetta *et al.* (2000) also observed an increase of 25-50 % in operating specific flux, when filtering water that had undergone coagulant pretreatment.

The observed enhancement of membrane productivity due to ferric chloride pretreatment may be attributable to destabilization and coagulation of colloidal particles present in the feed water. As presented by Wiesner and Laine (1996), coagulation pretreatment can result in the following flux enhancement mechanisms:

- *Reduction of Foulants Entering Pores* - As a result of charge neutralization, colloidal particles present in the feed water can form large aggregates and be captured on the membrane surface. In addition, colloids capable of entering the membrane surface may be removed by sweep coagulation of the precipitated metal hydroxide complexes.
- *Conditioning of the Cake Layer* - The formation of aggregated particles may act to alter the compressibility of the existing cake layer formed on the membrane. The specific resistance (resistance per cake depth) of the cake would be reduced with larger particles allowing more flow to pass through the membrane.

- *Enhanced Back Transport* - As particle size increases due to aggregation, the effect of inertial lift and shear force become more pronounced. As a result, more particles are back transported from the membrane surface minimizing concentration polarization. However, it should be noted that this mechanism is not applicable to our study because coagulant pretreatment experiments were performed at a dead-end filtration mode and there was no crossflow causing inertial lift and shear.

To further investigate the mechanisms responsible for enhanced HYDRAcap productivity resulting from ferric chloride dosing, K_w was plotted against the cumulative mass loading of particle counts, as presented in Figure 3-12. This plot was developed from data collected during approximately the first 134 hours of filtration time for experiments conducted with 0 and 14-ppm ferric chloride dosing. As expected the cumulative mass loading of particles was significantly higher (284%) during operation with 14-ppm ferric dosing, due to the presence of coagulated solids. The results also clearly indicate that pretreatment by ferric chloride caused much less hydraulic resistance to filtrate flow per given particle mass loading. This observation may be explained by the loose structure of the fouling layer formed by large flocs generated during coagulation. It is also postulated that the nature of this type of fouling layer may be removed more effectively by backwashing, lessening membrane fouling.

Figure 3-10: K_w vs. Operation Time for 0-ppm and 7-ppm Ferric Chloride Pretreatment. Operating Conditions: Flux varied between 32 gfd to 52 gfd for membranes one through six. Backwash Frequency = 20 min., and Cross Flow = 0 gpm. Regression lines are based on linear least squares fit.

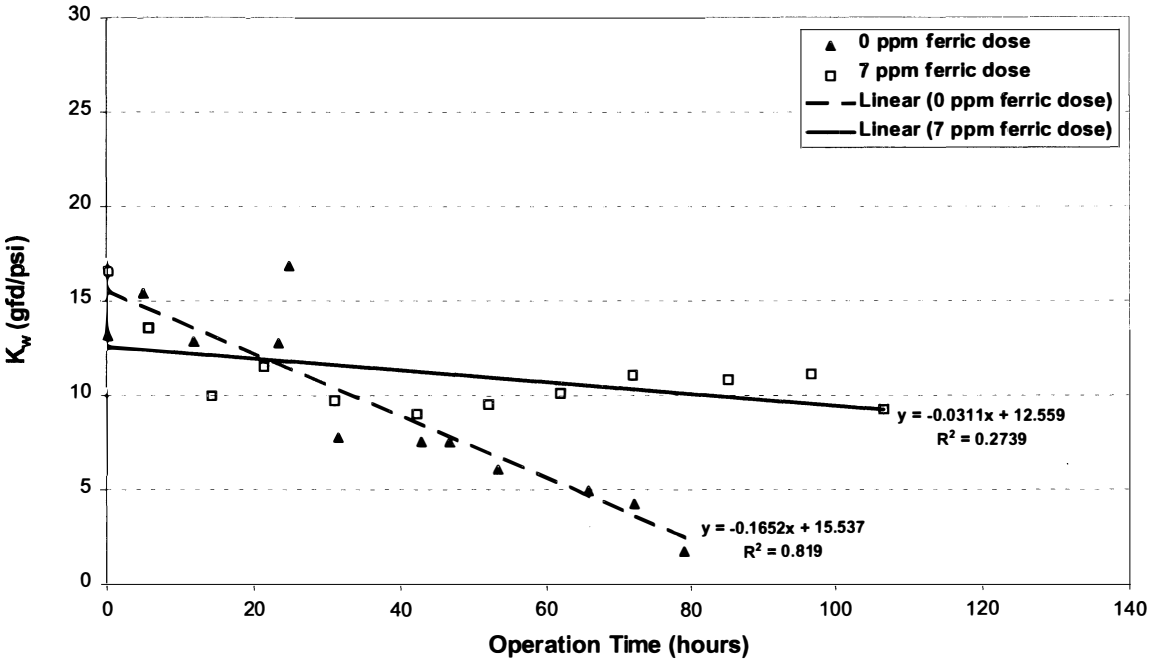


Figure 3-11: K_w vs. Operation Time for 0 ppm and 14 ppm Ferric Chloride Pretreatment: Operating Conditions: Flux = 30 gfd, BWF = 20 min., and Cross Flow = 0 gpm. Regression lines are based on linear least squares fit

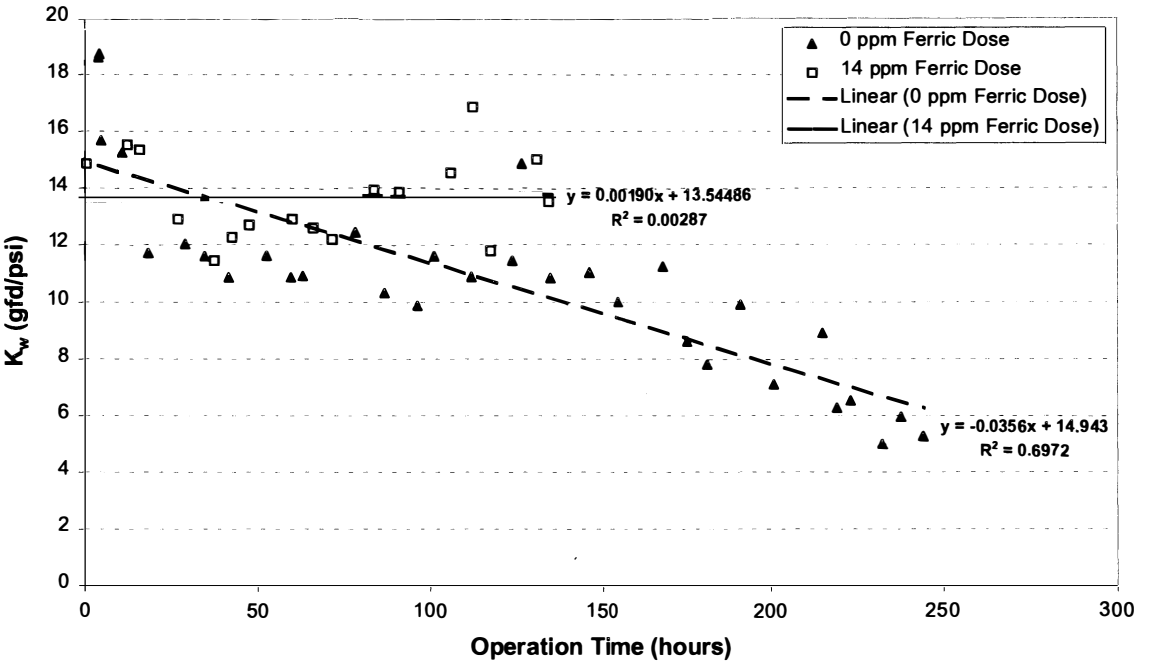
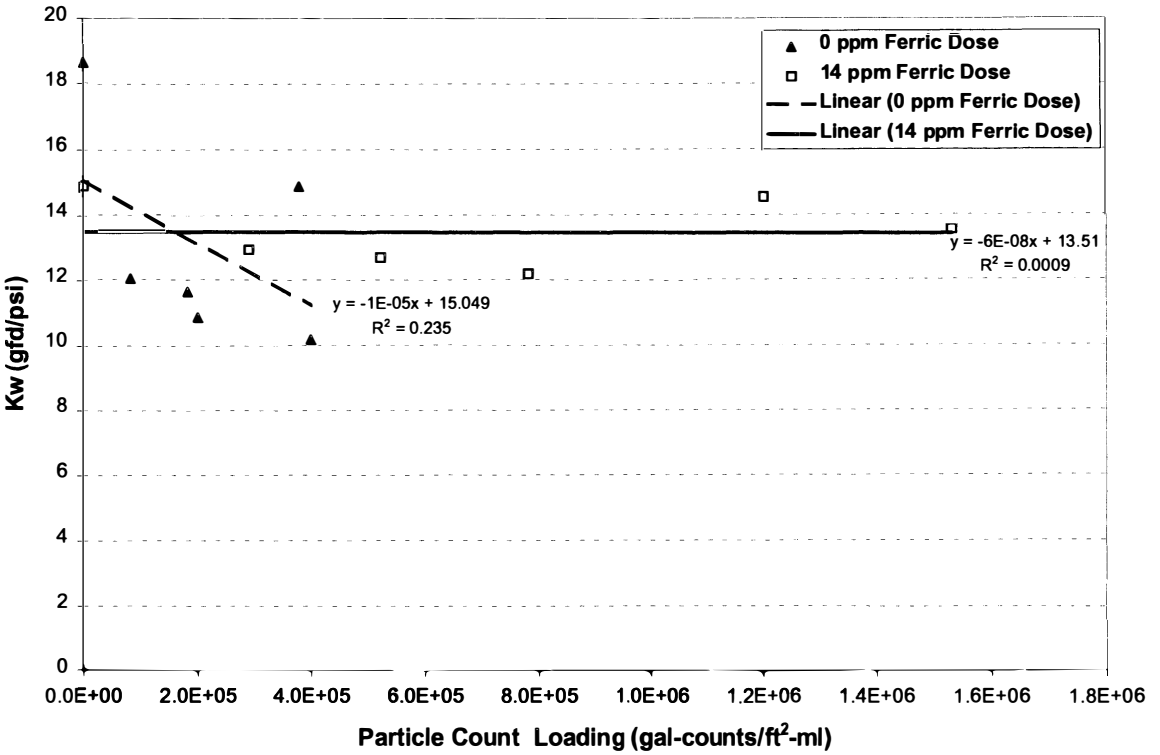


Figure 3-12: K_w vs. Particle Mass Loading Based on Particle Counts for 0 ppm and 14 ppm Ferric Chloride Pretreatment. Operating Conditions: Flux = 30 gfd, BWF = 20 min., and Cross Flow = 0 gpm. Particle loading is estimated by particle counts (counts/ml) × filtrate volume per unit membrane surface area (gal/ft^2). Regression lines are based on linear least squares fit.



3.2.5 Effect of Crossflow Velocity

The following section presents experimental results of the effect of cross flow velocity on membrane performance. Operational data was assessed from experiments conducted with 0 gpm crossflow (*i.e.* dead-end filtration) and 10 gpm crossflow identified as experiments F and I, respectively, (Table A-2). Both of these experiments were conducted under the following operating conditions: Flux = 30 gfd, BWF = 20 min. and Ferric Chloride Dose = 0-ppm.

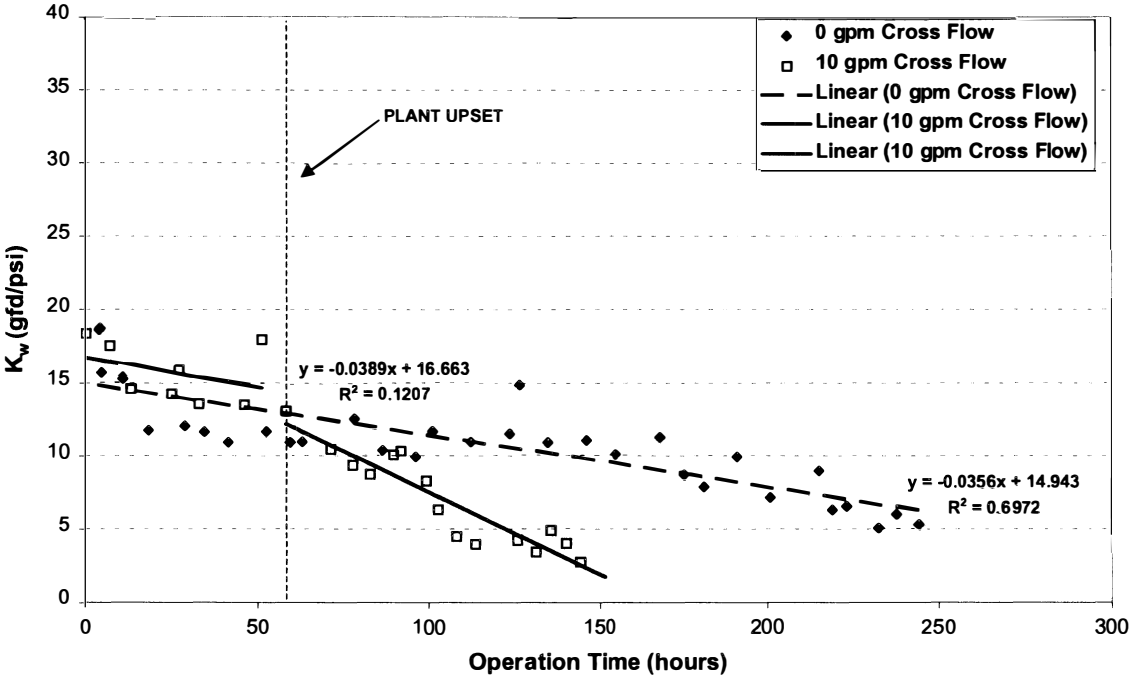
Figure 3-13 presents K_w versus operation time for experiments conducted with 0 and 10 gpm crossflow. During the operation with 10 gpm crossflow, a plant upset, which resulted in polymer loading to the membranes, occurred after approximately 50 hours of runtime. As a result, the trend line for the 10 gpm cross flow was developed only based on operational data for the first 50 hours of runtime. A comparison to the 0 gpm trend line over the same time period indicated that the decline rates were similar (*i.e.* -0.036 and -0.039 gfd/psi/hour for 0 and 10 gpm crossflow, respectively). Such results indicated that crossflow filtration had no significant affect on membrane productivity during UF filtration of tertiary treated wastewater.

The effect of crossflow on HYDRAcap productivity was not further investigated due to unit configuration limitations and the operational problems discussed above. In the current pilot unit, operation with 10 gpm crossflow only results in a cross flow velocity of approximately a 0.1 m/s. This appears inadequate to maintain solids in the suspension and to prevent particles from depositing on the membrane system. This has been verified by a previous HYDRAcap study conducted at San Luis Rey municipal wastewater treatment facility, Oceanside CA, in which crossflow up to 20 gpm (crossflow velocity = 0.25 m/s) had no or minimal enhancement of productivity. These results indicate that the

applied crossflow velocities may be insufficient to prevent solid and organic foulants present in the feed water from accumulating on the membrane surface.

The effectiveness of crossflow filtration may be also verified by assessing the solids feed concentration with respect to experimental runtime. Because the concentrate was recycled to the feed stream, an increase in feed solids would be observed if the crossflow velocity was adequate in preventing solid particles from accumulating on the membrane surface. However, in our study, the feed concentration of turbidity remained less than 1.5 NTU, indicating the crossflow velocity was inadequate to suspend solid particles to prevent fouling. Similar results were observed by Laine *et al.* (1991) in a study conducted using hollow fiber UF membranes for the treatment of two different quality surface waters with mean turbidity concentrations of 0.5 NTU and 4.1 NTU, respectively. The authors concluded that, under the certain operating conditions, even a cross flow velocity of ~ 0.9 m/s was insufficient to prevent fouling.

Figure 3-13: K_w vs. Operation Time for 0 gpm and 10 gpm Cross Flow. Experimental Conditions: Flux = 30 gfd, BWF = 20 min., and Ferric Dose = 0 ppm: Regression lines are based on linear least squares fit.



3.3 Filtrate Water Quality

The following section contains results of the water quality analysis performed during the current project. The purpose of this analysis was to assess the effectiveness of the HYDRAcap UF membranes at retaining solid, organic and microbial contaminants under various operating conditions. The results are presented as percent rejection of solid and organic contaminants and log removal values (LRV) of microbial contaminants, based on average values of the six HYDRAcap membranes. In addition, plots of average feed and filtrate concentrations measured under various operating flux and backwash conditions are provided.

3.3.1 Solids Rejection

Turbidity and particle counts were measured in the feed and filtrate water during pilot experiments to assess the solids rejection of the HYDRAcap membranes. Tables C-2 and C-3 located in Appendix C present rejection values of turbidity (NTU) and particle counts (counts/ml) measured during each experiment, respectively. Results of the turbidity and particle counts analyses indicated that HYDRAcap membranes achieved high rejection of particulate contaminants. Specifically, 82.4 % of the water quality data showed filtrate turbidity $\leq$ 0.10 NTU. The membranes consistently rejected both turbidity and particle counts up to a maximum percent rejection of 99.6% and 99.5 % with an average rejection of 92.8 % and 92.1 %, respectively. The high level of rejection of turbidity and particle counts is due to the ability of the HYDRAcap UF membrane to remove particles by size exclusion (MWCO: 150,000 Dalton). Lastly, it is important to note that high turbidity and particle counts were generally observed for filtrate samples taken immediately after a given backwashing event (*e.g.* samples taken during experiments A and B). This would result in contamination of filtrate water by particles

lifted from the membrane surface during backwashing. Accordingly, these measurements may not represent actual performance of the HYDRAcap membranes.

Figures 3-14 and 3-15 present average feed and average filtrate values of turbidity and particle counts, respectively measured during experiments conducted at operating fluxes of 20, 30, 44, and 60 gfd. As shown, the effectiveness of the HYDRAcap membrane at rejecting turbidity was independent of operating flux. The average filtrate concentrations of turbidity were below 0.25 NTU for each operating flux. Similarly, average particle count values were measured as 405, 97, 252, and 374 (counts/ml) for experiments conducted at operating fluxes of 20, 30, 44 and 60 (gfd), respectively, again showing no clear trend for the effect of operating flux.

Figures 3-14 and 3-15 also suggest that coagulation pretreatment resulted in enhanced particle removal even if the addition of ferric chloride increased feed turbidity and particle counts. The increased particle concentration in feed water is explained by introduction of ferric hydroxide precipitate resulting from the applied 14-ppm ferric chloride. Ferric chloride addition promoted aggregation of small colloidal particles and improved particle removal by enhancing size exclusion. As a result, the highest LRV (>2) and the lowest filtrate particle concentration (79 counts/ml) were measured during the experiment conducted at 14-ppm ferric chloride dose.

The effect of backwash frequency (BWF) on filtrate turbidity and particle counts is illustrated in Figures 3-16 and 3-17, respectively. These figures represent average feed and filtrate values measured during experiments conducted at 15, 20, and 30 min BWFs. As shown, average filtrate turbidity were consistently < 0.1 NTU, indicating that turbidity removal is independent of BWF. Similar results were observed for particle counts. Filtrate particle concentrations measured at BWF ranging from 15-30 minutes varied from 85 to 155 (counts/ml) without any specific trends. Thus, it is concluded that

varying backwash frequency during pilot operation did not have any significant influence on filtrate turbidity or particle counts.

Lastly, the results of particle analysis indicate that filtrate turbidity and particle counts are independent of feed concentration. The average turbidity of 0.10 NTU and the average particle counts of 192 counts/ml were consistently obtained for the filtrate water, while feed turbidity and particle counts ranged from 0.35 to 16.1 NTU and from 800 to 9720 counts/ml, respectively. A plot of feed versus filtrate particle counts measured during experiments conducted with 0 and 14-ppm ferric chloride dose is presented in Figure 3-18. As illustrated even though the addition of ferric chloride resulted in increased feed particle counts the filtrate water quality remained low, implying that size exclusion is a main mechanism for particle removal. Similar results were reported from numerous previous studies. Taylor and Kothari (1998) demonstrated that particulate filtrate water quality was independent of feed water quality during MF pilot studies of Manitowoc River water. Randles (1996) reports filtrate produced from a Memcor® continuous microfiltration (CMF) system at the Saratoga water treatment plant as low as 0.1 NTU for feed water concentrations above 250 NTU. Hofman *et al.* (1998) also reported that extreme conditions of feed water quality during UF pilot study involving surface water did not effect filtrate water quality. Wiesner *et al.* (1996) also reported similar results in which UF filtrate concentrations were consistently as low as 0.2 NTU with feed concentrations as high as 300 NTU.

Figure 3-14: Feed and Filtrate Turbidity vs. Operating Flux (20-60 gfd). Experimental Conditions: BWF = 20 min. and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

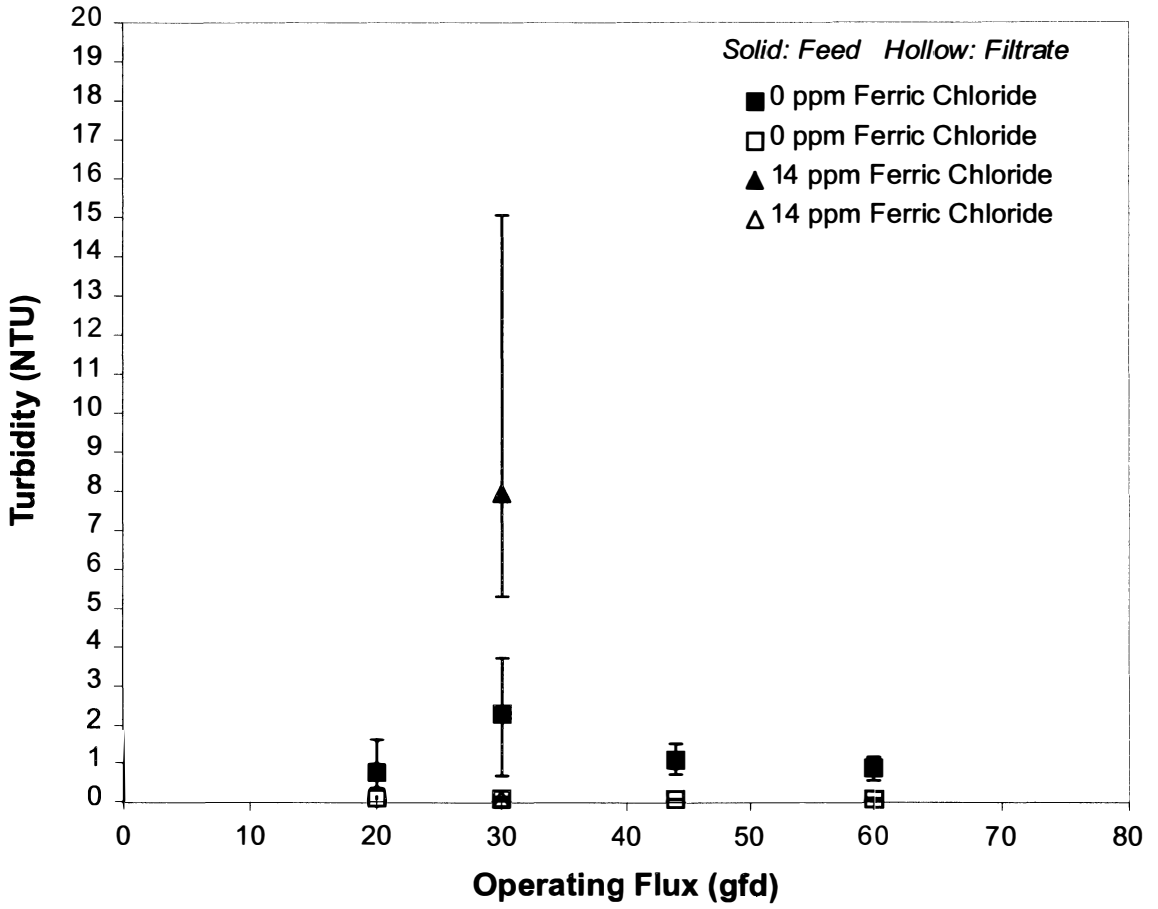


Figure 3-15: Feed and Filtrate Particle Counts vs. Operating Flux (20-60 gfd). Experimental Conditions: BWF = 20 min. and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

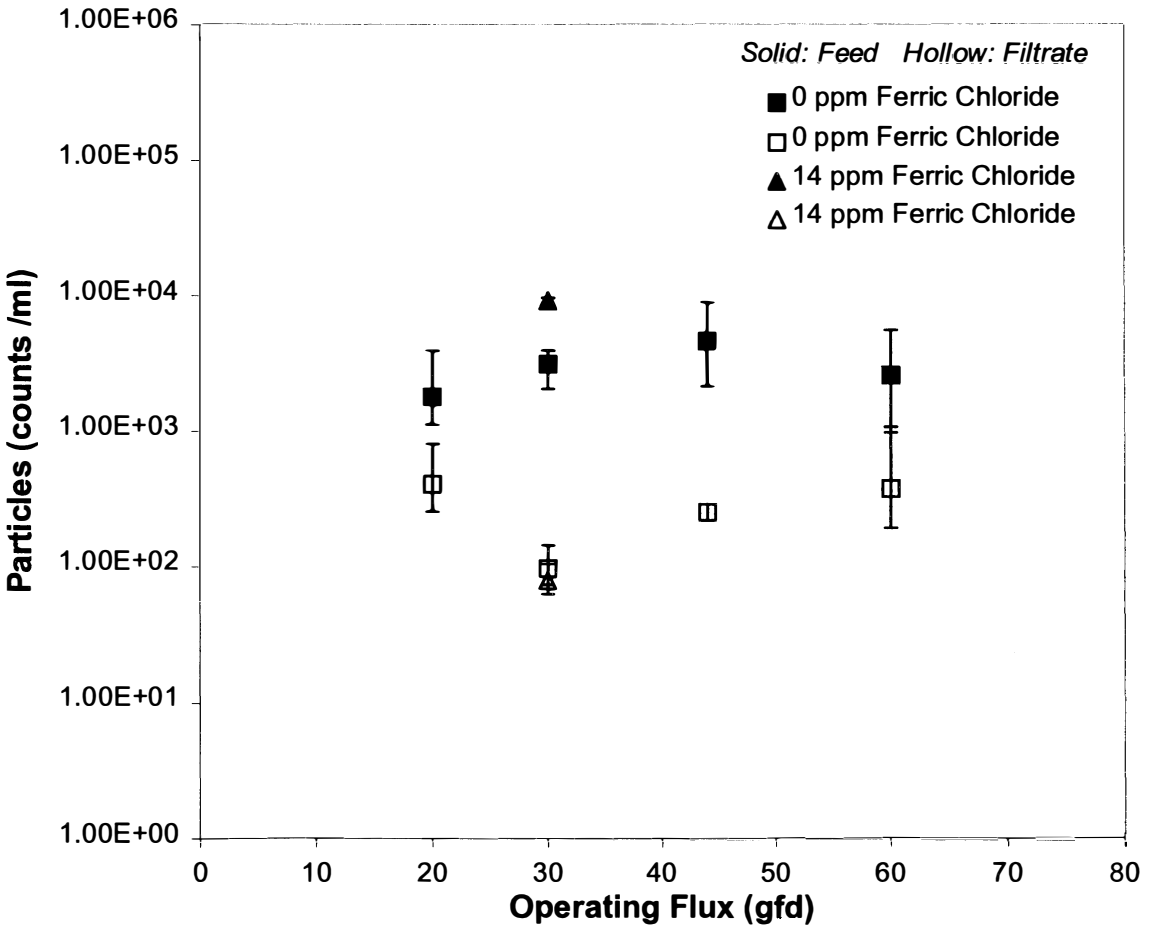


Figure 3-16: Feed and Filtrate Turbidity vs. Backwash Frequency (15-30 min.). Experimental Conditions: Flux = 30 gfd and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

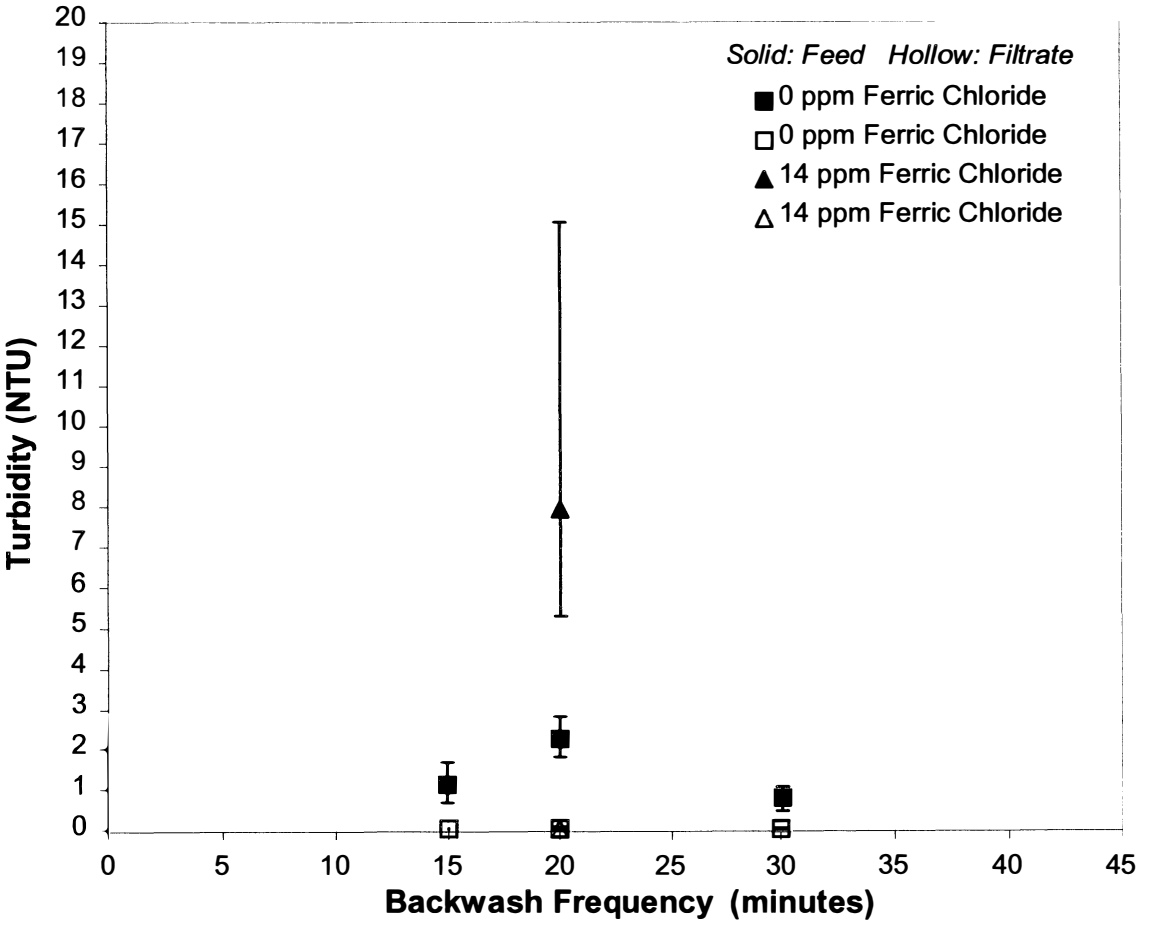


Figure 3-17: Feed and Filtrate Particle Counts vs. Backwash Frequency (15-30 minutes). Experimental Conditions: Flux = 30 gfd and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

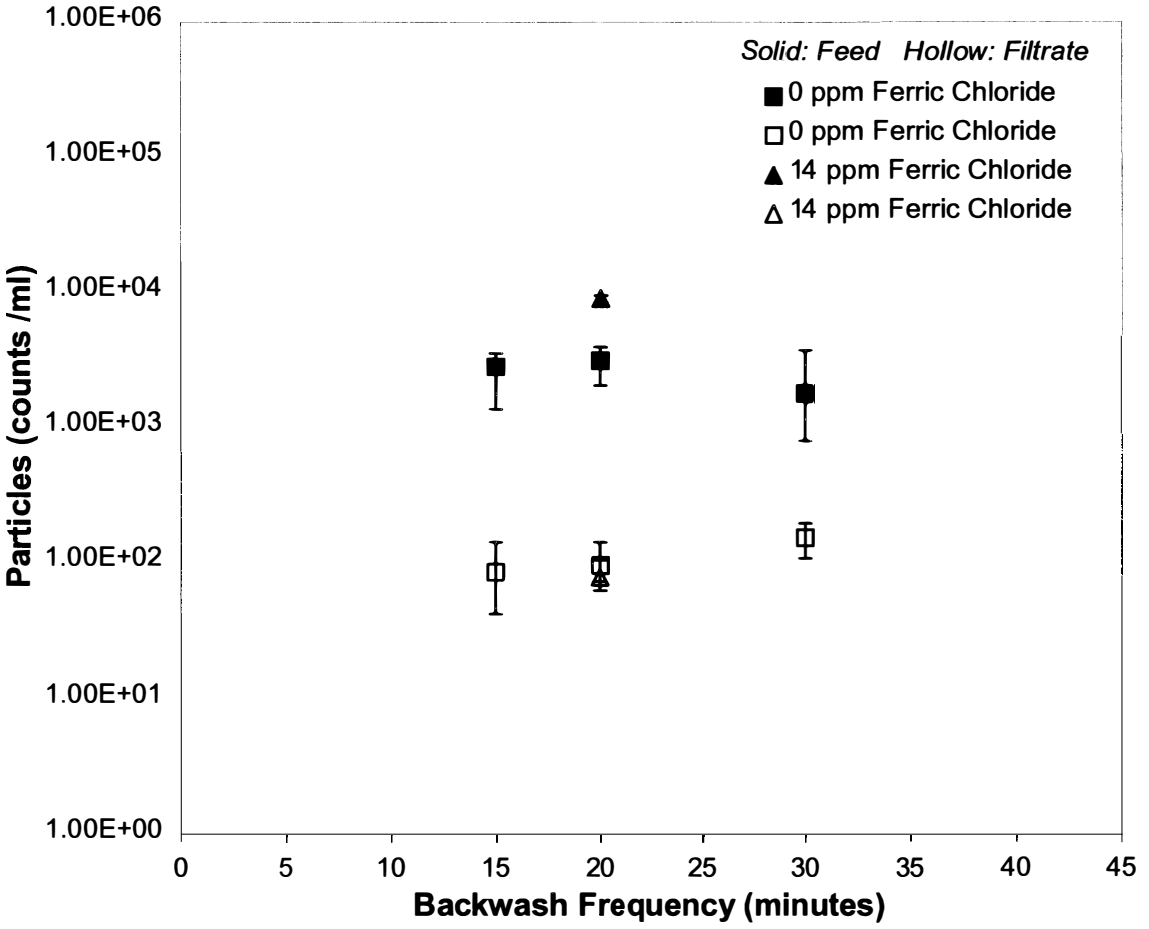
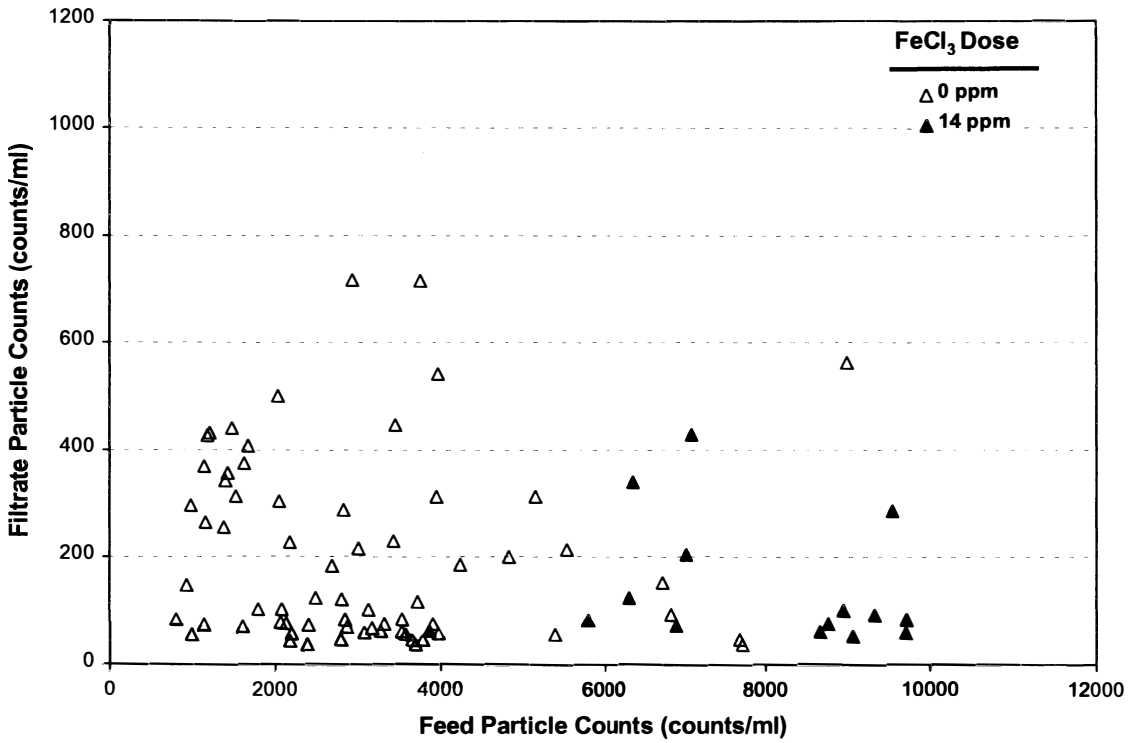


Figure 3-18: Filtrate vs. Feed Particle Counts measured during experiments with 0 and 14-ppm ferric chloride pretreatment.



3.3.2 Organic Rejection

Organic rejection of the HYDRAcap UF membranes was assessed by measuring UV_{254} and TOC in the feed and filtrate water during pilot experiments. Tables C-4 and C-5 in located in Appendix C present rejection values of UV_{254} (cm^{-1}) and TOC (mg/L), respectively. The measured rejection values indicated that the HYDRAcap membranes were not effective at removing UV_{254} or TOC. Maximum rejections measured were 8.6% and 17.2 %, with an average rejection of 3.6% and 5%, respectively, excluding negative values. It should be noted that several measurements, particularly TOC, showed negative rejections. This anomaly was suspected to be a result of filtrate sample contamination, which was associated with extended periods of sample storage due to operational problems incurred with the TOC analyzer during the course of the project. The passage of UV_{254} and TOC through the HYDRAcap membranes is not surprising since their MWCO is approximately 150,000 Dalton. The main mechanism of organic removal by UF membranes is size exclusion and small organic matter was not rejected significantly by the HYDRAcap membranes. The occurrence of low organic rejection observed is consistent with a recent study by Adham *et al.* (2000) who reported no DOC removal using UF membranes with MWCO from 100,000 to 150,000 Daltons. Similarly Clark *et al.* (1991) also reported low UV_{254} removal (< 20%) using a UF membranes with MWCO of 100,000 Daltons.

Figures 3-19 and 3-20 present average feed and filtrate measurements of UV_{254} and TOC, respectively conducted at operating fluxes of 20, 30, 44, and 60 gfd. As shown, filtrate UV_{254} were within a close range (0.182 to 0.213 cm^{-1}) for operating fluxes between 20 and 60 gfd, without any clear trends. The TOC measurements showed less than 3% TOC removal for 20 and 30 gfd operating fluxes and negative rejection for 44 and 60 gfd operating fluxes. The results generally suggested that organic removal by UF membranes is independent of operating flux and feed concentration. Finally, the results showed that

the addition of ferric chloride was not effective at enhancing TOC removal. Further investigation is needed for the enhancement of organic removal by optimizing coagulation process.

The effect of backwash frequency on filtrate water quality of organic contaminants is illustrated in Figures 3-21 and 3-22. These figures present average feed and filtrate values of UV_{254} and TOC respectively, measured during experiments conducted at 15, 20, and 30 min. BWFs. As shown, with the exception of the negative rejection values measured during the experiment conducted at 30 min BWF, the differences in feed and filtrate UV_{254} and TOC values were insignificant for BWF of 15 min. and 20 min. Such results indicated that backwash frequency has no effect on organic rejection by UF membranes.

Figure 3-19: Feed and Filtrate UV_{254} absorbency vs. Operating Flux (20-60 gfd). Experimental Conditions: BWF = 20 min. and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

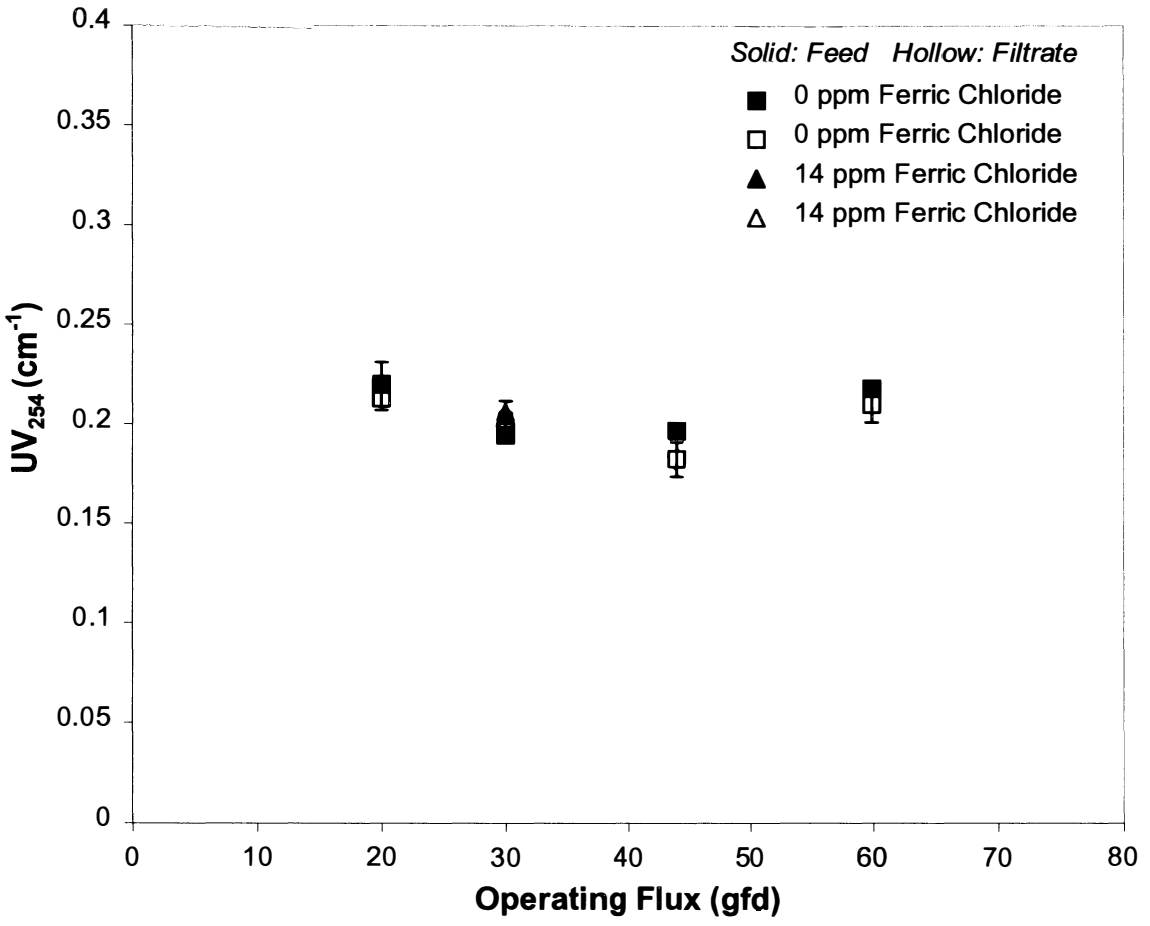


Figure 3-20: Feed and Filtrate TOC vs. Operating Flux (20-60 gfd). Experimental Conditions: BWF = 20 min. and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

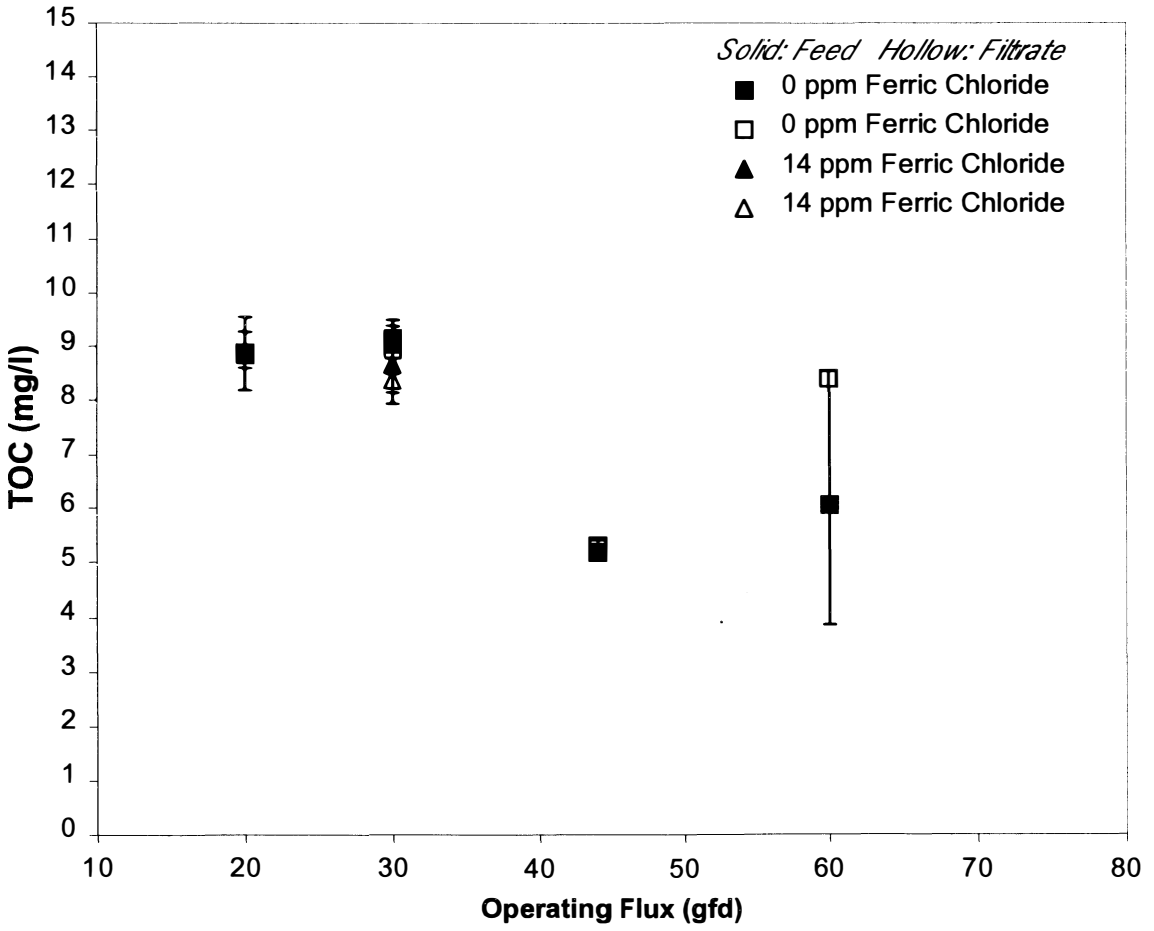


Figure 3-21: Feed and Filtrate UV_{254} absorbency vs. Backwash Frequency (15-30 min.). Experimental Conditions: Flux = 30 gfd and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

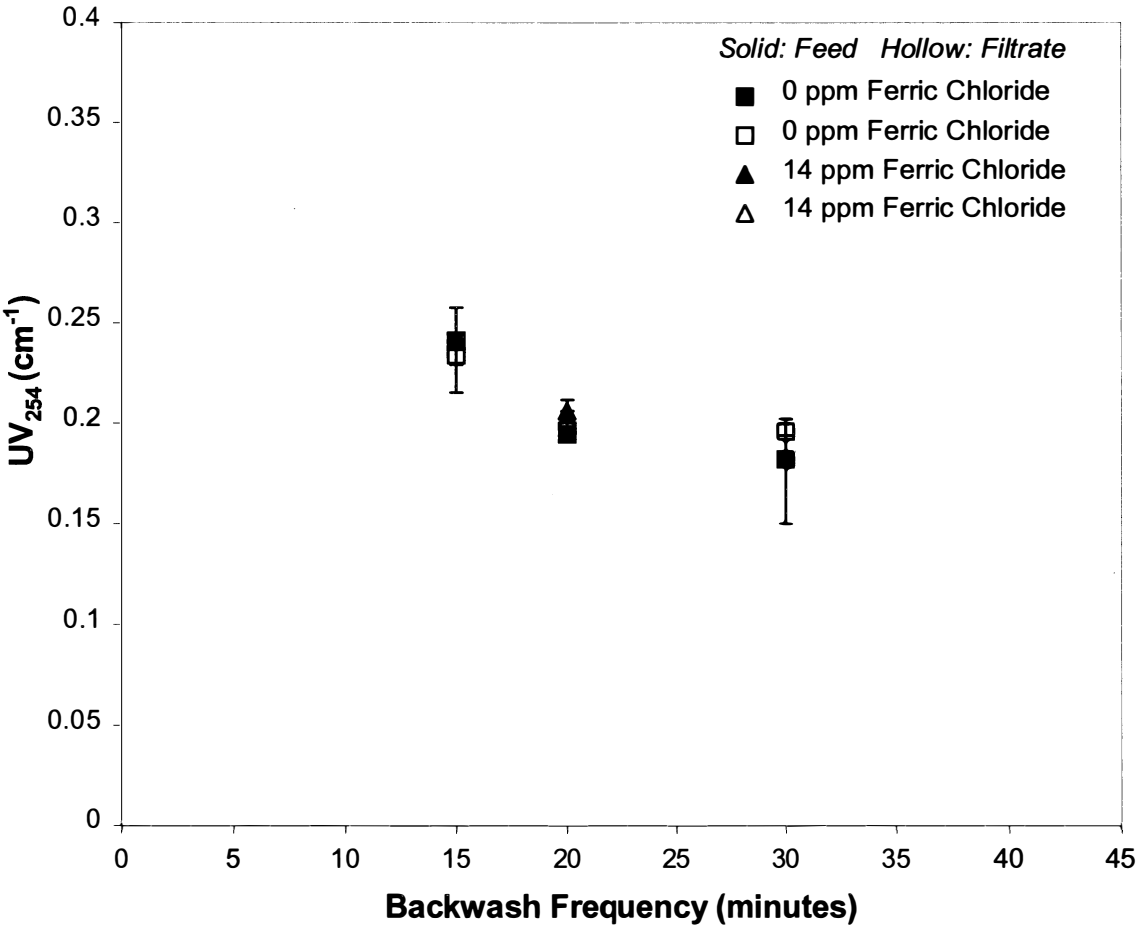
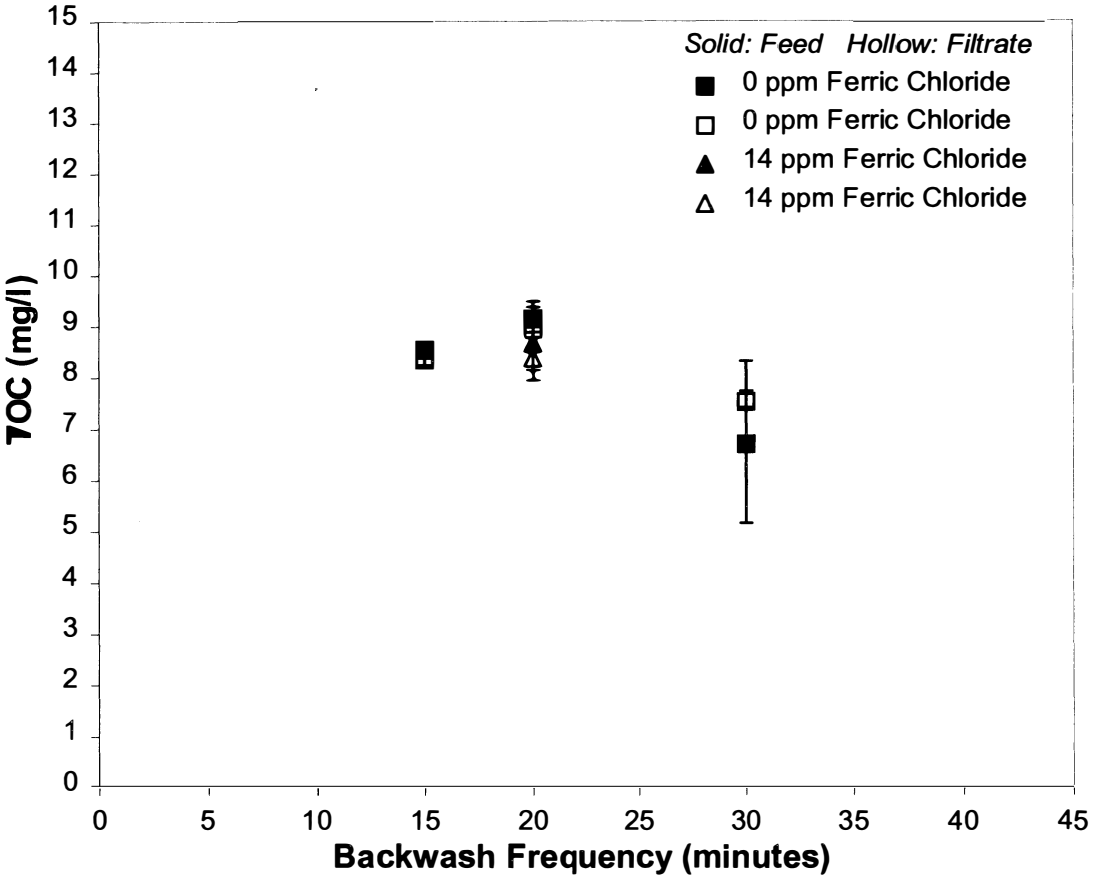


Figure 3-22: Feed and Filtrate TOC vs. Backwash Frequency (15-30 min.). Experimental Conditions: Flux = 30 gfd and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.



3.3.3 Microbial Rejection

Heterotrophic Plate Count (HPC) and Total Coliform (TC) measurements were performed to assess the microbial rejection capacity of the HYDRAcap membranes. These parameters are good indicators of microbial contamination and are regulated by various water quality rules. Tables C-6 and C-7 located in Appendix C lists log rejection values (LRV) of HPC and TC, respectively. As indicated, the membranes effectively achieved between 2.0 to 4.9 LRV of HPC. It is expected the LRV of HPC is limited due to regrowth in the permeate system which has also been reported by Hofman *et al.* (1998). In addition log rejection values for TC ranged from 1.2 - 7.0 with 33% of the filtrate samples containing TC concentrations less than 0.1 CFU/ml, indicating infinite rejection. Similar results were shown by Miller (1999), who reported LRV's of total coliform ranging from 5.39-8.90 during MF pilot studies. The author also illustrated LRV can be limited by the feed water concentration which may explain the slightly lower LRV's of TC obtained during this study. Jacangelo *et al.* (1995) summarizes the removal mechanisms responsible for microbial rejection in MF/UF processes as follows: sieving or size exclusion, adsorption to the surface or internal structure of the membrane, attachment to particles present in the water, and removal by cake layer formed on the membrane surface.

Figures 3-23 and 3-24 illustrate the effect of operating flux on microbial rejection. In these figures, average filtrate and feed concentrations of HPC and TC were plotted against operating flux. As shown, the average filtrate concentrations of HPC (counts/ml) decrease sharply with increasing operating flux as follows: 20 gfd =24733, 30 gfd =3883.3, 44 gfd =1516.7 and 60 gfd =21.7. A similar trend was observed from the total coliform measurements, with an exception of 30 gfd run. Filtrate concentrations (counts/100ml) for 20 gfd, 44 gfd and 60 gfd decrease as follows 383<5.5<1.5. The increase of HPC rejection resulting from an increase in operating flux may be due to

increased cake layer formation at higher flux. Enhancement of microbial removal by cake layer was also observed by Jacangelo *et al.* (1995) during several bench scale studies in which kaolinite cake layers ranging from 0.74-1.48 g/m^2 (8 to 16 g/ft^2) were applied to hollow fiber polymeric MF membranes. The applied cake layer resulted in an increase of virus rejection from 1.2-2.5 log, up to 3.7 log removal. The authors also demonstrated that increased fouling, as measured by a decrease in specific flux, increased log MS2 virus removal during a MF pilot study involving three different source waters.

The effect of backwash frequency on microbial feed water quality is illustrated in Figures 3-25 and 3-26, respectively. These figures present average feed and filtrate values of HPC and total coliform measured during experiments conducted at 15, 20, and 30 min BWFs. As shown, filtrate concentrations (counts/ml) of HPC associated with 15, 20 and 30 min. BWF are 3400, 3883, and 665. The lower counts associated with less frequent backwashing (*i.e.* 30 min.) may be due to a decrease in membrane pore size resulting from increased irreversible fouling. However, total coliform measurements indicated infinite rejection at the 20 min. BWF and did not show any clear trend. Additional experiments are required to further assess the effect of BWF on microbial rejection.

Finally, HPC removals were related to particle removals measured by turbidity and particle counts to examine if there is any correlation. It should be noted that turbidity and particle counts are often used as surrogate parameters to predict microbial removal by UF membranes. The results are shown as Log Reduction Values (LRV) in Figures 3-25 and 3-26 for turbidity and particle counts, respectively. An ideal, 1:1 relationship is defined by the dotted 45° line in these figures. It was shown that there was no clear correlation between microbial removal and particle removal by the HYDRAcap UF membranes. The results also indicated that turbidity and particle counts measurements consistently underestimated HPC removals regardless of operating conditions. The log reductions of turbidity and particle counts were variable, but mostly fell within the 0.5 to 2.5 log range.

This observation mainly resulted from the low feed particle concentrations and poor sensitivity of turbidity and particle counts. The weak correlation is also attributable to the scattered microbial challenge data due to inherent difficulties involving microbial analysis.

Figure 3-23: Feed and Filtrate Heterotrophic Plate Counts vs. Operating Flux (20-60 gfd). Experimental Conditions: BWF = 20 min. and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

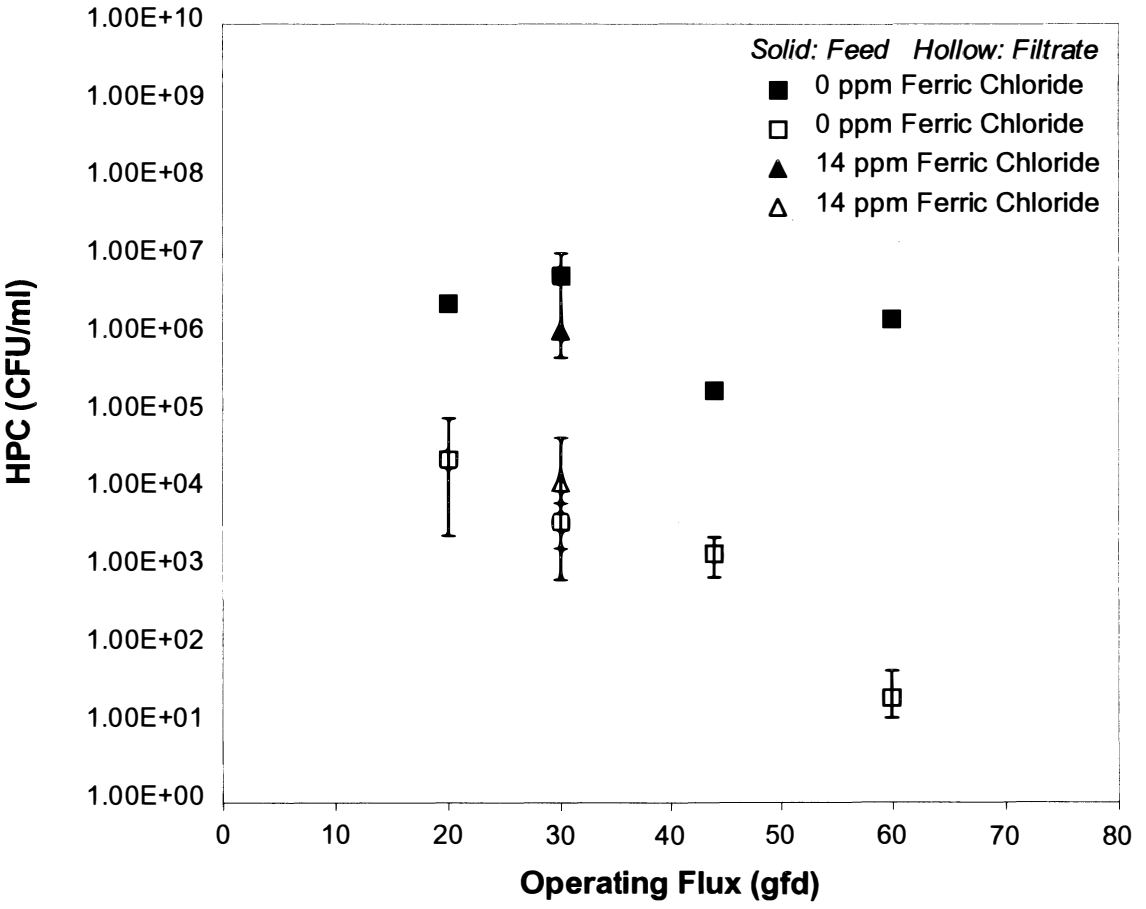


Figure 3-24: Feed and Filtrate Total Coliform vs. Operating Flux (20-60 gfd). Experimental Conditions: BWF = 20 min. and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

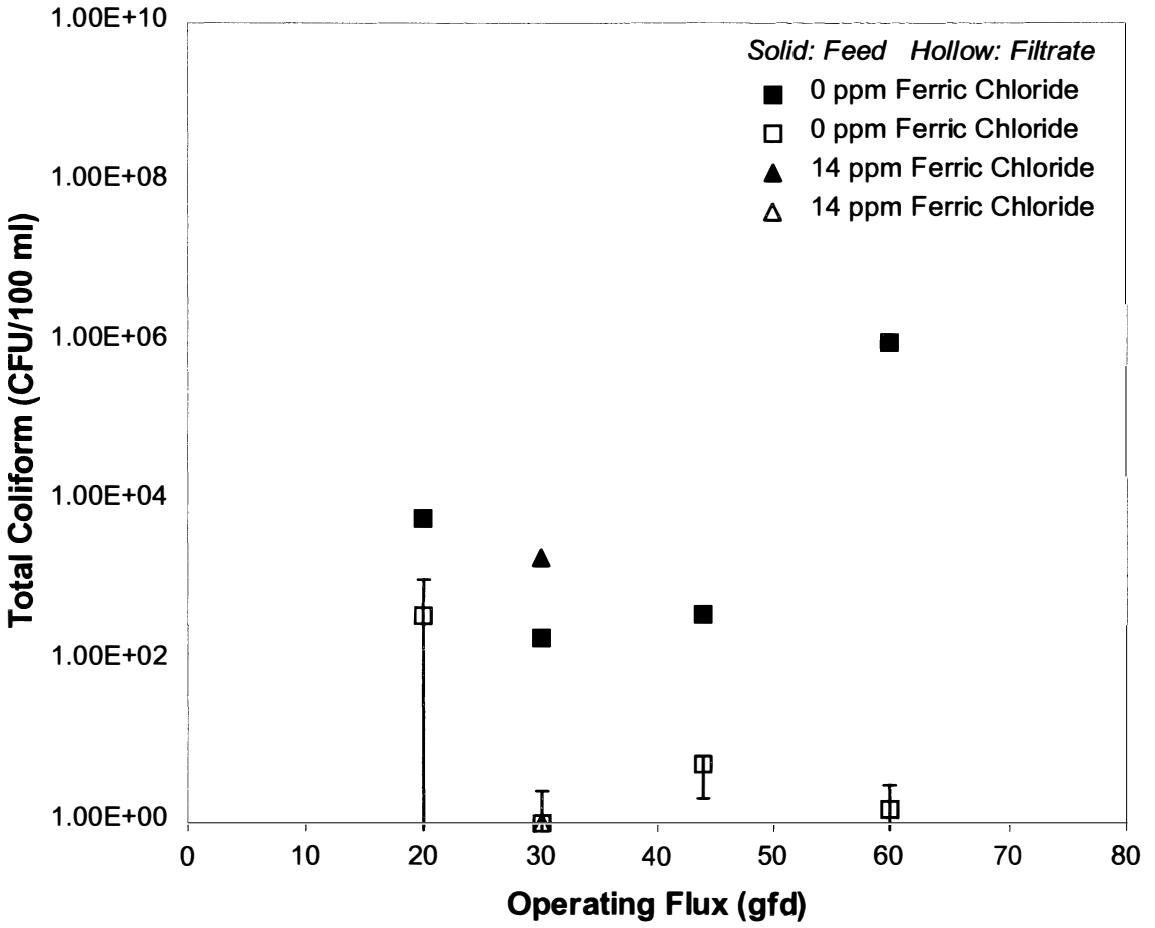


Figure 3-25: Feed and Filtrate Heterotrophic Plate Counts vs. Backwash Frequency (15 -30 min.). Experimental Conditions: Flux = 30 gfd and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

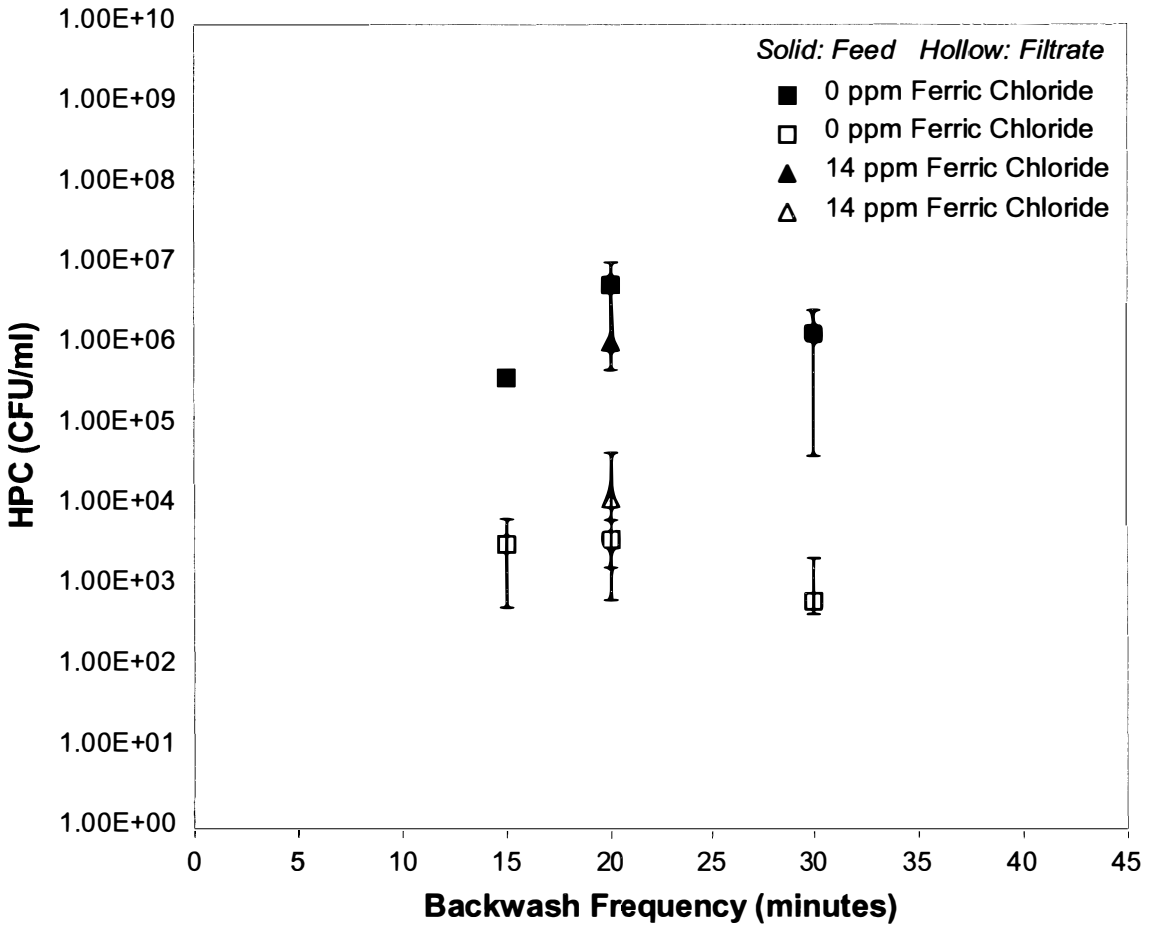


Figure 3-26: Feed and Filtrate Total Coliform vs. Backwash Frequency (15-30 min.). Experimental Conditions: Flux = 30 gfd and Cross Flow = 0 gpm. Feed and filtrate values are based on average values measured during a given experiment. Filtrate values are average values of the six UF HYDRAcap membranes.

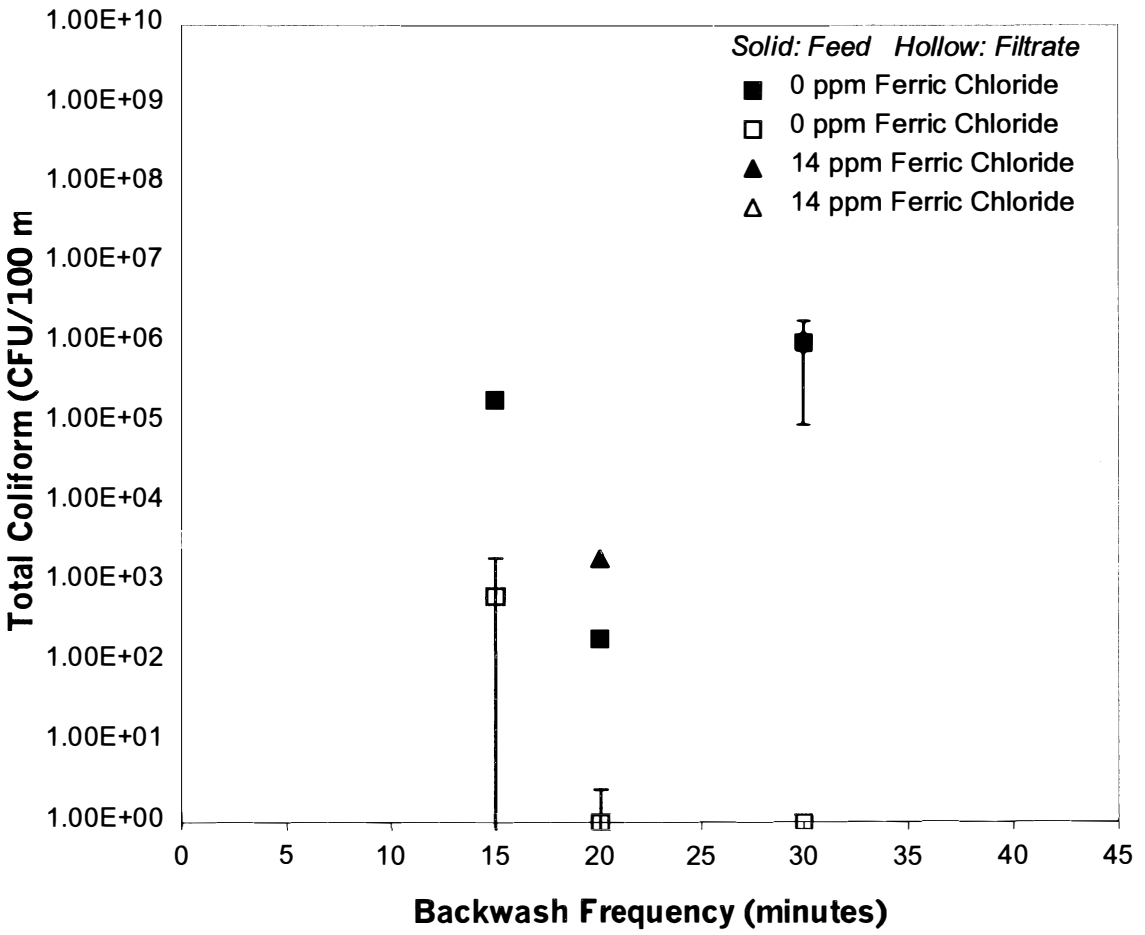


Figure 3-27: Turbidity LRV vs HPC LRV.

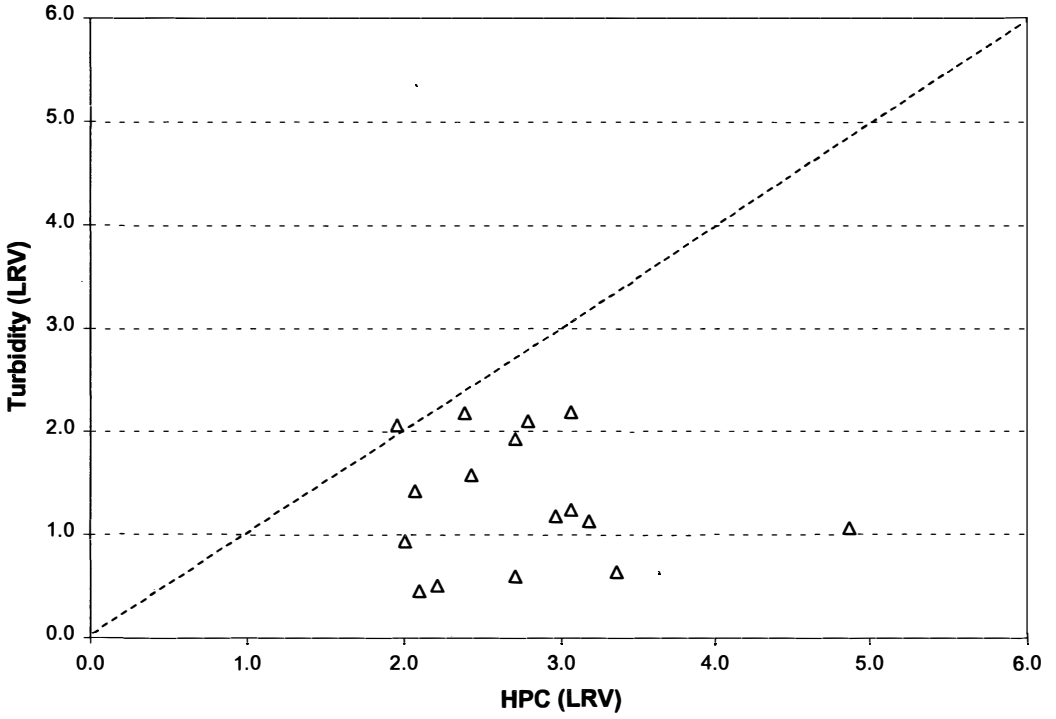
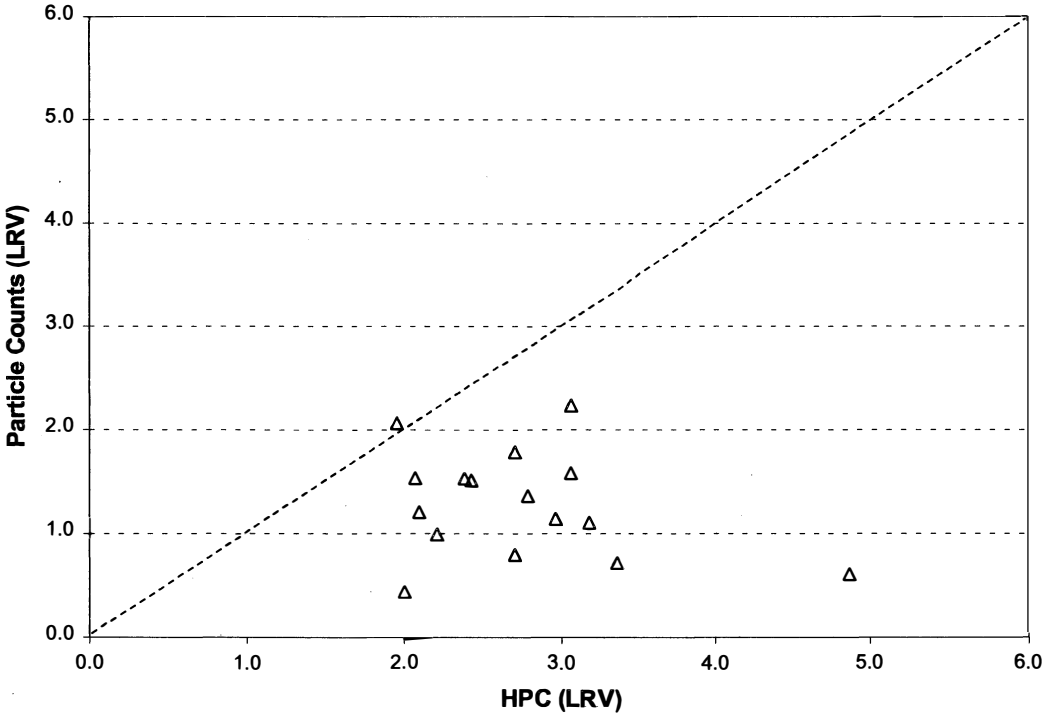


Figure 3-28: Particle Counts LRV vs HPC LRV.



3.4 Statistical Model Development

A resistance model describing productivity loss of the HYDRAcap UF membrane was developed on the basis of statistical analysis of the experimental data obtained in this study. The purpose of developing this model was two-fold: to determine the significance of mass loading of solid, organic and microbial contaminates on membrane productivity, and to assess the variation among membrane elements used in the mini HYDRAcap UF membrane system. In this section, the results of model development, model verification, and sensitivity analyze are presented.

3.4.1 Model Development

As described in Section 3.1.3, the resistance model is often used to describe the productivity decline of MF and UF membranes. In this study, this model was further developed based on mass loading of solid, organic, and microbial foulants to the membrane system. The total resistance is often expressed as a series of hydraulic resistances caused by the membrane, and solid, organic, and microbial foulants present in the feed water:

$$R_t = R_m + R_{solid} + R_{organic} + R_{microbial} + R_{coagulated\ solids} \qquad \text{(3-9, Repeated)}$$

Where: R_m = membrane resistance

R_{solid} = resistance due to mass loading of solids

$R_{organic}$ = resistance due to mass loading of organic

$R_{microbial}$ = resistance due to mass loading of microorganisms

$R_{coagulated\ solids}$= resistance due to mass loading of coagulated solids

I. *Membrane Resisitance (R_m)* - This term is used to account for resistance intrinsic to the membrane and the effect of the mass loading of water on membrane resistance. The latter can result in an increase of resistance due to irreversible fouling or a decrease in resistance due to membrane degradation. This term is expressed below:

$$R_m = R_{m0} \pm X_1 F_w t \tag{3-13}$$

Where: R_{m0} = intrinsic membrane resistance
F_w = operating flux
t = filtration time
X_1= regression coefficient

II. *Solids Resistance (R_{Solids})* – Particulate matter in the feed water during membrane filtration can cause fouling by forming cake layer and/or plugging membrane pores. The cummulative mass loading of particle counts was used to model the effect of solids on membrane resistance as follows:

$$R_{Solids} = (X_2)(F_w)(Particle\ Counts)(t) \tag{3-14}$$

Where: R_{solid} = resistance due to particulate loading during membrane filtration.
X_2= regression coefficient

III. *Organic Resistance ($R_{Organics}$)* – Organic material present in the feed water can foul membranes through gel formation and/or adsorbtion to the internal matrix of the membrane. The cummulative mass loading of UV_{254} was used to model the effect of organics on membrane resistance. This paramater was chosen due to the more frequent measurment of UV_{254} over TOC during the course of this project

and the common use of UV_{254} as a surrogate to TOC. The cummulative mass loading term used is provided below.

$$R_{Organics=}(X_3)(F_w)(UV_{254})(t) \quad (3\text{-}15)$$

Where: $R_{organics}$ = resistance due to organic loading during membrane filtration.
X_3= regression coefficient

IV. *Microbial Resistance ($R_{microbial}$)* – Microorganisms present in the feed water can also lead to fouling by forming biofilm. The cummulative mass loading of HPC was used to model the effect of microrganisms on membrane resistance. This parameter was chosen as an alternative to total coliform because HPC provides a broad measurment of microorganims including total coliform. The cummulative mass loading was calculated as follows.

$$R_{Microbial} = (X_4)(F_w)(HPC)(t) \quad (3\text{-}16)$$

Where: $R_{microbial}$ = resistance due to particulate loading during membrane filtration.
X_4= regression coefficient

V. *Coagultated Solid Resistance (R_{CS})* – The use of coagulant pretreatment prior to membrane filtration results in the destabilization of coloidal particles and the formation of hydroxide precipitates. Because the coagulant dose alters the feed water particle characterstics, it is nessecary to perform a separate model when analyzing the effect of coagulant pretreatment on membrane. resistance. The cummulative mass loading of ferric chloride was used to model the effect of coagulant pretreatment on membrane resistance.

$$R_{CS} = (X_5)(F_w)(FeCl_3)(t) \quad (3\text{-}17)$$

Where: R_{CS} = resistance due to coagulated solid loading resulting from the addition of ferric chloride prior to membrane filtration.

X_5= regression coefficient

By combining the above resistance terms with Equation 3-7 (refer to section 3.1.3), the following model equation is developed to determine the relatioship between productivity (*i.e.* MTC) and foulant mass loading. As shown, an additional term is included to account for the effect of backwashing frequency.

$$\frac{1}{K_w} = \mu_{20^\circ C}\left[\begin{array}{l} R_{m0} + (X_1)(F_w t) + (X_2)(PC)(F_w t) + (X_3)(UV_{254})(F_w t) \\ + (X_4)(HPC)(F_w t) + (X_5)(F_w t)(FeCl_3) + (X_6)(F_w t)(1-R)) \end{array}\right] \quad (3\text{-}18)$$

The water viscosity (μ) term is considered constant becasuse all K_w values used in the model were normalized to 20°C. In addition an average value of R_{m0} was used in the model because of the variation among experiments. Lastly, X_1-X_6 are regression coefficients to be determined in regression analysis. A summary of each resistance term including the units is provided in Table 3-1. The sign and magnitude of these coefficients will provide information on the effect of each term on membrane productivity.

Table 3-1: Description and Units of Regression Coefficients

Coefficient	Description	Units
Rm_0	Resistance due to membrane characteristics	psi/gfd-cp
X_1	Change of resistance with respect to irreversible fouling	ft^4-psi-d^2/gal^2-hr-cp
X_2	Change of resistance with respect to particulate loading	ft^4-psi-d^2-ml/gal^2-counts-hr-cp
X_3	Change of resistance with respect to organic loading	ft^4-psi-d^2/gal^2-cm^{-1}-hr-cp
X_4	Change of resistance with respect to microbial loading	ft^4-psi-d^2-ml/gal^2-cfu-hr-cp
X_5	Change of resistance with respect to ferric chloride dose	ft^4-psi-d^2-l/gal^2-mg-hr-cp
X_6	Change of resistance with respect to backwash frequency	ft^4-psi-d^2/gal^2-hr-cp

3.4.2 Statistical Model Results and Verification

The following section presents results of multiple linear regression of total membrane resistance on operation time using the resistance model identified in Equation 3-18. Regression analysis was performed using the data analysis tool in MS Excel™. This software uses the method of least squares to determine unknown regression coefficients and provides the user with a statistical and analysis of variance approach (ANOVA) summary report; both of which are used to assess the utility of the model.

Two series of models, identified as A & B, were regressed to model membrane resistance as a function of mass loading. Series A models were regressed using the K_w and mass loading terms based on operational data collected for element four during direct filtration experiments in which no ferric chloride pretreatment was applied. Series B models were also evaluated using element four operational data but only measurements collected during experiments operated in direct filtration with ferric chloride dosing prior to membrane filtration. The approach used in the regression analysis for each series was to eliminate statistically insignificant terms from the model and repeat the analysis until each remaining term indicated a statistical significant effect on membrane resistance. The final developed model equations were used to predict the membrane performance of other elements present on the pilot to assess the variation in the fouling behavior among the elements. Lastly sensitivity analysis was conducted to determine the degree in which each mass loading term effected membrane resistance and to illustrate the productivity enhancement realized by the use of ferric chloride pretreatment.

3.4.2.1 Series "A" Model Results

The results of the multiple linear regression analysis are presented in Table 3-2. As shown, regression results are presented for model series A & B, which comprise of

models A1-A2 and B1-B3, respectively. The regression of model A1 resulted in the identification of coefficient X_4, corresponding to the mass loading of HPC, as being statistically insignificant in effecting membrane resistance. This decision was inferred from evaluation of the 95% confidence interval (CI) and the P-value presented in Table E-1 (Appendix E). As indicated the 95% CI passes through zero; this observation indicates there is ambiguity in the true sign of the coefficient. In addition, the high P-value (0.44) indicates there is a significant risk of committing a Type 1 error by rejecting the null hypothesis that $dK_w/dt = 0$. Though the regression indicates that HPC mass loading was not significant at effecting membrane resistance, the model doesn't account for added resistance resulting from biogrowth on the membrane surface.

Removing X_4 subsequently developed model A2 and the regression was repeated. As presented in Table 3-2, regression results of model A2 shows that each remaining term is statistically significant based on the established confidence interval and P-value criteria; specific values based on ANOVA results are presented in Table E-2 (Appendix E). In addition, several inferences can be made from the resulting signs of the regression coefficients. Accordingly, the negative sign of X_1 indicates that the mass loading of water to the membrane surface (F_wt) resulted in membrane degradation, which in effect decreased overall membrane resistance. Similarly, the negative sign of X_6 suggests that an increase in the volume of water used in backwashing (F_wt)(1-R) also decreases membrane resistance. Such results show that backwashing was effective in removing solid foulants from the surface of the membrane surface, which minimized the effect of irreversible fouling attributed to increased operating flux. Additionally, the positive signs of X_2 and X_3 indicate that the mass loading of particulate and organic contaminants, measured by particle counts and UV_{254}, respectively, have a significant role in increasing membrane resistance. The former can increase resistance by forming cake layer and plugging of the membrane pores. The latter can cause fouling due to gel formation and/or adsorbtion to the internal matrix of the membrane.

Table 3-2: Multiple Linear Regression Results

Model No.	Rm_0	X_1	X_2	X_3	X_4	X_5	X_6	R^2
Series A								
A1	0.0670	-1.13E-02	1.57E-06	7.34E-02	***4.49E-11***	---------	-2.33E-02	0.69
A2	0.0670	-1.01E-02	1.55E-06	6.68E-02	---------	---------	-2.22E-02	0.68
Series B								
B1	.0699	***6.91E-04***	-1.40E-07	***3.09E-03***	***-4.89E-10***	***1.09E-04***	***-3.13E-03***	0.75
B2	.0696	---------	-1.45E-07	***3.98E-03***	***-1.57E-10***	***8.41E-05***	***-1.45E-03***	0.75
B3	.0694	---------	-1.42E-7	3.13E-03	----------	6.97E-05	-9.02E-04	0.75

Series A: models regressed from element four operational data with no ferric chloride pretreatment; Series B: models regressed from element four operational data with ferric chloride pretreatment; Italicized/bold values were not in attainment with statistical criteria of 95% confidence interval and P-value <0 .05

Accordingly, the final model equation describing the total membrane resistance, developed from element four operational data collected during direct filtration with no coagulant pre-treatment, is as follows:

$$R_T = -1.01\times10^{-2}(F_w t) + 1.55\times10^{-6}(Particle\ Counts)(F_w t) + 6.68\times10^{-2}(UV_{254})(F_w t) - 2.22\times10^{-2}(1-R)(F_w t) \quad (3\text{-}19)$$

3.4.2.2 Series "B" Model Results

Table 3-2 also presents the results of the multiple linear regression analysis for series B models, which include the effect of ferric chloride dosing on membrane resistance. The regression of model B1 resulted in the identification of the following coefficients being statistically insignificant X_1, X_3, X_4, X_5, and X_6. As defined above, these terms correspond to the mass loading of water, UV_{254}, HPC, ferric chloride and backwash water volume, respectively. This decision was inferred from evaluation of the 95% confidence intervals and the P-values presented in Table E-3 (Appendix E). As indicated each of the confidence intervals passes through zero and have P-value greater than 0.05, which as stated above, indicates there is a significant risk of committing a Type 1 error.

Because X_1 had the highest P-value (0.714) it was removed and subsequently model B2 was developed and regressed. As presented in Table 3-2, regression results of model B2 indicate the insignificance of the resistance terms represented by X_3, X_4, X_5 and X_6. As described above, this decision was based on the established confidence interval and P-value criteria; specific values of these results are presented in Table E-4 (Appendix E). Next model B3 was developed by dropping X_4 and the regression was repeated. The results of model B3 are also presented in Table 3-2. As indicated each remaining resistance term including X_2, X_3, X_5 and X_6 have a statistically significant effect on resistance.

Several inferences can be made from the resulting signs of the regression coefficients. Accordingly, the negative sign of X_2 suggests an increase of particle mass loading acts to decrease the overall membrane resistance. This result is opposite to that shown in model A3 and is indicative of the effect coagulant pretreatment on altering particle characteristics and reducing membrane fouling. Similarly, the negative sign of X_6 indicates an increase in the volume of water used in backwashing also decreased membrane resistance, which is consistent with model A3 results. Additionally, the positive signs of X_3 and X_5 indicate the mass loading of UV_{254} and ferric chloride, respectively, each have a significant role in increasing membrane resistance. The former result is consistent with model A3, however the latter is unexpected due to the observation of steady membrane performance during 7 and 14 ppm ferric chloride dosing as presented in Section 3.2.4. Because the mass loading of particle counts increases with coagulant dose it is necessary to asses the net effect of these two terms when evaluating the effect of dose on resistance.

The final model equation describing the total membrane resistance, developed from element four operational data collected during direct filtration with ferric chloride pre-treatment, is provided as Equation 3-20.

$$R_T = -1.42\times10^{-7}(Particle\ Counts)(F_w t) + 3.13\times10^{-3}(UV_{254})(F_w t) - 9.02\times10^{-4}(1-R)(F_w t) + 6.97\times10^{-5}(FeCl_3)(F_w t) \quad (3\text{-}20)$$

3.4.2.3 Model Verification

The final model equations presented as 3-19 and 3-20 (A2 & B3, respectively) were used to predict the individual performance of HYDRAcap elements two & six, in order to assess the variation in fouling behavior among the elements. Accordingly Figures 3-29 and 3-30 present actual vs. predicted values of total resistance (R_T) for membrane elements two and six, respectively. The predicted values presented were calculated using model A2, presented as Equation 3-19. As shown, the slopes of the linear regression trend lines are 0.5341 and 0.9707, respectively. This result indicates that the model over predicted the actual resistance values for element number two, but adequately predicted the expected 1:1 relationship of actual to predicted for element six. The ability of the model to accurately predict element six performance was confirmed by conducting a paired two sample t-test to determine if the means of the actual and predicted values for element six were equal (*i.e.* $H_0 = \mu_{actual}-\mu_{predicted} = 0$). Such results are presented in Table F-1; as shown $t < T$ (*i.e.* $-0.404 < 1.67$) indicating the validity of the null hypothesis. The fact that the resistance model developed from element four data more accurately describes the effect of mass loading on productivity for element six than element two, verifies the productivity variations observed among the elements during the course of this project.

Similarly the resistance values predicted by Equation 3-20 (model B3) were also compared to actual values measured for elements two and six data, as presented in Figures 3-31 and 3-32, respectively. As shown in Figure 3-31, the slope of the linear regression line for element two data is 0.9796 and the majority the data falls within the 95% CI, which ranges from 0.9243-1.0349. However inspection of Figure 3-32 reveals element six data is scattered and only a small fraction of the points are incorporated in the

95% CI, which ranges from 0.8181-0.9796. These results suggest model B3, which was developed from element four ferric chloride pretreatment data, more accurately predicted performance for element two than element six. This result is opposite to that seen by the application of model A2, which as previously discussed more accurately predicted fouling behavior for element six data than element two. However, as stated above for model A2, the variation in model B3 to accurately describe the performance of other elements is also attributed to productivity variation among the elements.

3.4.3 Sensitivity Analysis

Sensitivity analysis was conducted on models A2 and B3 to determine the degree in which each mass loading term effected membrane resistance and illustrate the productivity enhancement realized by the use of ferric chloride pretreatment. Accordingly, models A2 and B3 were used to calculate runtimes for various sets of operational and water quality conditions as presented in Tables 3-3 and 3-4, respectively. As described in Section 3.1.2, the runtimes shown were calculated as the time required to reach the maximum TMP of 17.5 psi. In addition, because the models were based on resistance Equation 3-6 was rewritten in terms of total resistance (R_T) as presented below.

$$Runtime = \frac{R_{T_f} - R_{T_i}}{\Delta R_T / \Delta t} \times (CF) \qquad \text{(3-6 Repeated, for } R_T\text{)}$$

Where:

R_{T_f} = final value of R_T (psi/gfd)

R_{T_i} = initial value of R_T (psi/gfd)

$\Delta R_T/\Delta t$ = R_T decline rate (psi/gfd-hour)

CF = conversion factor (days/hours)

As shown in Table 3-3, a runtime of 12.7 days was calculated for the following base operating conditions and water quality using model A2: Operating Flux = 30 gfd; BWF = 20 minutes, UV_{254} = 0.2084 cm^{-1}; and Particle Counts = 2997 counts/ml. The values of

UV_{254} and particle counts are average values of water quality used in developing the model. The effect on runtime resulting from an increase of each resistance term by +10%, +25%, +50% and +100% from the base conditions is also shown in Table 3-3. It is important to note the runtimes were calculated by only increasing one resistance term and holding all others at base conditions. As shown a +10% increase in UV_{254} resulted in a decrease in runtime of 49.6%, followed by particle counts (26%) and flux (15.7 %). Such results suggest that organic and solid mass loading played the most significant role in causing membrane fouling. Also shown increasing the backwash volume by just 10% increased the runtime by a factor of 4.6 (*i.e.* 12.7 to 71.7 days). It should also be noted the infinite runtimes associated with +25 and +50 % backwash frequency indicates the limitations of the model.

Similarly, runtimes were also calculated using model B2, which accounts for the effect of ferric chloride pretreatment dosing on membrane productivity. Such results are presented in Table 3-4. As indicated, the established base conditions were identical to those used for model A2 sensitivity analysis, but included the addition of 7 ppm ferric chloride dose. The calculated runtime before reaching the maximum TMP of 17.5 psi under the base conditions was 42.8 days; which when compared to the 12.7 days achieved without ferric chloride (model A2) clearly illustrates the enhancement of coagulant pretreatment on membrane productivity. It should be noted that the runtimes presented for values of percent increase of particle counts and ferric dosing were calculated by increasing both parameters and therefore resulted in identical values. As shown a +100% increase of these parameters only resulted in a decline in runtime of 16.6%. Also as shown an increase in UV_{254} decreased runtime by 16.6% and 64.3 % for an increase of +10% and +100%, respectively. Comparing the dramatic decline of runtime predicted by model A2 for a 10% and 100% increase in UV_{254} (*i.e.* 49.6 and 91.3%, respectively) suggests that ferric chloride pretreatment alters the characteristics and hence the fouling behavior of organic matter as well as particulate matter present in the feed water. Also shown, model B3 also predicted an increase of runtime of 25%, and 151%, for a +25% and +50 % increase of backwash volume.

Table 3-3: Sensitivity Analysis of Model A2

Resistance Terms	Runtime (days)				
	*base	+10%	+25%	+50%	+100%
Flux	12.7	10.7	7.9	5.4	2.8
particle counts	12.7	9.4	6.9	4.7	2.9
UV_{254}	12.7	6.3	3.6	2.0	1.1
Backwash Volume	12.7	71.7	**infinite	**infinite	***nd

*base conditions: UV_{254} = 0.2084 cm^{-1}; Particle Counts = 2997 counts/ml; Flux = 30 gfd; BWF=20 minutes. **resulted in negative values of runtime. *** not defined for BWF=0 minutes.

Table 3-4: Sensitivity Analysis of Model B3

Resistance Terms	Runtime (days)				
	*base	+10%	+25%	+50%	+100%
Particle Counts	42.8	42.8	35.7	35.7	35.7
UV_{254}	42.8	35.7	30.6	23.8	15.3
Backwash Volume	42.8	42.8	53.5	107.1	**nd
$FeCl_3$	42.8	42.8	35.7	35.7	35.7

*base conditions: UV_{254} = 0.2084 cm^{-1}; Particle Counts = 2997 counts/ml; Flux = 30 gfd; BWF=20 minutes. Ferric Chloride Dose = 7 ppm. **not defined for BWF=0 minutes.

Figure 3-29: R_T (actual) vs. R_T (predicted) for Membrane Element Two. Predicted values based on mass loading resistance model A2 developed using membrane element four operational data without ferric chloride pretreatment. The 95% confidence interval (CI) is based on linear regression analysis.

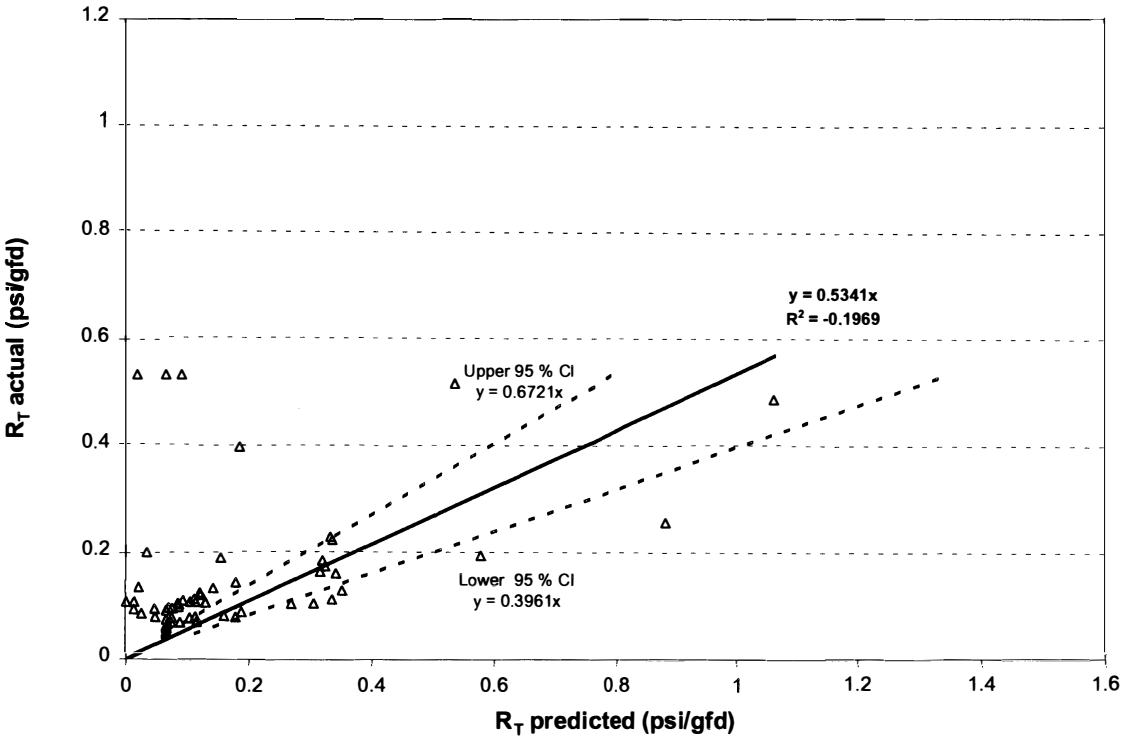


Figure 3-30: R_T (actual) vs. R_T (predicted) for Membrane Element Six. Predicted values based on mass loading resistance model A2 developed using membrane element four operational data without ferric chloride pretreatment. The 95% confidence interval (CI) is based on linear regression analysis.

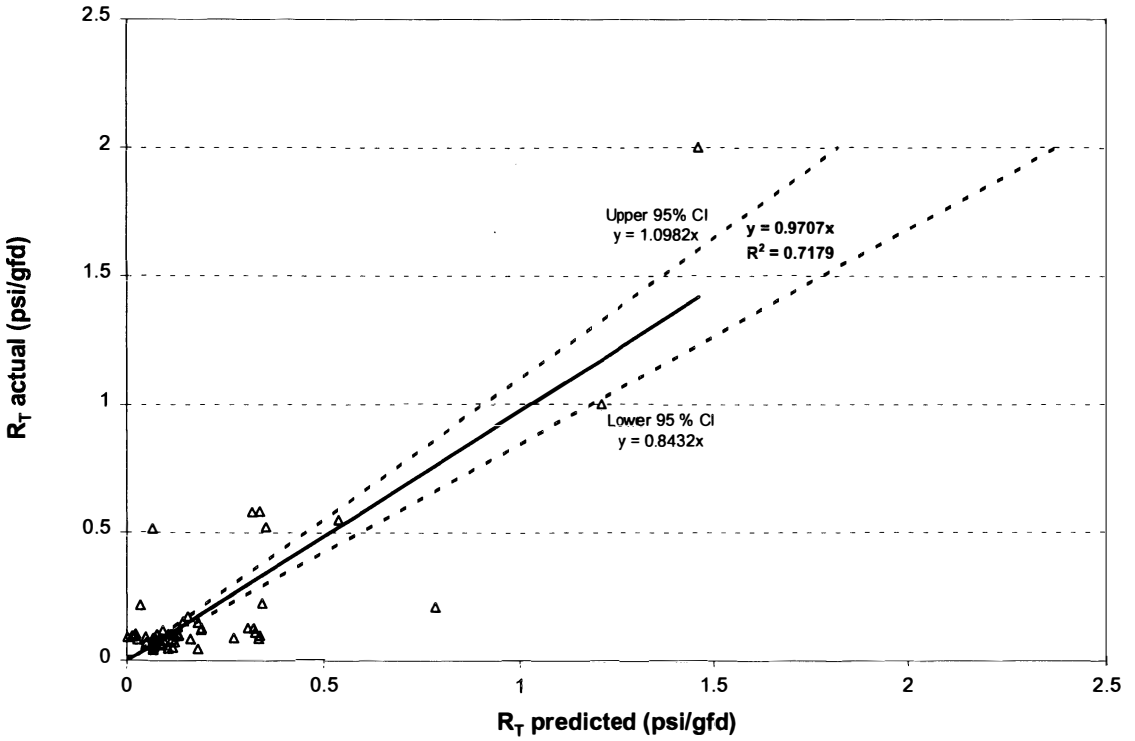


Figure 3-31: R_T (Actual) vs. R_T (Predicted) for Membrane Element Two. Predicted values based on mass loading resistance model B3 developed from membrane element four operational data during ferric chloride pretreatment. The 95% confidence interval (CI) is based on linear regression analysis.

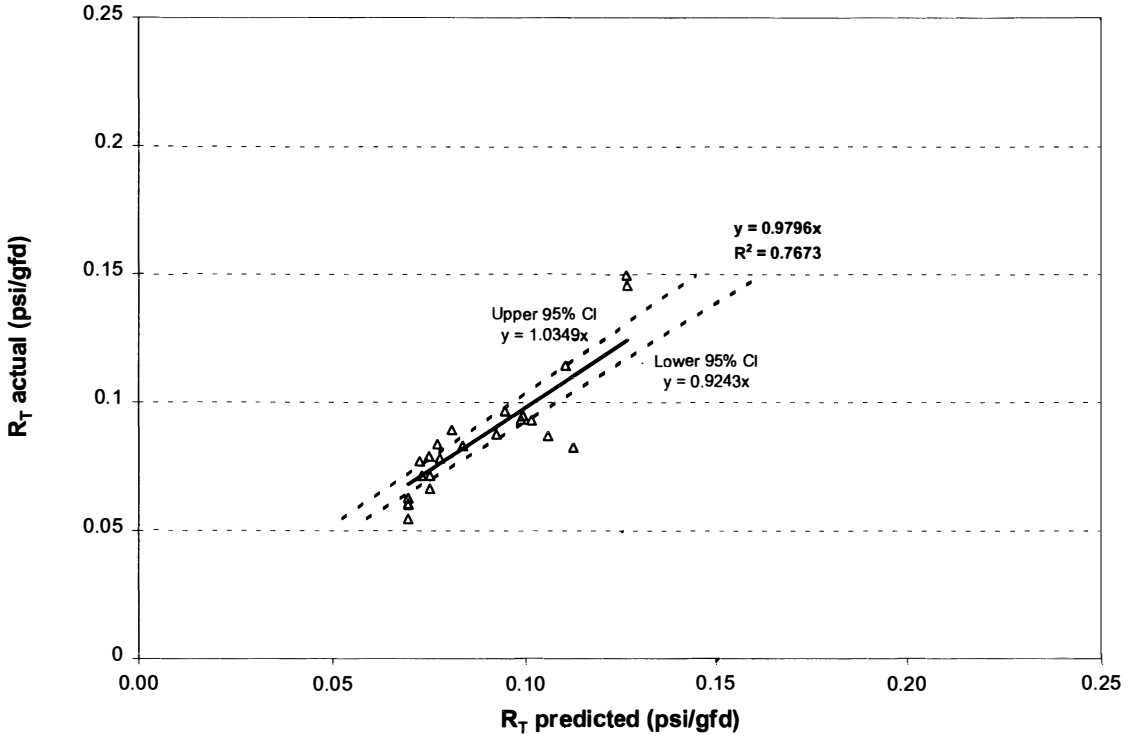
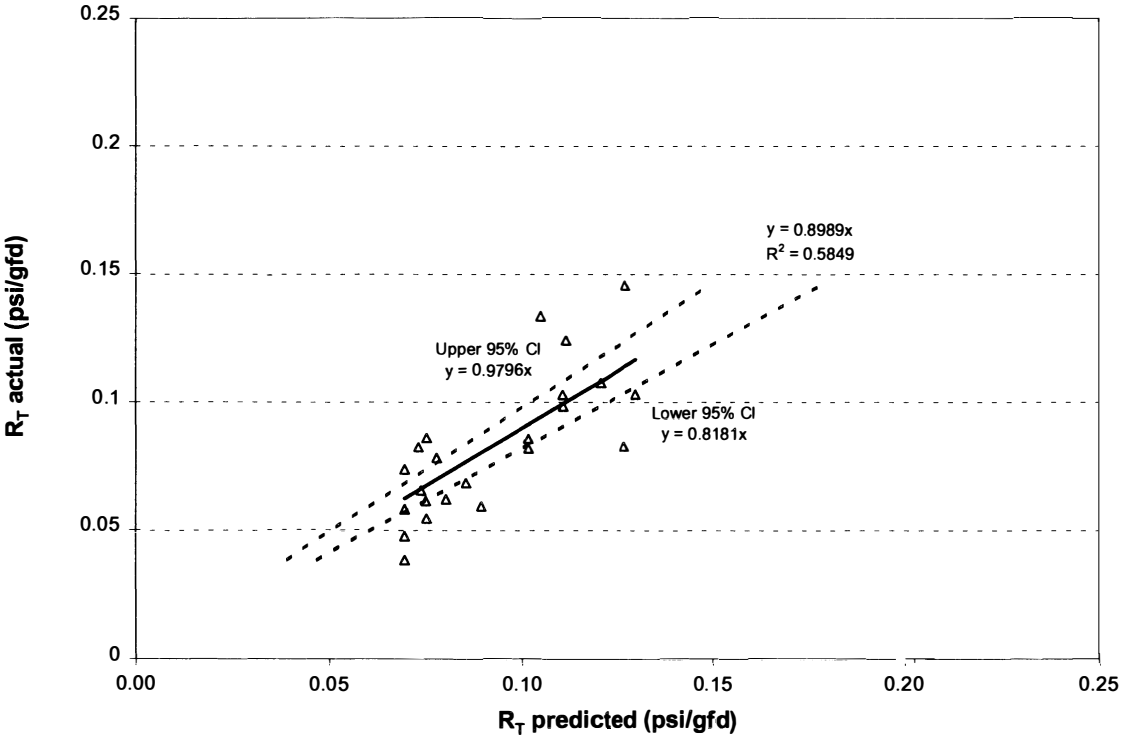


Figure 3-32: R_T (Actual) vs. R_T (Predicted) for Membrane Element Six. Predicted values based on mass loading resistance model B3 developed using membrane element four operational data during ferric chloride pretreatment. The 95% confidence interval (CI) is based on linear regression analysis.



4.0 CONCLUSIONS AND RECOMMENDATIONS

The following chapter summarizes important inferences concurred from experimental results obtained during the course of this project. In addition, recommendations are provided concerning the operation and design of the Mini-HYDRAcap pilot unit.

4.1 General

I. *A newly developed capillary UF membrane was effective at producing reclaim water from tertiary wastewater.*

The capillary UF membrane developed by Hydranautics consistently produced low turbid water under various operating conditions. Furthermore, this membrane removed a significant degree of microbial contaminants present in typical wastewater. In addition, stable performance without significant productivity loss was achieved with the addition of coagulants and adequate backwashing. More specifically, the desired operating conditions for the reclamation of UCF's wastewater were:

Filtrate Flux:	30 gfd
Backwash Frequency	20 min
Chlorine Enhanced Backwash Frequency	26 ppm Cl_2 every 20 min.
$FeCl_3$ Dose	7 to 14 ppm continuous feeding
Recovery	70 %

Operating with a 15 minute backwash frequency also resulted in minimal fouling even without $FeCl_3$ addition.

II. *The Mini-HYDRAcap pilot system provided an effective and practical means to assess membrane performance and optimize operating conditions for specific source water.*

A distinguishing feature of the pilot unit is the configuration of six small hollow fiber elements in parallel. This design was useful for two purposes. First, it allowed the user

to simultaneously assess the productivity of the HYDRAcap membranes at six different values of operating flux. Secondly, the operation of each membrane at the same flux rate made it possible to verify the reproducibility of each membrane present on the unit under specific operating conditions.

4.2 Membrane Productivity

I. *HYDRAcap productivity increased linearly with increasing feed water temperature.*

The temperature correction factor for MTC values, determined form operational data, was found to be 0.022. This value was consistent with previous studies conducted during the development of the HYDRAcap membranes in which the temperature correction factor was determined to be 0.019.

II. *HYDRAcap productivity decreased with increasing operating flux.*

Experimental data indicated that the decline of K_w with respect to time was much greater at higher operating fluxes. Specifically, the decline rates of MTC measured during operation at 30, 44, and 60 gfd were 2.0, 2.5, and 9.8 times faster than that measured during operation at 20 gfd, respectively. The increase in MTC decline observed at higher operating fluxes is primarily attributed to the increase of mass loading to the membrane system. This was verified by assessing particle and organic mass loading, which showed increasing productivity loss with increasing mass loading. Enhanced hydraulic resistance of the fouling layer due to the stronger drag force induced by filtrate flow may also contribute to severe fouling observed at high operating flux. In addition, the achievable runtimes before reaching the maximum HYDRAcap TMP of 17.5 psi decreased significantly (25-1.6 days) for operating flux rates ranging from 20-60 gfd, respectively.

III. *HYDRAcap productivity decreased with increasing backwash frequency.*

Experimental data clearly showed that decreasing the time between backwashing (*i.e.* decreasing the backwash frequency) increased membrane productivity. The productivity (*i.e.* MTC decline rate) measured during operation at 20 min. BWF resulted in a 41.2% improvement over 30 min. BWF operation. Furthermore, operating at a 15 minute BWF showed no decline of MTC values, indicating fouling did not occur. The increase in productivity is ascribed to several flux restoration mechanisms including convection, oxidation and biofilm control. It was also found that flux enhancement per unit backwashing water volume decreased with increasing backwash frequency, suggesting that the effectiveness of backwashing was a function of backwash frequency. This observation may be explained by the formation of a thicker fouling layer and enhanced microbial growth associated with an increased time interval between backwash events.

IV. *HYDRAcap productivity was significantly enhanced by the addition of ferric chloride to the feed water prior to UF filtration.*

Ferric chloride pretreatment significantly enhanced membrane productivity. The decline rate of K_w measured during operation with 7-ppm ferric chloride dose was approximately 82 % less than with no ferric pretreatment. In addition, dosing of 14-ppm ferric chloride stabilized K_w for 150 hours of runtime with minimal fouling. The observed enhancement of membrane productivity due to ferric chloride pretreatment may be attributable to destabilization and coagulation of colloidal particles present in the feed water.

V. *HYDRAcap productivity was not improved by operating at crossflow mode under the given experimental condition.*

Experimentation involving the effect of crossflow velocity on membrane productivity during this project was limited, however, the results indicated that the applied crossflow velocity was insufficient in increasing membrane productivity. Specifically, the MTC decline rates measured under crossflow velocities of 0 and 0.1 m/s differed by less than 10%. Similar result has been obtained by a previous study on HYDRAcap performance (San Luis Rey municipal wastewater treatment facility, Oceanside, CA), in which

crossflow velocities up to 0.25 m/s had minimal enhancement of productivity. Such results indicated that the applied crossflow velocities were inadequate to prevent a large portion of solid and organic foulants present in the feed water from accumulating on the membrane surface.

VI. *HYDRAcap productivity varied among the membrane elements.*

The average K_w values for membranes one through six measured after cleaning ranged from 13.3 to 21.5 gfd/psi. This variation may be attributed to accuracy limitations of the filtrate pressure gages and potential differences in membrane properties such as pore size distribution. In addition, the ability of each membrane element to recover flux after chemical cleaning may be partially responsible for the observed variation.

4.3 Filtrate Water Quality

I. *HYDRAcap membranes consistently removed a high degree of particulate contaminants, independent of feed concentration.*

Results of the water quality analysis indicated that HYDRAcap membranes achieved relatively high rejection of particulate contaminants as measured by turbidity and particle counting. Specifically, the average rejections of turbidity and particle counting were estimated at 92.8 % and 92.1 %, respectively. The good rejection of particulate matter resulted from size exclusion by the relative small pores of UF membranes (MWCO: 150,000 Dalton). The rejection of particulate matter during UF filtration was independent of feed concentration. Several important findings also exist regarding the effect of operating conditions on particulate water quality. First, the average filtrate concentrations of turbidity and particle counts were consistently low during filtration regardless of operating filtrate fluxes, indicating that operating flux has no or marginal effect on particulate removal. Secondly, varying backwash frequency during pilot operation did not influence filtrate turbidity or particle counts significantly. Lastly,

although the addition of ferric chloride increased feed turbidity and particle counts, coagulation pretreatment improved particle removal through enhancing size exclusion by increasing particle size.

II. *Organic removal by HYDRAcap membranes was not significant as expected for typical UF membranes.*

The measurement of UV_{254} and TOC in the feed and filtrate water during the course of this project indicated low rejection of organic matter. This is attributed to the passing of dissolved organic species through the membrane pores. Specifically, the UV_{254} average rejection values indicated the membranes only rejected an average of 3.6%. Similarly, the average TOC rejection was estimated at only 5%. In addition, water quality analysis suggested that the amount of organic contaminants rejected was independent of flux and backwash frequency.

III. *High log removals of microbial contaminants present in the feed wastewater were achieved under varying operating conditions by the HYDRAcap membranes.*

The HYDRAcap membranes successfully removed heterotrophic plate count (HPC) with LRVs ($-\log_{10}(filtrate/feed)$) ranging from 2.0–4.9. In addition, total coliform (TC) LRV's ranged from 1.2-7.0 with approximately 33% of the filtrate samples measured during the course of this project indicating infinite rejection of TC. Several conclusions are also drawn regarding the effect of operating conditions on microbial filtrate water quality. First, the concentrations of HPC and total coliform measured in filtrate water decreased with increasing operating flux. The enhancement of microbial removal may be explained by the increased cake layer formation associated with higher operating flux, which can block large pores that may exist in the pore size distribution. In addition to operating flux, experimental evidence indicates that microbial rejection may be influenced by backwash frequency. Specifically, HPC measured in the filtrate during operation with at a 30 minute BWF was 80.4% and 82.9% lower than those measured

during a 15 and 20 min BWF. This may be a result of the increased fouling state of the membranes due to less frequent backwashing; however further experimentation is required to assess the effect of BWF on microbial rejection.

4.4 Statistical Modeling

I. *Multiple linear regression analysis of operational data based on the resistance model indicated that both particle and organic contaminants contribute to increasing HYDRAcap resistance.*

The resistance model was applied to pilot operational data of a single element to assess the effect of the mass loading of particulate counts, UV_{254}, and HPC on total resistance. In addition, the mass loading of water (F_w) and the volume of water used for backwashing (1-R)(F_w) was included in model. Interpretation of statistical results from linear regression analysis indicated the following terms were statistically significant at effecting HYDRAcap resistance: particle counts, UV_{254}, F_w and (1-R)(F_w). In addition regression results demonstrated that increased mass loading of particulate counts and UV_{254} contribute to increasing total membrane resistance. However, increasing the mass loading of water and the volume of water used in backwashing contribute to decreasing total membrane resistance. A similar model, developed from ferric chloride operational data alone, showed increased particle count mass loading reduced membrane resistance. This result is evident of the impact that ferric dosing has on altering feed water particle characteristics.

II. *The statistical model developed based on a single element was inconsistent in accurately predicting the productivity of other HYDRAcap membranes tested in this project.*

The developed models were utilized to predict the productivity of other HYDRAcap elements studied during this project. In general the success of the models at predicting the productivity performance varied among the elements. This may be explained by the

variation among the membrane modules and the limited data set used in the model development.

III. *Sensitivity analysis of the developed resistance models revealed the fouling order of foulants increasing HYDRAcap resistance: UV_{254}>Particle Counts>Membrane Degradation. In addition ferric chloride significantly decreased the resistance per filtration time corresponding to the mass loading of UV_{254} and particle counts.*

Runtimes were determined for identical mass loading and operating conditions using the models developed with and without ferric chloride data. Results indicated the filtration time required to reach the maximum TMP of 17.5 psi was increased by a factor of 2.37 by the addition of 7-ppm ferric chloride. In addition the sensitivity of the models was evaluated by quantifying the effect of increasing a single resistance term on runtime. Accordingly, based on the model without ferric chloride dosing, a 10% increase in UV_{254}, particle counts, and flux resulted in a decrease in runtime of 49.6%, 26%, and 15.7 %, respectively. However, the model predicted runtime to increase by a factor of 4.6 by decreasing the backwash frequency (*e.g.* decreasing time between backwashing) by only 10%. Similar analysis using the ferric dose model, clearly demonstrated that the addition of ferric chloride decreased the decline in runtimes associated with an increase in particle counts and UV_{254}.

4.5 Recommendations

The following section provides recommendations, which are intended to provide a means of further developing the Mini-HYDRAcap pilot system as an effective tool in optimizing operating conditions to enhance membrane performance. These recommendations focus on both the operation and design of the pilot of the system.

Process Optimization for Improving Performance

I. *Additional experimentation on the effect of backwashing frequency is needed for flux optimization.*

As stated above, the optimal operating flux determined in this project was identified as 30 gfd. However, this decision was made on the basis of a series of filtration experiments conducted with a 20 minute BWF only. A more systematic investigation is required to determine the effect of backwashing frequency on the optimal flux.

II. *Further investigation is required for the optimization of backwashing steps including Cl_2 dosing and sequence times.*

Though the results indicate that decreasing the backwash frequency leads to stability in membrane productivity, further investigation is necessary to optimize backwashing to maximize HYDRAcap performance. In particular, the effect of the chlorine dose used during backwashing and the sequence times of each backwashing step should be studied. In addition further evaluation of the effect of backwash frequency on system recovery should be conducted to determine the optimal backwash frequency to maximize HYDRAcap production.

III. *Additional experimentation should be conducted to optimize ferric chloride dosing to improve membrane productivity and filtrate water quality.*

Based on results of the current project, 7 to 14 ppm ferric in-line dosing enhanced membrane productivity. However, it is suggested that further experimentation be conducted to determine the optimum dose of ferric chloride. In addition, a more fundamental study on the interaction between ferric chloride and the HYDRAcap UF membrane is required to ensure the long-term integrity of the newly developed membranes. Lastly, the effect of ferric chloride pretreatment on removal of particle, organic, and microbial contaminants should be investigated.

IV. *The role of organic contaminants on HYDRAcap productivity should be studied to determine the mechanisms responsible for membrane fouling.*

Results of the statistical modeling described above, indicate the mass loading of organic contaminants as measured by UV_{254} contribute to increasing total HYDRAcap resistance. Combining this result with the consistently low rejection of UV_{254} measured during the course of the project indicates a small portion of organic matter retained by the membrane can result in fouling. It is recommended further experimentation be conducted to determine the significance of organic foulants on HYDRAcap productivity and the specific mechanisms responsible for organic fouling. Such experimentation may include the comparison of productivity decline during filtration of a high and low organic content feed water that have similar particulate and microbial characteristics. In addition, correlation between organic characteristics and fouling potential of the HYDRAcap UF membrane should be established.

V. *Further statistical modeling should be performed to develop a semi-empirical equation to predict HYDRAcap productivity.*

The multiple linear regression analysis performed during this project provides useful information regarding the effect of various mass loading terms on HYDRAcap productivity. However, the developed linear model equation is inadequate to accurately describe the variation in the fouling behavior among the six HYDRAcap membranes studied. As a result, it is recommend that more HYDRAcap data be collected and further modeling be performed using a non-linear approach that incorporates a wide range of operational data measured during HYDRAcap filtration.

VI. *Membrane performance for specific source water using the Mini-HYDRAcap pilot system and a full scale HYDRAcap system should be collected and compared.*

Though the HYDRAcap pilot system investigated in this study is effective at predicting the effect of various operating conditions on Mini-HYDRAcap performance, the ability of the system to predict full-scale membrane performance needs to be assessed. It is

recommended studies be conducted involving filtration experiments of a specific source water using both mini and full size HYDRAcap membranes.

Pilot System Modifications

I. *The current filtrate pressure gages equipped on the pilot unit should be replaced with new gages that can provide more accurate pressure measurements.*

The variations in MTC values among the elements may be associated with difficulty in reading pressure gages provided in the pilot unit. Significant differences in MTC can result from the relatively low TMPs applied during typical operation of the HYDRAcap pilot system. For example, although only a 1-psi difference exists between a TMP of 1 and 2 psi, the actual MTC difference for a flux of 40 gfd would be 40 gfd/psi vs. 20 gfd/psi. Consequently, the energy efficiency of the membranes increases the difficulty of MTC interpretation.

II. *The productivity variation among the HYDRAcap elements should be minimized.*

Due to the variation of MTC (K_w) among the membranes measured at the onset of the project and during filtration of clean water following cleaning events, it is recommended that the Mini HYDRAcap elements be designed to a specific productivity standard. This would allow for a more accurate assessment of the impact various operating conditions have on membrane productivity and enhance the systems ability to optimize these conditions.

III. *The pilot system should be designed to provide higher cross flow velocity during cross flow filtration.*

The current configuration of the pilot system allows for a maximum crossflow of 10 gpm, which corresponds to a crossflow velocity of approximately 0.10 m/s. As stated above, results from the current project and previous studies indicated that this velocity was inadequate to enhance membrane productivity. Therefore, it is recommended that the

concentrate gage and piping system be replaced to accommodate higher crossflow velocities. In addition, operation in "cross flow" mode resulted in a build up of air in the system. An air release valve may need to be placed within the concentrate recycle line to alleviate this occurrence.

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APPENDIX A: EXPERIMENT IDENTIFICATION

Table A-1: Flux (Flow) Settings by Experiment

Experiment ID	Flux in GFD (Flow in GPM) by Membrane Element					
	1	2	3	4	5	6
A	32(0.45)	36(0.50)	40(0.55)	44(0.60)	48(0.65)	52(0.70)
B	20(0.30)	20(0.30)	20(0.30)	20(0.30)	20(0.30)	20(0.30)
C	60(0.80)	60(0.80)	60(0.80)	60(0.80)	60(0.80)	60(0.80)
D	44(0.60)	44(0.60)	44(0.60)	44(0.60)	44(0.60)	44(0.60)
E	44(0.60)	44(0.60)	44(0.60)	44(0.60)	44(0.60)	44(0.60)
F	30(0.40)	30(040)	30(0.40)	30(0.40)	30(0.40)	30(0.40)
G	30(0.40)	30(040)	30(0.40)	30(0.40)	30(0.40)	30(0.40)
H	30(0.40)	30(040)	30(0.40)	30(0.40)	30(0.40)	30(0.40)
I	30(0.40)	30(040)	30(0.40)	30(0.40)	30(0.40)	30(0.40)
J	30(0.40)	30(040)	30(0.40)	30(0.40)	30(0.40)	30(0.40)
K	32(0.45)	36(0.50)	40(0.55)	44(0.60)	48(0.65)	52(0.70)
L	30(0.40)	30(0.40)	30(0.40)	30(0.40)	30(0.40)	30(0.40)
M	32(0.45)	36(0.50)	40(0.55)	44(0.60)	48(0.65)	52(0.70)
N	32(0.45)	36(0.50)	40(0.55)	44(0.60)	48(0.65)	52(0.70)
O	32(0.45)	36(0.50)	40(0.55)	44(0.60)	48(0.65)	52(0.70)

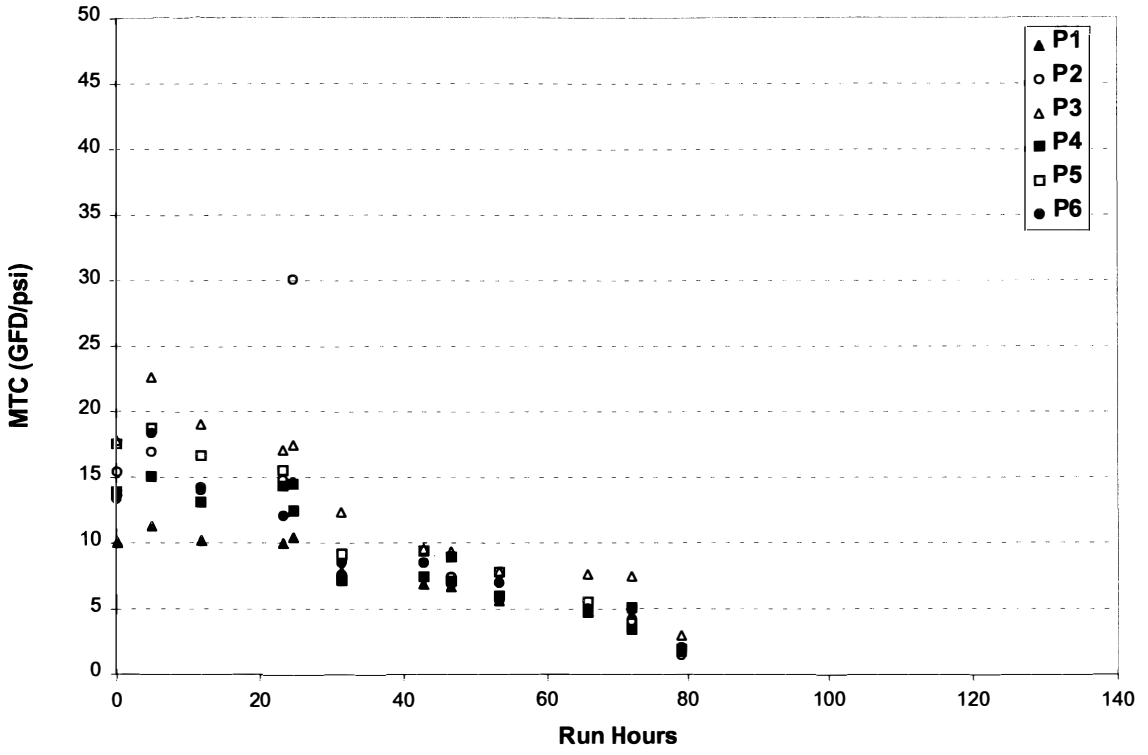
Table A-2: Operating Conditions by Experiment

Experiment ID	Backwash Frequency (Min.)	Concentrate Flow (GPM)	Ferric Chloride Dose (ppm)
A	20	0	0
B	20	0	0
C	20	0	0
*D	20	0	0
E	20	0	0
F	20	0	0
G	15	0	0
H	30	0	0
I	20	10	0
J	20	0	14
*K	20	0	7
L	20	0	14
M	30	0	0
N	15	0	14
O	20	0	7

***Repeated experimental conditions**

APPENDIX B: MEMBRANE PRODUCTIVITY DATA

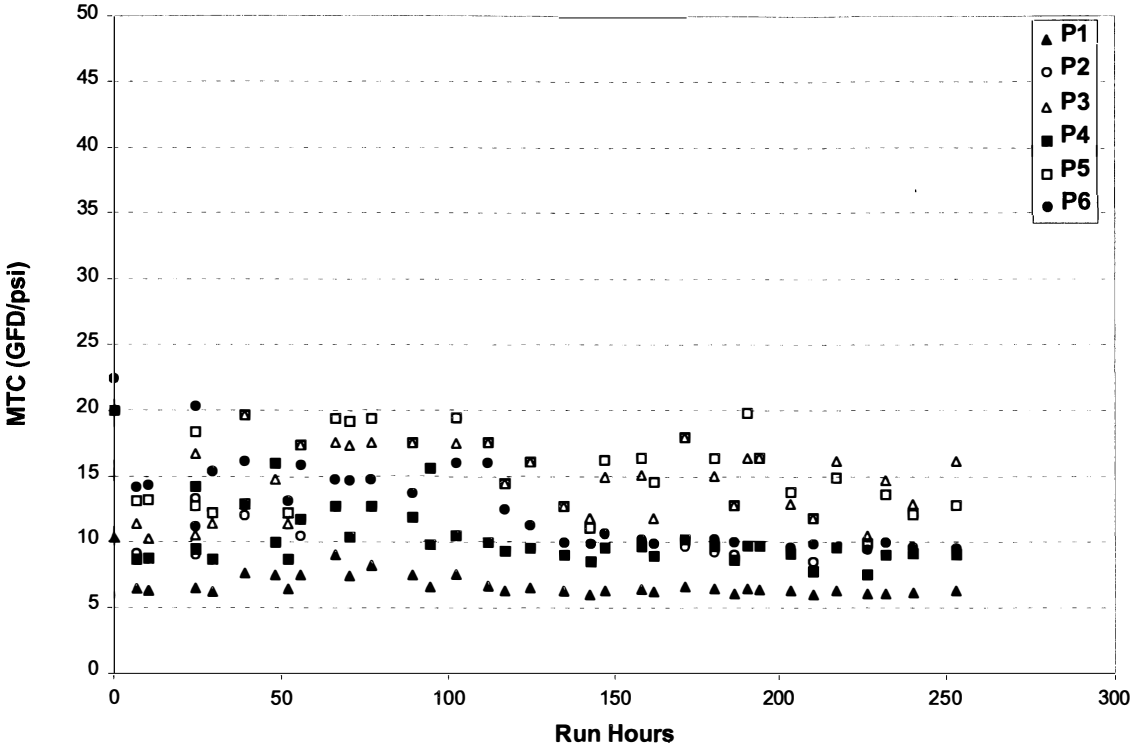
Figure B-1: MTC vs. Run Hours Experiment A



Notes:

- On 8/17/99 @ 1:40 p.m. (approx. one day after start), the system was found off and the pressure alarm light was on. The system was restarted at 2:06 p.m. It was later discovered a power failure caused the system to shut down.
- On 8/19/99 @ 11:14 p.m., the membranes were fouled severely. The filter pressures (psi) recorded were 7.5 @ 0.45 GPM, <1 @ 0.49 GPM, 9.9 @ 0.55, <1 @ 0.48 GPM, <1 @ 0.53 GPM, <1 @ 0.5 GPM for the membranes #1-#6, respectively. Inquiry with the wastewater plant indicated the plant had doubled its hydraulic capacity reducing the normal retention time by a factor of 50%. The experiment was terminated and the unit was cleaned.

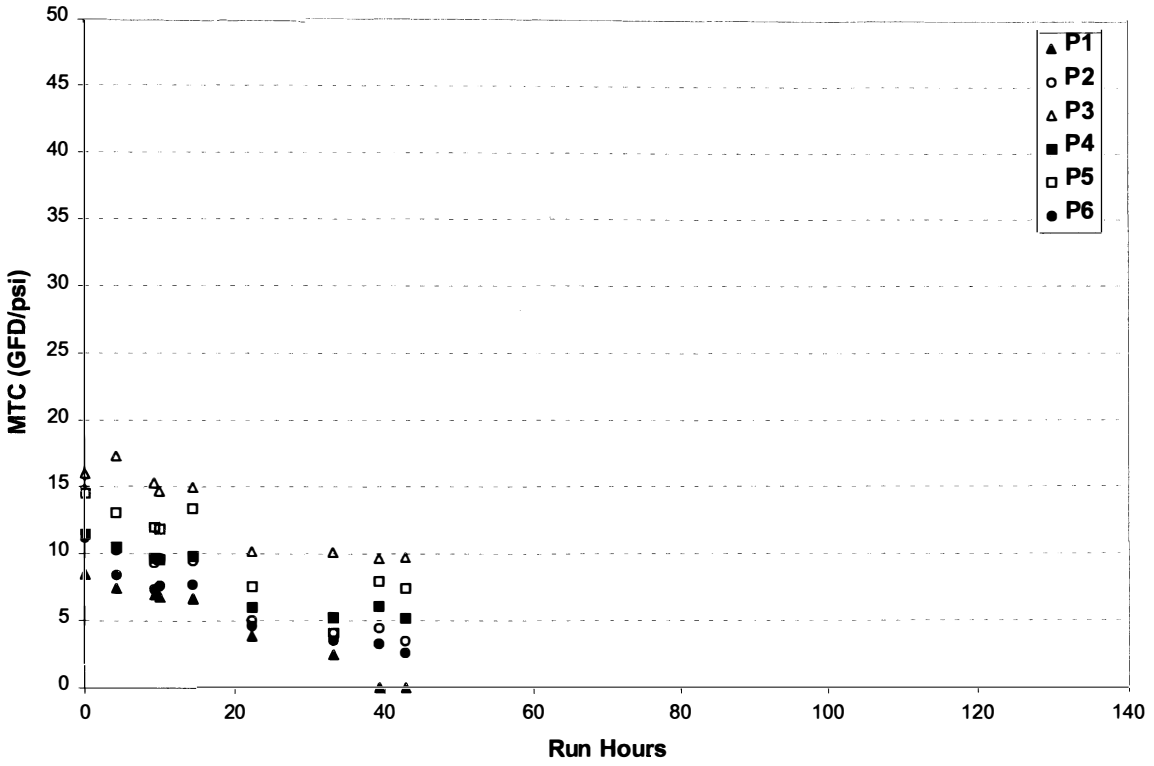
Figure B-2: MTC vs. Run Hours for Experiment B



Notes:

- On 9/14/99 @ 11:30 a.m. (approx. one day after start), the unit was shut off due to severe potential weather form hurricane Floyd. The unit was covered with boards and all pumps were wrapped in plastic. The unit was restarted on 9/16/99 @ 9:41 a.m., and the experiment was completed on 9/26/99.

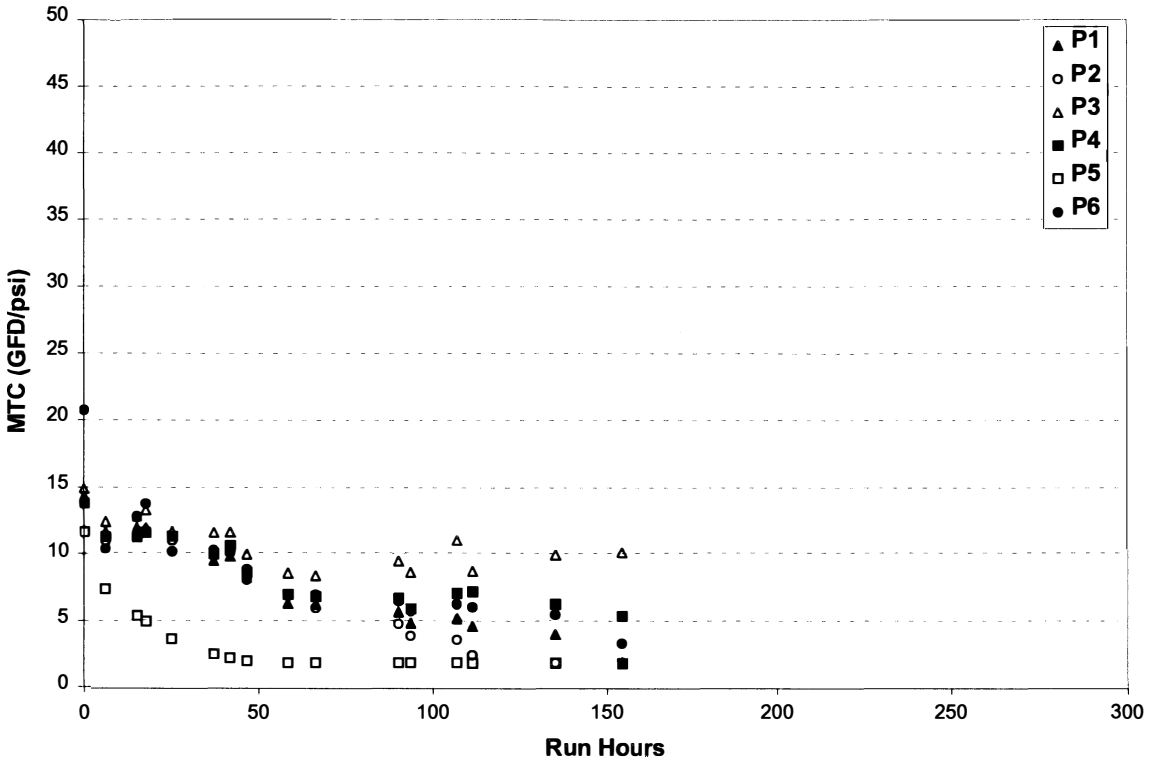
Figure B-3: MTC vs. Run Hours for Experiment C



Notes:

- On 10/3/99 @ 12:00 p.m., a strong smell of chlorine was detected in the feed water. A "free chlorine" test on the feed water indicated only a 2-ppm residual. However it was discovered that the plant operator had been diverting the wastewater to an emergency holding pond since 10:00 am, and that the feed water to the unit was probably from the front of the chlorine contact chamber. As a result the unit was shut off at 12:20 p.m. and restarted at 1:41 p.m. (after the plant resumed normal operation). In addition the permeate valve on membrane module #1 was closed due to severe fouling
- On 10/4/99, permeate valves on modules, #2, #4 and #6 were shut due to fouling.
- On 105/99 the experiment was terminated (three days before scheduled) because four of the six membranes were severely fouled. It should be noted despite the severe fouling state of the other membranes, membrane #3 maintained the 0.8 GPM flow with a TMP of approx. 5-psi.

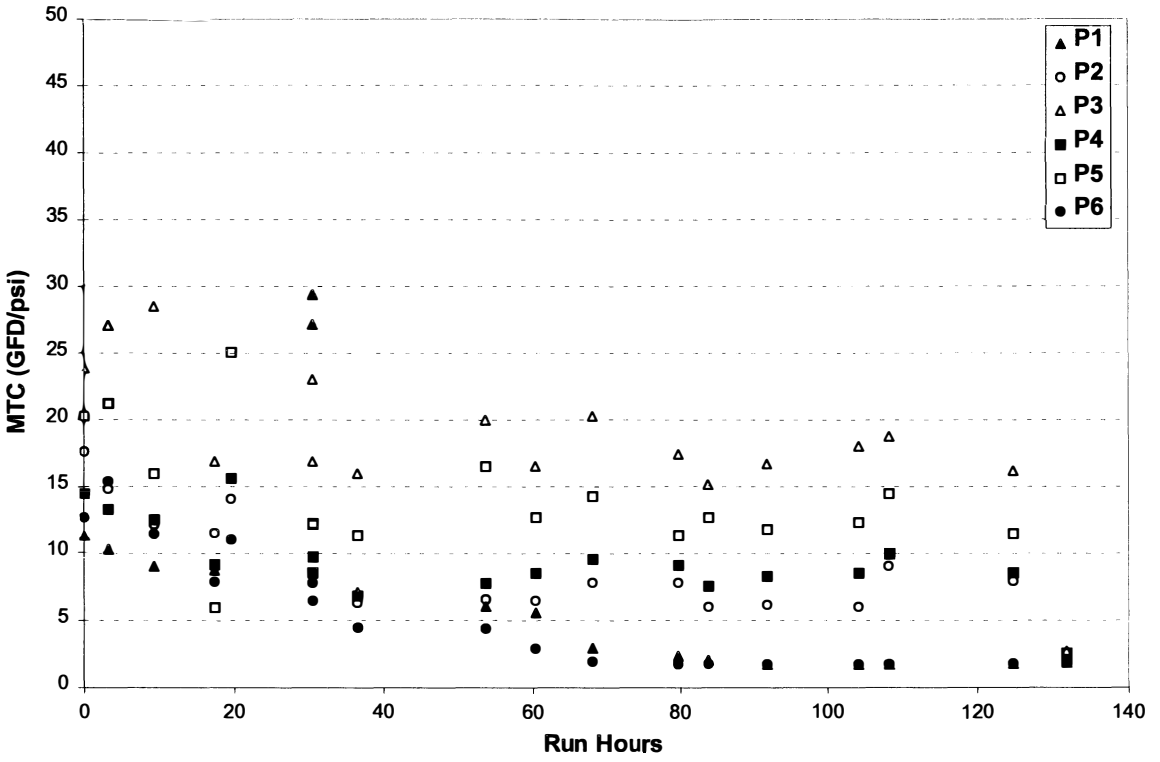
Figure B-4: MTC vs. Run Hours Experiment D



Notes:

- The positions of membrane modules #1 and #3 were reversed before start-up. This was done to determine if the position of the module had an effect on membrane performance; previous experiments indicate that membrane #3 maintains productivity a significant amount of time longer than membrane #1. As shown above regardless of position membrane #3 showed the lowest decline in MTC which suggests position is not the reason the or increased productivity observed from this module.

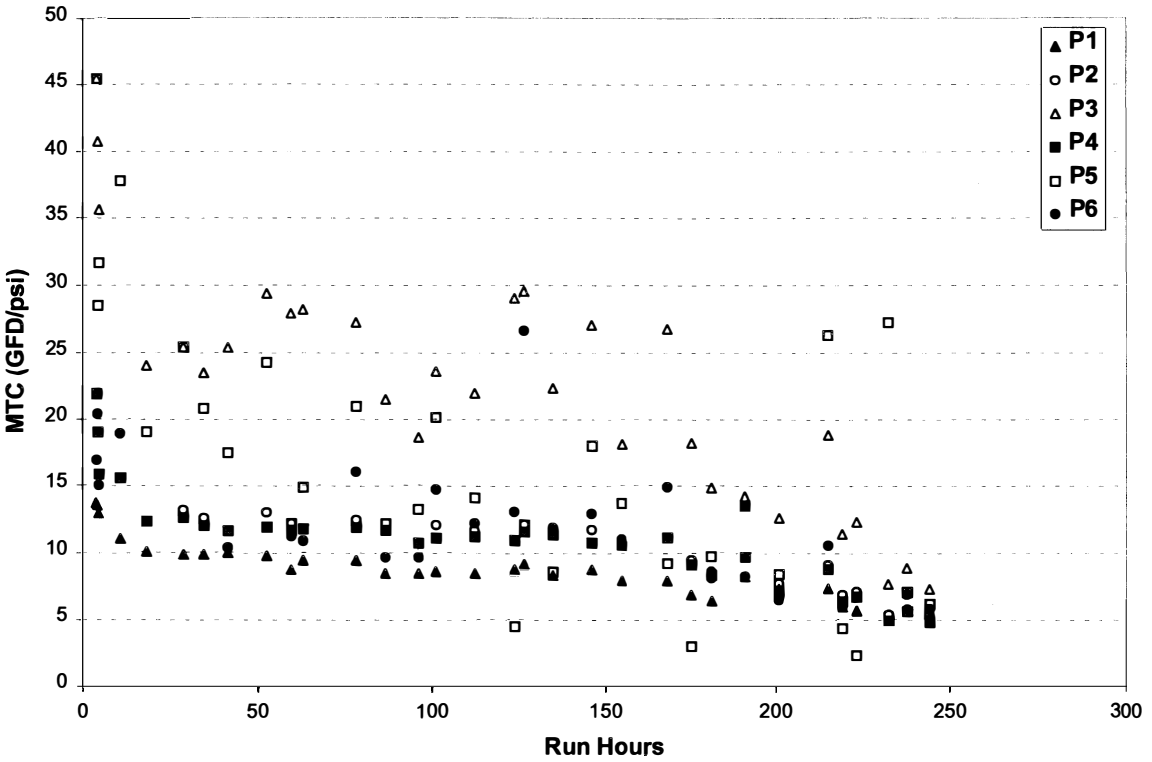
Figure B-5: MTC vs. Run Hours Experiment E



Notes:

- This experiment was conducted under the same operational parameters as Experiment D. It was necessary to repeat these operational parameters because no water quality measurements were performed during Experiment D.

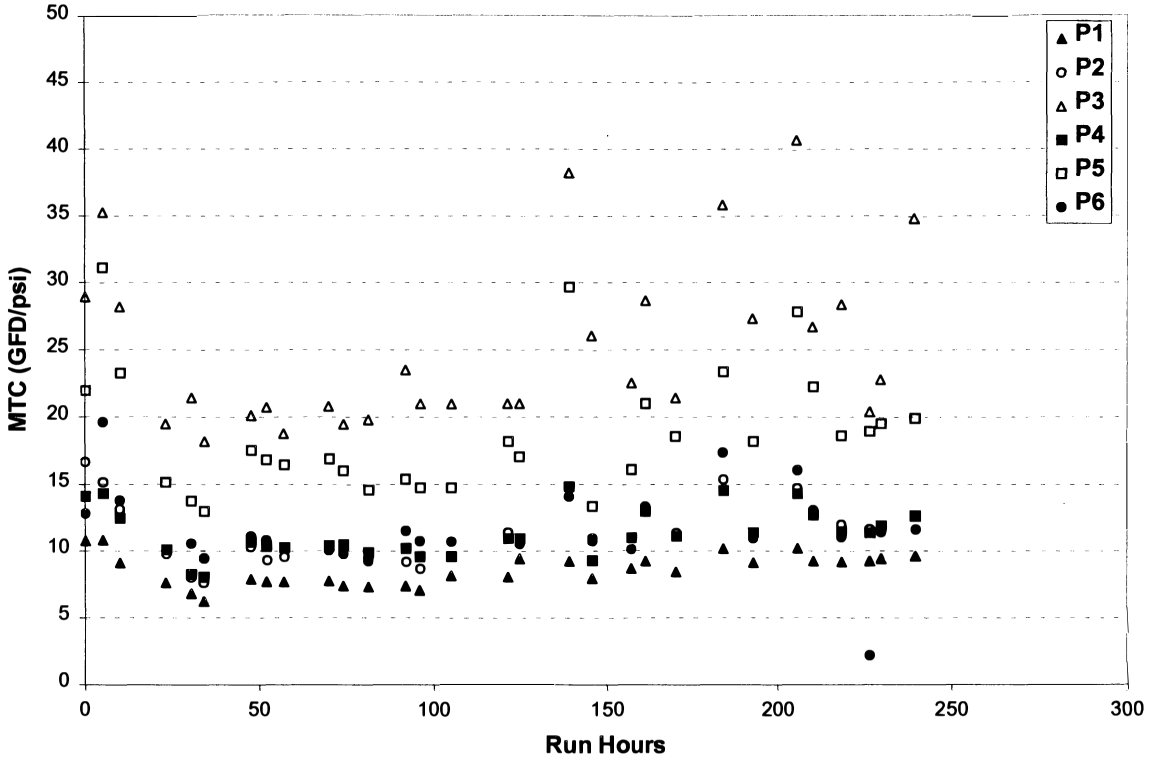
Figure B-6: MTC vs. Run Hours Experiment F



Notes:

- On 12/04/00 @ run hour 990.7 (approx. 5 days after start), the system was found off and the pressure alarm light was on. The system was restarted and back on line at 12:36 p.m. It was later discovered a power failure caused the system to shut down.

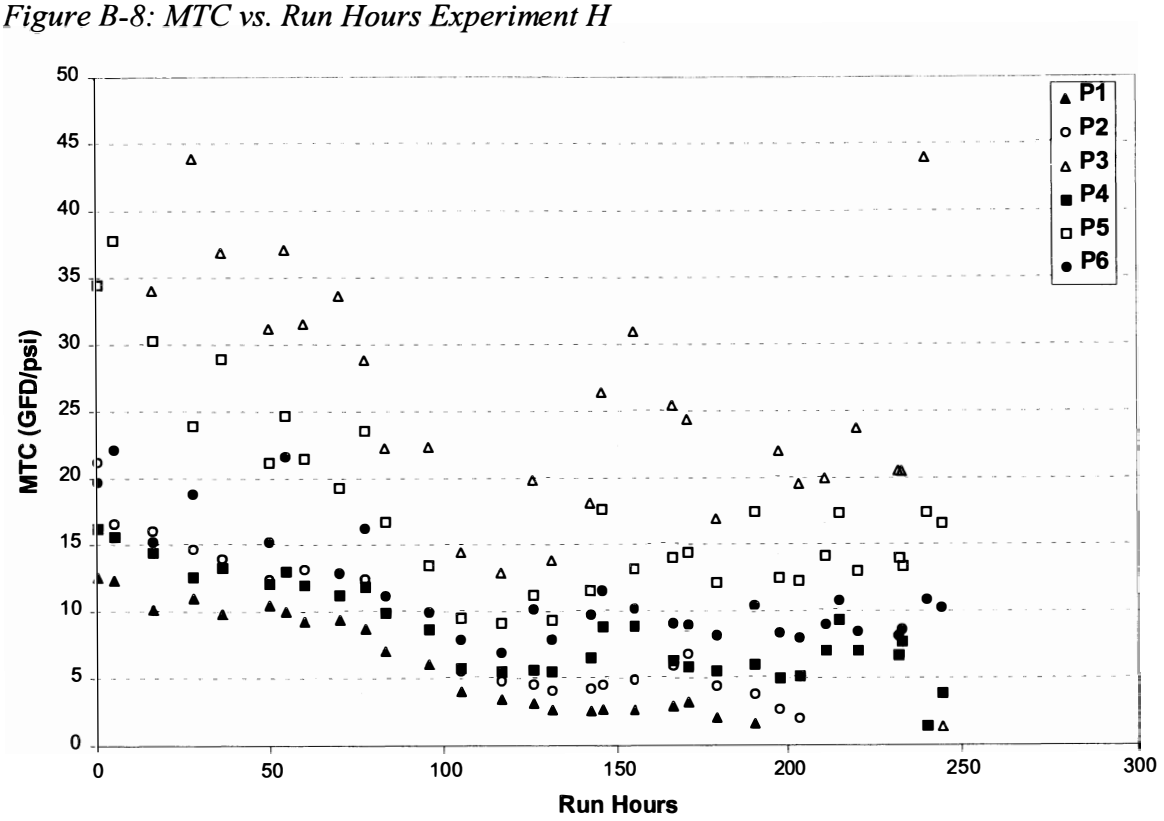
Figure B-7: MTC vs. Run Hours Experiment G



Notes:

- No unexpected occurrences noted.

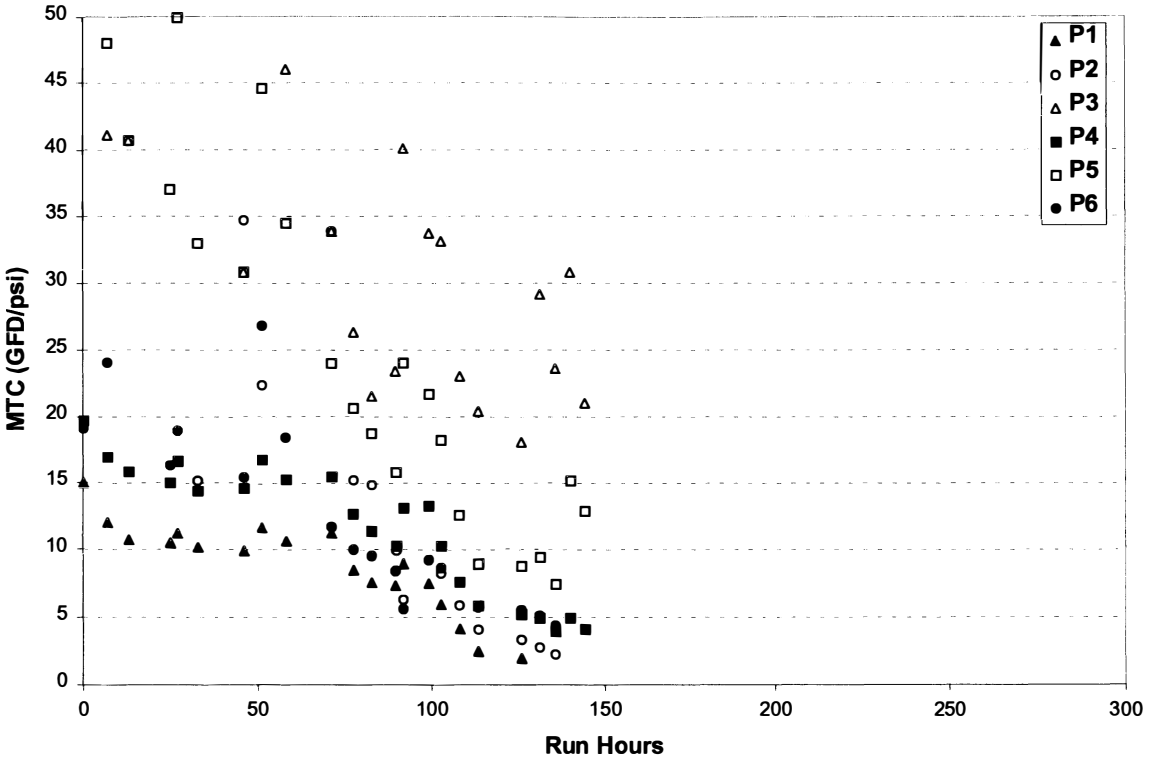
Figure B-8: MTC vs. Run Hours Experiment H



Notes:

- On 1/15/00 @ 12:31 p.m., membrane #1 was severely fouled and the permeate valve was closed.
- On 1/16/00 @ 2:30 p.m., membrane #2 was severely fouled and the permeate valve was closed.

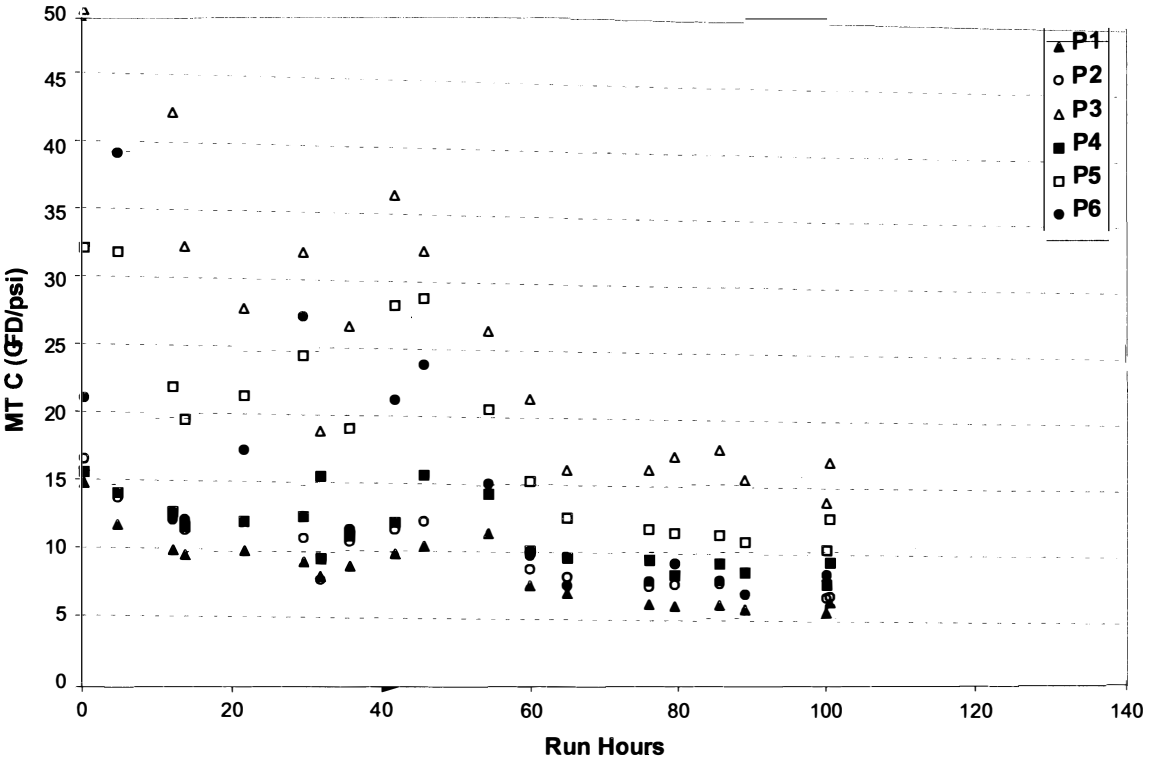
Figure B-9: MTC vs. Run Hours Experiment I



Notes:

- On 1/25/00 @ run hour 1645.2, polymer was discovered in the feed water. The run was aborted and the unit was cleaned. The run was repeated on 1/28/00 with original operating conditions (productivity data for the repeated run is shown above).
- On 2/01/00 @ run hour 1743.55 (approx. 4 days after start), the system was found off and the pressure alarm light was on. The system was restarted and back on line at 1:49 a.m. It was later discovered the feed valve had been shut due to polymer present in the plant effluent.
- On 2/03/00 @ run hour 1750.75 (approx. 4 days after start), the system was found off and the pressure alarm light was on. The system was restarted and back on line on 2/4/00 @ 8:00 a.m. It was not determined what caused the system to shut down.

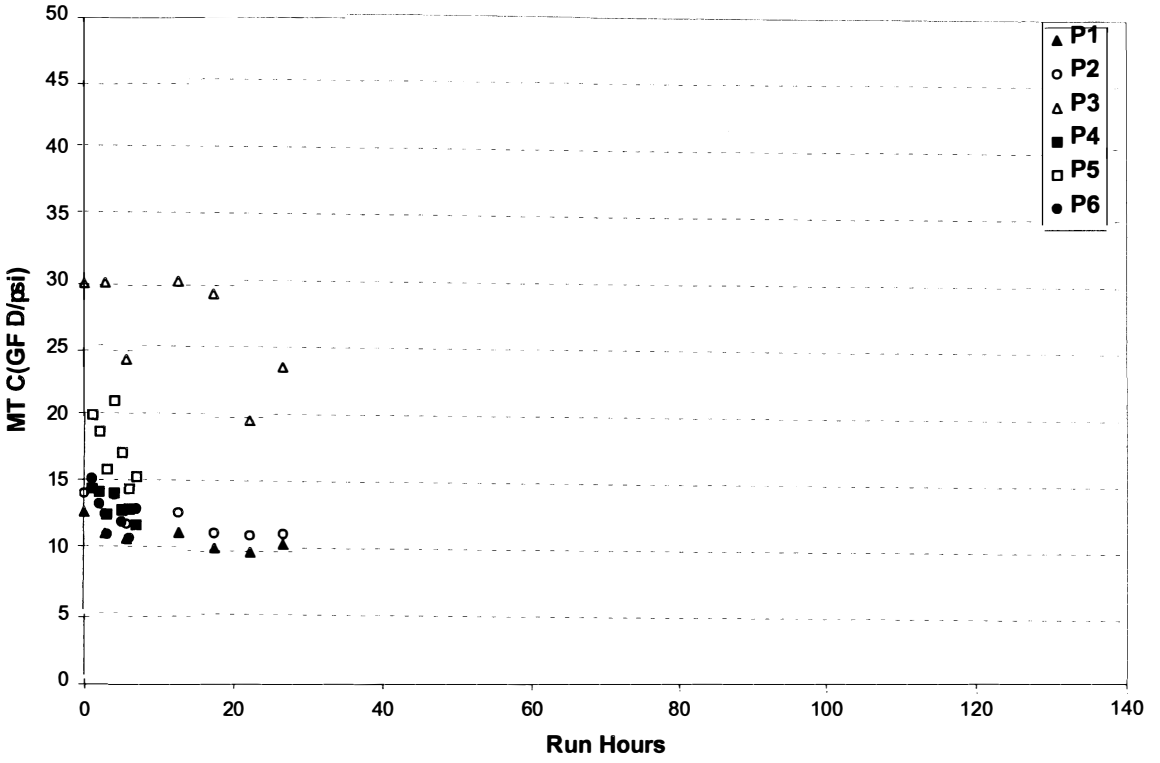
Figure B-10: MTC vs. Run Hours Experiment J



Notes:

- On 2/20/00 @ run hour 1902.4, it was discovered the air compressor on the unit was unplugged. It was determined the air compressor was never plugged back in after checking the chlorine pump. This resulted in the unit running with the air compressor off from 2:05 a.m. to 11:13 a.m.

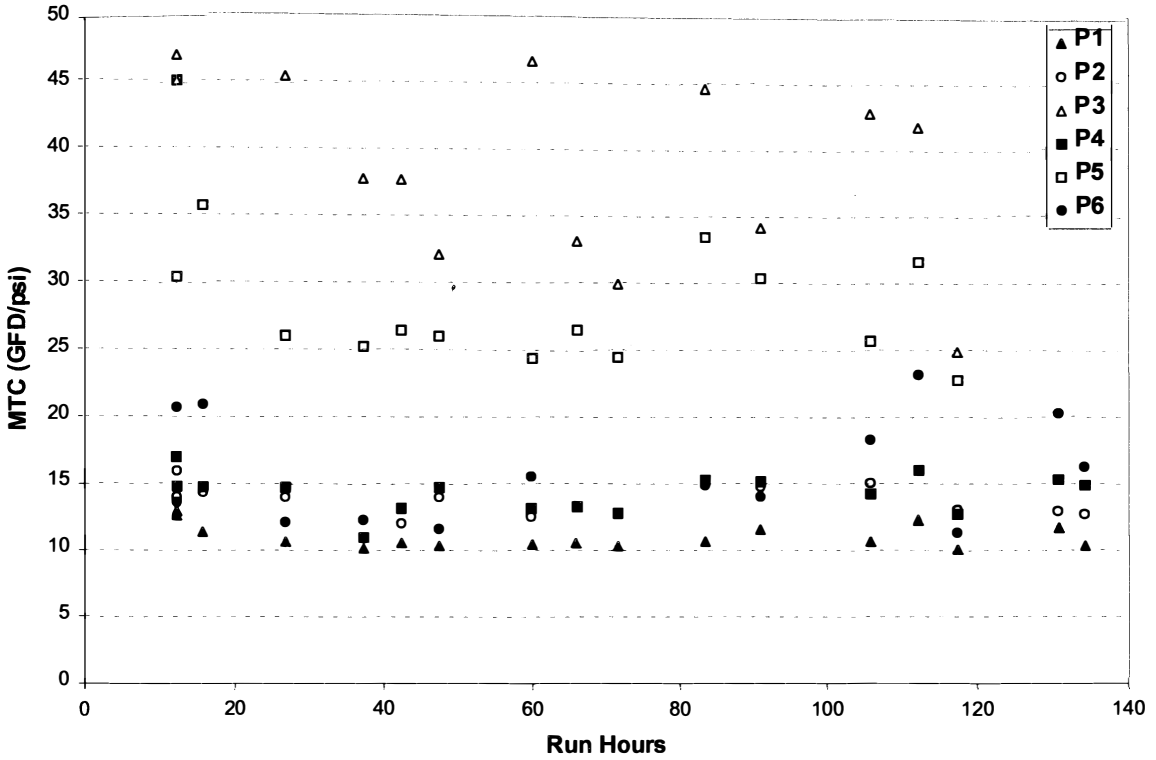
Figure B-11: MTC vs. run hours Experiment K



Notes:

- On 3/6/00 from 5:00 p.m.-11:00 p.m. the unit was fed chlorinated wastewater.
- On 3/07/00 (2:46 p.m.) the pre-filter was cleaned due to a loss of feed pressure.
- On 3/08/00 the unit was found off @ run hour 1997.75; the pre-filter was cleaned again and the unit was back on line @ 4:00 p.m. Shortly after 4:00 p.m., the plant was upset and the unit was stopped. The unit was restarted at approximately 12:00 a.m.
- On 3/09/00 the experiment was terminated due to diversion of wastewater to Seminole County

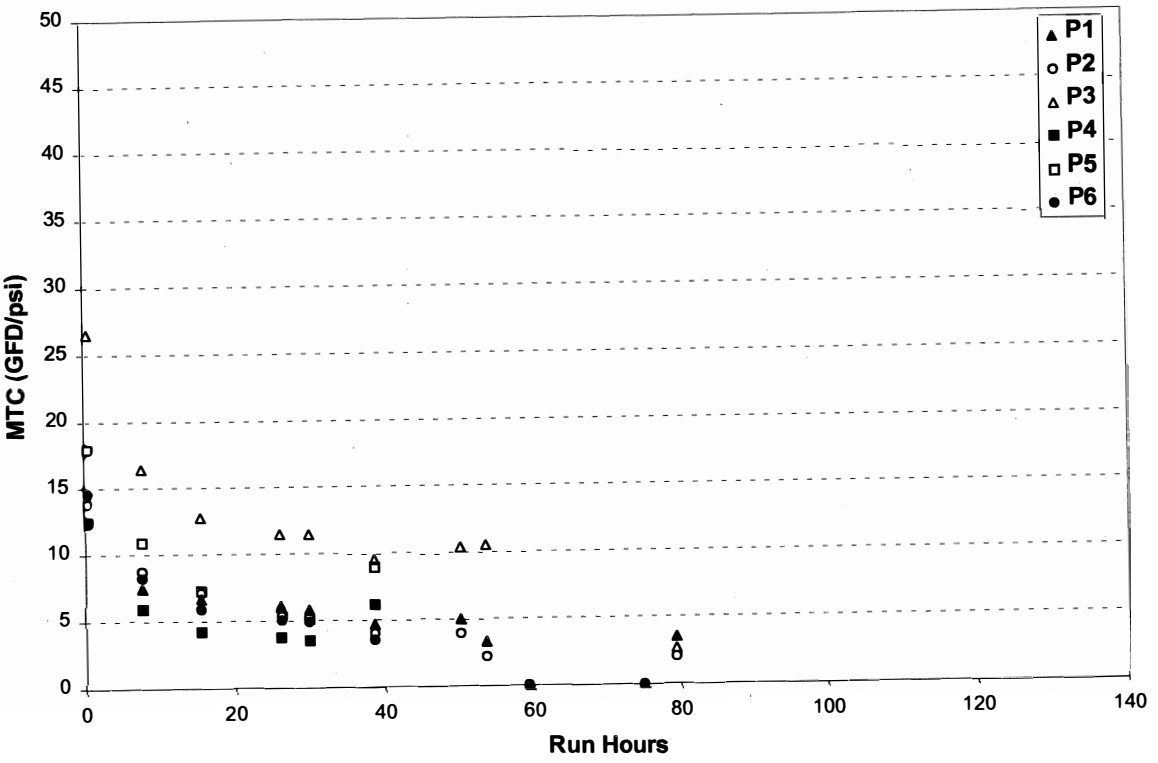
Figure B-12: MTC vs. Run Hours Experiment L



Notes:

- On 3/14/00, the original experiment was terminated after approximately 8 hrs of run time due to operational problems. Specifically air present in the feed stream rendered the system inoperable (this appears to occur when the unit is operated in the cross flow mode). After several attempts to rid air from the system, the experiment was terminated. The membranes were cleaned and the experiment was repeated in the direct flow mode.
- On 3/17/00, during the repeated experiment, the WWTP chlorinated excessively which resulted in chlorine loading to the membranes; the operator was notified and the proper adjustment was made to the plant. It was approximated the heavy chlorine dose was from 1:00-4:00 p.m.

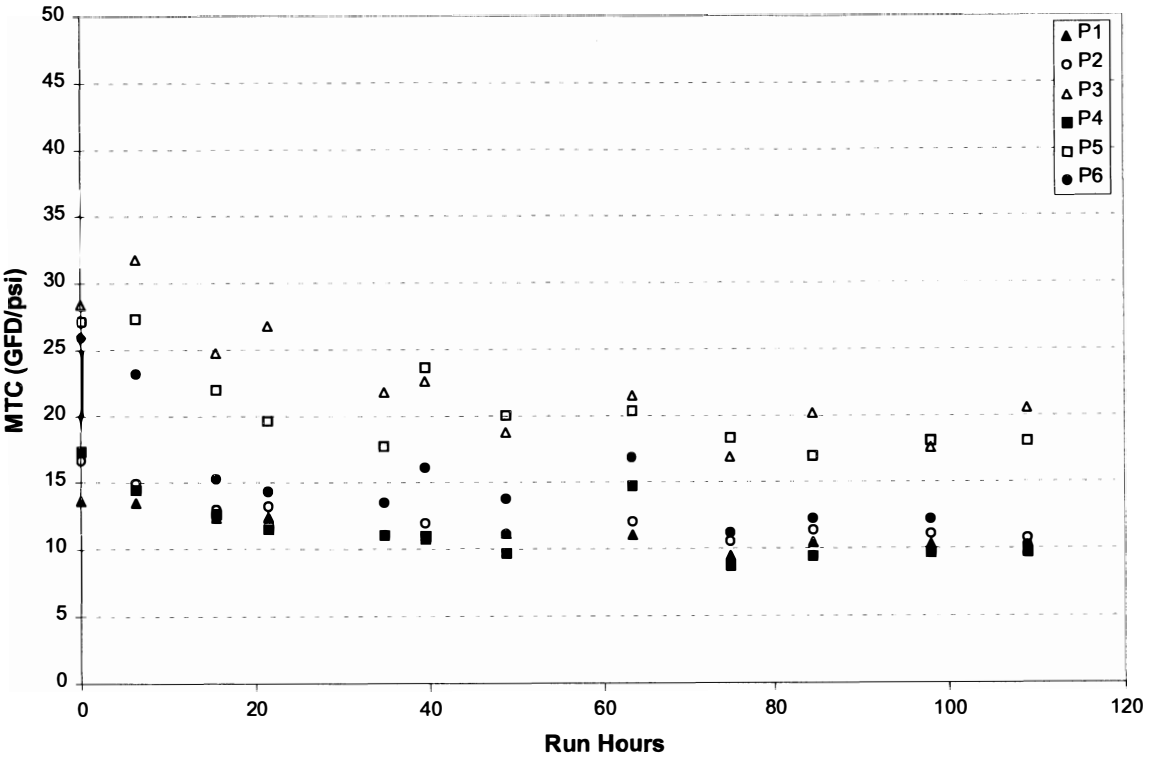
Figure B-13: MTC vs. Run Hours Experiment M



Notes:

- No unexpected occurrences noted.

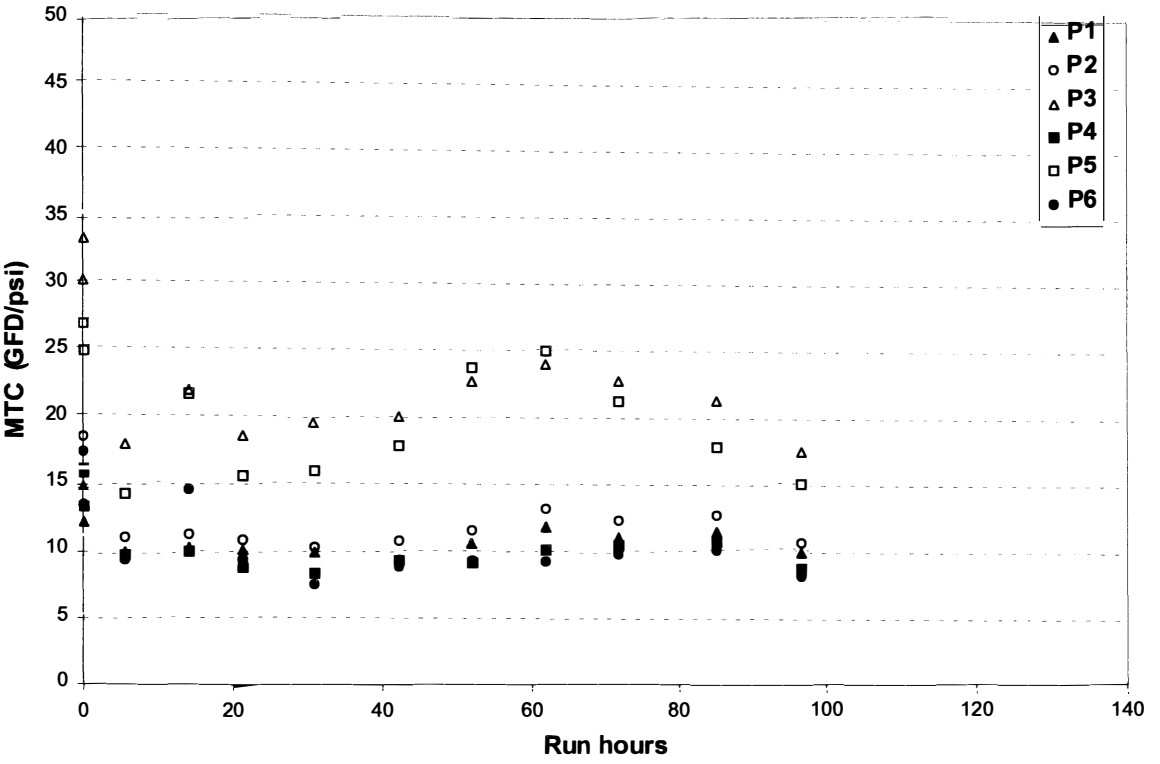
Figure B-14: MTC vs. Run Hours Experiment N



Notes:

- On 4/30/00 (approx. 5 days after start-up) the unit was found off due to clogging of the pre-filter. The pre-filter was cleaned at 7:12 p.m. and the unit was restarted.

Figure B-15: MTC vs. Run Hours Experiment O



Notes:

- On 5/5/00 and 5/6/00 (approx. 1 and 2 days after start-up, respectively) the unit was found off. In each case disruption was do to clogging of the pre-filter. After each occasion, the pre-filter was cleaned and the unit was restarted.

Table B-1: Membrane Productivity Experiment A

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.08	78	21.9	21.9	0.45	0.5	0.55	0.6	0.65	0.7	19	20	19.9	19.1	20	18.5	10.1	15.4	17.8	13.9	17.5	13.3
4.9	89	21.3	21.1	0.45	0.5	0.55	0.6	0.65	0.7	19	20	19.8	18.9	19	19	11.3	17.0	22.7	15.0	18.7	18.4
11.8	87	21.5	21.5	0.45	0.5	0.55	0.6	0.65	0.7	19	19	19.8	18.8	19	18.6	10.2	14.0	19.1	13.1	16.6	14.2
23.3	82	27.1	27.1	0.45	0.5	0.55	0.6	0.65	0.7	24	25	25.1	24.5	25	23.5	10.0	14.8	17.1	14.3	15.5	12.1
24.7	85	20.9	20.9	0.45	0.5	0.55	0.6	0.65	0.7	18	20	19	18	18	18	10.4	30.1	17.4	12.4	14.5	14.5
31.4	84	21	21	0.45	0.5	0.55	0.6	0.65	0.7	18	17	18.3	15.9	17	16	7.8	7.6	12.4	7.2	9.2	8.5
42.8	84	21	21	0.45	0.5	0.55	0.6	0.65	0.7	17	17	17.5	16.1	17	16	6.8	7.4	9.6	7.4	9.4	8.5
46.7	87.5	20.5	20.4	0.45	0.5	0.55	0.6	0.65	0.7	17	17	17	15.5	16	15.9	6.7	7.4	9.3	7.1	9.0	9.0
53.3	85	21	21	0.45	0.5	0.55	0.6	0.65	0.7	16	16	16.8	15	16	15	5.6	5.7	7.9	6.0	7.8	7.0
65.7	84	21	21	0.45	0.5	0.55	0.6	0.65	0.7	16	15	16.6	13.4	14	12.6	5.1	4.9	7.6	4.8	5.6	5.1
72.1	88	20.5	20.1	0.45	0.5	0.55	0.6	0.65	0.7	15	13	16	10.1	13	12.1	4.6	4.0	7.5	3.4	5.1	5.0
79.1	82.5	21.2	21.2	0.45	0.5	0.55	0.6	0.65	0.7	7.5	0	9.9	0	0	0	2.0	1.5	3.0	1.7	1.9	2.0

Sample Calculation of MTC using Experiment A (Membrane #3) data:

$$MTC = \frac{F_{w20}}{NDF} = \frac{F_{w20}}{\Delta P} = \frac{35.67\,gfd}{2\,psi} = 17.8\,gfd/psi$$

Where:

$$F_{W20} = \frac{F_w}{2.72^{0.019(T-20^\circ C)}} = \frac{Q_p/A}{2.72^{0.019(T-20^\circ C)}} = \frac{.55gpm/20\,ft^2}{2.72^{0.019(25.5^\circ C-20^\circ C)}} \times \frac{1440\,\text{min.}}{day} = 35.67\,gfd$$

$$\Delta P = \left(\frac{P_f + P_c}{2}\right) - P_p = \left(\frac{21.9\,psi + 21.9\,psi}{2}\right) - 19.9\,psi = 2\,psi$$

Table B-2: Membrane Productivity Experiment B

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0	80	21	21	0.3	0.3	0.3	0.3	0.3	0.3	19	20	20	20	20	20.1	10.3	20.0	20.0	20.0	20.0	22.4
6.6	87	20.5	20.1	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.4	18.9	20	19.7	6.4	9.1	11.4	8.6	13.1	14.1
10.2	86	20.5	20.1	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.2	18.9	20	19.7	6.3	8.7	10.2	8.7	13.2	14.3
24.2	83	20.6	20.1	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.2	19	20	19.3	6.5	9.0	10.5	9.5	12.7	11.2
24.3	79	21	20.6	0.3	0.3	0.3	0.3	0.3	0.3	19	20	19.8	19.6	20	20.0	9.4	13.3	16.7	14.2	18.3	20.2
29.4	87	20.5	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.4	18.9	20	19.8	6.2	8.6	11.4	8.6	12.2	15.4
39.0	82	21.1	21.1	0.3	0.3	0.3	0.3	0.3	0.3	19	19	20	19.5	20	19.8	7.6	12.0	19.6	12.8	19.6	16.2
48.1	83	20.9	20.5	0.3	0.3	0.3	0.3	0.3	0.3	19	19	19.7	19.1	20	19.8	7.5	10.0	14.7	10.0	16.0	16.0
51.9	87	20.5	20	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.4	18.9	20	19.6	6.4	8.6	11.4	8.6	12.2	13.1
55.6	84	20.9	20	0.3	0.3	0.3	0.3	0.3	0.3	19	19	19.9	19.4	20	19.8	7.4	10.4	17.4	11.8	17.4	15.9
66.0	83	21	21	0.3	0.3	0.3	0.3	0.3	0.3	19	20	19.9	19.5	20	19.7	9.0	12.7	17.6	12.7	19.4	14.7
70.3	84	21	20.7	0.3	0.3	0.3	0.3	0.3	0.3	19	19	19.9	19.2	20	19.7	7.4	10.4	17.4	10.4	19.2	14.6
76.9	83	21	21	0.3	0.3	0.3	0.3	0.3	0.3	19	20	19.9	19.5	20	19.7	8.2	12.7	17.6	12.7	19.4	14.7
89.3	83	21.1	21	0.3	0.3	0.3	0.3	0.3	0.3	19	19	19.9	19.4	20	19.6	7.5	11.9	17.6	11.9	17.6	13.7
94.4	85	20.9	20.5	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.8	19.1	20	19.8	6.6	9.8	15.7	9.8	15.7	15.7
102.3	83	21	21	0.3	0.3	0.3	0.3	0.3	0.3	19	19	19.9	19.2	20	19.8	7.5	10.5	17.6	10.5	19.4	16.0
111.8	83	21	20.9	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.9	19.1	20	19.8	6.7	10.0	17.6	10.0	17.6	16.0
116.9	85	20.8	20.5	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.7	19	20	19.5	6.3	9.3	14.4	9.3	14.4	12.4
124.5	82.5	21	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.8	19	20	19.3	6.5	9.5	16.1	9.5	16.1	11.2
134.7	83	20.9	20.9	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.5	18.9	20	19.1	6.2	9.0	12.7	9.0	12.7	10.0
142.4	84	20.9	20.8	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.4	18.8	19	19.1	6.0	8.5	11.8	8.5	11.1	9.9
146.8	82	21	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.7	19	20	19.2	6.3	9.6	14.9	9.6	16.2	10.6
158.2	81	21.1	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.7	19	20	19.1	6.4	9.7	15.1	9.7	16.4	10.2
162.0	84	20.9	20.5	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.4	18.9	20	19.1	6.2	8.9	11.8	8.9	14.6	9.9
171.5	81	21.1	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.9	19.1	20	19.1	6.6	9.7	17.9	10.2	17.9	10.2
180.5	81	21	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.7	19	20	19.1	6.4	9.2	15.1	9.7	16.4	10.2
186.6	83	21	20.5	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.5	18.8	20	19.1	6.0	9.0	12.7	8.6	12.7	10.0

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
190.6	81	21	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.8	19	20	19.0	6.4	9.7	16.4	9.7	19.8	9.7
194.2	81	21	21	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.8	19	20	19.0	6.4	9.7	16.4	9.7	16.4	9.7
203.7	82	21	20.9	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.5	18.9	20	19.0	6.3	9.6	12.8	9.1	13.8	9.6
210.6	84.5	20.8	20.2	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.4	18.6	19	19.1	5.9	8.4	11.7	7.7	11.7	9.8
217.6	82	21	20.9	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.8	19	20	19.0	6.3	9.6	16.2	9.6	14.9	9.6
226.9	83.5	20.9	20.5	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.2	18.5	19	19.0	6.0	7.5	10.5	7.5	9.9	9.4
232.4	83	21	20.9	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.7	18.9	20	19.1	6.0	9.0	14.7	9.0	13.7	10.0
240.5	82	21	20.9	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.5	18.9	19	19.0	6.1	9.1	12.8	9.1	12.0	9.6
253.2	82.5	20.9	20.5	0.3	0.3	0.3	0.3	0.3	0.3	18	19	19.8	18.9	20	19.0	6.3	9.5	16.1	9.0	12.8	9.5

Table B-3: Membrane Productivity Experiment C

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0	84.0	21.5	21.0	0.8	0.8	0.8	0.8	0.8	0.8	15.5	16.9	18.2	17.0	17.9	16.9	8.5	11.2	15.9	11.4	14.5	11.2
4.2	86.0	22.9	22.4	0.8	0.8	0.8	0.8	0.8	0.8	16.2	18.0	19.9	18.1	19.0	17.0	7.4	10.2	17.3	10.5	13.0	8.4
9.3	82.0	23.5	23.0	0.8	0.8	0.8	0.8	0.8	0.8	16.1	17.9	20.0	18.1	19.1	16.5	6.9	9.3	15.3	9.6	12.0	7.4
10.0	83.0	21.5	21.0	0.8	0.8	0.8	0.8	0.8	0.8	14.0	16.1	17.9	16.1	17.1	14.8	6.8	9.5	14.7	9.5	11.8	7.6
14.4	84.0	21.8	21.1	0.8	0.8	0.8	0.8	0.8	0.8	14.1	16.3	18.2	16.5	17.8	15.1	6.6	9.4	15.0	9.8	13.3	7.7
22.4	83.0	22.0	21.5	0.8	0.8	0.8	0.8	0.8	0.8	8.8	11.9	16.9	13.5	15.2	11.0	3.8	5.0	10.1	6.0	7.5	4.6
33.2	81.5	25.0	24.5	0.8	0.8	0.8	0.8	0.8	0.8	4.5	12.5	19.8	15.2	12.5	10.5	2.5	4.1	10.1	5.2	4.1	3.5
39.3	83.9	25.2	24.9	*0.0	0.8	0.8	0.8	0.8	0.8	n.a	14	20	17	18.9	10	n.a	4.4	9.6	6.0	7.9	3.2
42.8	83.0	25.2	24.9	*0.0	0.8	0.8	0.8	0.8	0.8	n.a	10.8	20	15.6	18.4	6	n.a	3.4	9.7	5.2	7.4	2.6
51.1	83	25.5	25.1	*0.0	0.75	0.8	0.8	0.8	0.8	n.a	0.75	20	8.9	15.1	0.0	n.a	1.9	9.3	3.0	4.8	1.9
55.5	85	25.5	25	*0.0	*0.0	0.8	0.8	0.8	*0.0	n.a	n.a	20	3.9	13.1	n.a	n.a	0.0	9.2	2.3	4.0	n.a
66.3	81	26.1	26	*0.0	*0.0	0.8	*0.0	0.8	*0.0	n.a	n.a	14.1	n.a	1	n.a	n.a	0.0	4.2	0.0	2.0	n.a

***Permeate valve was closed due to severe membrane fouling.**

Table B-4: Membrane Productivity Experiment D

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0	82.0	20.6	20.0	0.6	0.6	0.6	0.6	0.6	0.6	17.8	17.6	17.7	17.6	17.1	18.5	14.9	13.8	14.3	13.8	11.6	20.7
6.0	81.0	20.5	20.2	0.6	0.6	0.6	0.6	0.6	0.6	17.3	16.9	17.1	17.0	15.2	16.7	12.3	10.9	11.6	11.2	7.3	10.3
15.3	83.5	20.1	19.5	0.6	0.6	0.6	0.6	0.6	0.6	16.9	16.5	16.7	16.5	12.9	16.9	12.6	11.1	11.8	11.1	5.3	12.6
17.8	85.0	20.0	19.1	0.6	0.6	0.6	0.6	0.6	0.6	16.8	16.4	16.5	16.4	12.2	16.9	13.1	11.5	11.8	11.5	4.9	13.6
25.1	82.0	20.4	20.1	0.6	0.6	0.6	0.6	0.6	0.6	17.0	16.8	16.9	16.9	10.0	16.5	11.5	10.8	11.1	11.1	3.6	9.9
37.2	83.0	20.2	19.8	0.6	0.6	0.6	0.6	0.6	0.6	16.8	16.3	16.1	16.3	5.2	16.4	11.5	10.0	9.5	10.0	2.5	10.2
41.9	84.0	20.1	19.6	0.6	0.6	0.6	0.6	0.6	0.6	16.7	16.2	16.1	16.4	3.1	16.2	11.6	10.0	9.7	10.6	2.2	10.0
46.7	82.0	20.7	19.8	0.6	0.6	0.6	0.6	0.6	0.6	16.5	15.6	15.7	15.9	1.0	16.0	9.9	8.0	8.2	8.6	1.9	8.8
58.5	81.5	20.7	20.3	0.6	0.6	0.6	0.6	0.6	0.6	16.1	15.0	14.5	15.1	0.0	15.1	8.5	6.8	6.2	6.9	1.8	6.9
66.5	84.5	20.3	19.8	0.6	0.6	0.6	0.6	0.6	0.6	15.7	13.9	14.2	14.7	0.0	14.8	8.3	5.9	6.2	6.8	1.8	6.9
90.3	84.5	20.1	19.6	0.6	0.6	0.6	0.6	0.6	0.6	16.0	12.2	13.4	14.4	0.0	14.2	9.4	4.7	5.6	6.7	1.8	6.4
93.8	82.0	20.8	20.1	0.6	0.6	0.6	0.6	0.6	0.6	16.1	10.8	12.7	14.1	0.0	13.9	8.6	3.9	4.8	5.9	1.8	5.7
107.1	83.0	20.4	19.9	0.6	0.6	0.6	0.6	0.6	0.6	16.8	9.7	13.0	14.9	0.0	14.2	11.0	3.5	5.2	7.0	1.8	6.2
111.6	84.0	20.3	19.9	0.6	0.6	0.6	0.6	0.6	0.6	15.9	4.9	12.2	15.0	0.0	14.0	8.7	2.4	4.6	7.2	1.8	6.0
135.4	82.5	20.8	20.1	0.6	0.6	0.6	0.6	0.6	0.6	16.7	0.0	11.1	14.5	0.0	13.6	9.9	1.8	4.0	6.2	1.8	5.4
154.5	79.5	20.9	20.7	0.6	0.6	0.6	0.6	0.6	0.6	17.0	0.0	0.8	13.6	0.0	8.9	10.1	1.8	1.9	5.3	1.8	3.2

Table B-5: Membrane Productivity Experiment E

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.0	74.0	25.5	24.9	0.6	0.6	0.6	0.6	0.6	0.6	21.6	22.9	23.5	22.4	23.2	22.0	11.3	17.6	23.9	14.5	20.3	12.7
3.2	77.0	25.8	24.9	0.6	0.6	0.6	0.6	0.6	0.6	21.5	22.7	23.9	22.4	23.5	22.8	10.2	14.8	27.1	13.3	21.2	15.4
9.3	75.5	25.9	24.9	0.6	0.6	0.6	0.6	0.6	0.6	21.0	22.1	24.0	22.2	22.9	21.9	9.1	12.1	28.5	12.5	16.0	11.4
17.4	75.8	26.4	25.9	0.6	0.6	0.6	0.6	0.6	0.6	21.6	22.7	23.8	21.8	19.5	21.1	8.7	11.5	16.9	9.1	6.0	7.9
19.7	72.0	21.0	20.5	0.6	0.6	0.6	0.6	0.6	0.6	21.5	17.8	20.0	18.1	19.1	17.0	55.2	14.0	55.2	15.6	25.1	11.0
30.5	76.0	22.7	22.0	0.6	0.6	0.6	0.6	0.6	0.6	21.0	17.6	20.0	17.7	19.1	16.2	29.4	8.4	16.9	8.5	12.2	6.5
36.5	80.0	22.1	21.1	0.6	0.6	0.6	0.6	0.6	0.6	20.2	17.7	20.0	17.7	18.5	16.7	27.2	9.8	23.1	9.8	12.3	7.8
53.7	77.0	22.7	22.0	0.6	0.6	0.6	0.6	0.6	0.6	16.8	16.1	19.9	16.6	18.9	13.5	7.1	6.3	16.0	6.8	11.4	4.4
60.4	80.0	22.3	21.3	0.6	0.6	0.6	0.6	0.6	0.6	15.5	16.0	19.9	16.9	19.5	13.1	6.0	6.6	20.0	7.8	16.5	4.4
68.0	78.0	22.8	22.1	0.6	0.6	0.6	0.6	0.6	0.6	15.5	16.5	20.1	17.9	19.4	8.9	5.6	6.5	16.5	8.5	12.7	2.9
79.7	79.0	22.5	21.5	0.6	0.6	0.6	0.6	0.6	0.6	9.0	17.1	20.1	18.0	19.3	1.9	3.0	7.8	20.2	9.6	14.2	1.9
83.9	79.0	22.7	21.9	0.6	0.6	0.6	0.6	0.6	0.6	5.9	17.4	20.1	18.1	18.9	0.0	2.3	7.8	17.5	9.2	11.3	1.7
91.8	77.0	23.0	22.2	0.6	0.6	0.6	0.6	0.6	0.6	3.1	16.0	20.0	17.4	19.5	0.0	2.0	6.0	15.1	7.6	12.7	1.7
104.4	79.0	22.8	21.9	0.6	0.6	0.6	0.6	0.6	0.6	0.0	16.1	20.1	17.7	19.1	0.0	1.7	6.2	16.7	8.3	11.8	1.7
108.4	78.0	23.0	22.1	0.6	0.6	0.6	0.6	0.6	0.6	0.0	16.1	20.4	18.0	19.4	0.0	1.7	6.0	18.1	8.5	12.3	1.7
124.9	79.0	22.8	22.1	0.6	0.6	0.6	0.6	0.6	0.6	0.0	18.2	20.4	18.6	19.8	0.0	1.7	9.0	18.8	10.0	14.5	1.7
131.9	77.0	23.0	22.1	0.6	0.6	0.6	0.6	0.6	0.6	0.0	17.6	20.1	18.0	19.1	0.0	1.7	8.0	16.2	8.6	11.5	1.7
142.2	71.0	23.1	23.0	0.6	0.6	0.6	0.6	0.6	0.6	0.0	1.5	7.5	2.4	6.4	0.0	1.8	1.9	2.7	2.0	2.5	1.8

Table B-6: Membrane Productivity Experiment F

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
3.9	65.5	23.0	22.1	0.4	0.4	0.4	0.4	0.4	0.4	20.4	21.2	21.9	21.2	21.9	20.8	13.8	21.9	45.5	21.9	45.5	16.9
4.3	68.9	22.8	22.2	0.4	0.4	0.4	0.4	0.4	0.4	20.4	21.2	21.8	21.0	21.5	21.1	13.6	21.9	40.8	19.0	28.5	20.4
4.6	69.0	22.6	22.0	0.4	0.4	0.4	0.4	0.4	0.4	20.1	20.8	21.5	20.5	21.4	20.4	13.0	19.0	35.6	15.8	31.7	15.0
10.8	76.0	22.1	21.1	0.4	0.4	0.4	0.4	0.4	0.4	19.2	19.9	21.1	19.9	20.9	20.2	11.0	15.6	52.9	15.6	37.8	18.9
18.3	72.0	22.7	22.0	0.4	0.4	0.4	0.4	0.4	0.4	19.6	20.1	21.2	20.1	21.0	20.1	10.0	12.3	24.0	12.3	19.0	12.3
28.8	73.0	22.5	21.9	0.4	0.4	0.4	0.4	0.4	0.4	19.4	20.1	21.1	20.0	20.9	20.0	9.8	13.2	25.4	12.6	25.4	12.6
34.4	74.0	22.6	21.9	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.1	21.1	20.0	20.9	20.0	9.8	12.6	23.5	12.0	20.8	12.0
41.4	71.0	23.0	22.2	0.4	0.4	0.4	0.4	0.4	0.4	19.8	20.2	21.5	20.2	21.1	19.9	10.0	11.6	25.4	11.6	17.4	10.3
52.6	71.0	22.8	21.5	0.4	0.4	0.4	0.4	0.4	0.4	19.3	20.0	21.2	19.8	21.0	19.8	9.8	13.0	29.4	11.9	24.3	11.9
59.6	71.0	22.9	21.9	0.4	0.4	0.4	0.4	0.4	0.4	19.2	20.1	21.4	20.0	21.0	19.9	8.7	12.1	27.9	11.6	12.1	11.2
63.1	70.0	22.9	22.1	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.1	21.5	20.1	21.0	19.9	9.4	11.7	28.2	11.7	14.8	10.8
78.2	73.0	22.0	21.0	0.4	0.4	0.4	0.4	0.4	0.4	18.6	19.3	20.5	19.2	20.1	19.8	9.4	12.4	27.3	11.9	21.0	16.1
86.6	71.0	22.6	22.0	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.9	21.0	19.9	20.6	19.4	8.5	11.6	21.5	11.6	12.1	9.6
96.2	71.0	22.4	21.8	0.4	0.4	0.4	0.4	0.4	0.4	18.8	19.5	20.6	19.5	20.2	19.2	8.5	10.7	18.6	10.7	13.3	9.6
101.2	73.5	21.8	20.9	0.4	0.4	0.4	0.4	0.4	0.4	18.2	19.1	20.2	18.9	20.0	19.5	8.6	12.1	23.6	11.1	20.1	14.7
112.3	72.5	21.8	21.1	0.4	0.4	0.4	0.4	0.4	0.4	18.2	19.1	20.2	19.0	20.0	19.2	8.5	11.7	22.0	11.2	14.1	12.2
123.8	77.0	25.0	24.0	0.4	0.4	0.4	0.4	0.4	0.4	21.5	22.5	23.6	22.1	23.1	22.5	8.7	13.1	29.1	10.9	4.4	13.1
126.6	75.5	21.2	20.4	0.4	0.4	0.4	0.4	0.4	0.4	17.9	18.6	19.9	18.5	19.5	19.8	9.2	12.1	29.6	11.6	12.1	26.6
134.9	71.0	20.5	20.0	0.4	0.4	0.4	0.4	0.4	0.4	16.9	17.9	19.0	17.8	18.6	17.9	8.3	11.9	22.3	11.4	8.6	11.9
146.2	74.0	20.4	19.8	0.4	0.4	0.4	0.4	0.4	0.4	17.0	17.8	19.1	17.6	18.6	18.0	8.7	11.8	27.0	10.8	18.0	12.9
154.9	70.5	19.2	18.9	0.4	0.4	0.4	0.4	0.4	0.4	15.5	16.4	17.5	16.4	17.0	16.5	7.9	10.6	18.1	10.6	13.7	11.0
168.2	75.0	22.2	21.6	0.4	0.4	0.4	0.4	0.4	0.4	18.5	19.5	20.9	19.5	20.2	20.1	7.9	11.1	26.7	11.1	9.2	14.9
175.2	73.0	24.1	23.9	0.4	0.4	0.4	0.4	0.4	0.4	20.0	21.1	22.5	21.0	21.9	21.0	6.8	9.4	18.2	9.1	3.0	9.1
181.2	70.0	21.7	21.1	0.4	0.4	0.4	0.4	0.4	0.4	17.0	17.9	19.5	18.0	19.0	18.1	6.4	8.1	14.8	8.3	9.7	8.5
191.1	74.0	17.1	16.5	0.4	0.4	0.4	0.4	0.4	0.4	13.5	13.5	14.9	14.0	14.8	14.8	8.2	8.2	14.2	9.7	13.5	13.5
200.9	72.0	22.1	21.5	0.4	0.4	0.4	0.4	0.4	0.4	18.0	18.2	19.6	17.9	18.5	17.5	7.3	7.7	12.5	7.1	8.4	6.4
215.3	76.5	21.3	20.7	0.4	0.4	0.4	0.4	0.4	0.4	17.4	18.1	19.6	18.0	18.8	18.5	7.3	9.1	18.8	8.8	26.3	10.5

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
219.4	73.0	22.5	21.7	0.4	0.4	0.4	0.4	0.4	0.4	17.5	18.1	19.7	17.8	18.5	17.5	5.9	6.8	11.4	6.4	4.3	5.9
223.5	70.0	23.5	23.1	0.4	0.4	0.4	0.4	0.4	0.4	18.3	19.3	21.0	19.1	20.0	19.1	5.6	7.0	12.3	6.7	2.3	6.7
232.7	68.5	21.0	20.7	0.4	0.4	0.4	0.4	0.4	0.4	15.0	15.5	17.1	15.0	15.8	15.0	4.9	5.4	7.6	4.9	27.3	4.9
238.0	72.5	15.2	14.8	0.4	0.4	0.4	0.4	0.4	0.4	10.1	10.2	11.9	10.1	11.1	11.0	5.6	5.7	8.9	5.6	7.0	6.9
244.5	73.0	24.5	24.0	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.1	20.5	18.5	19.8	19.5	5.2	5.3	7.3	4.8	6.1	5.8

Table B-7: Membrane Productivity Experiment G

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.0	72.5	22.6	22.1	0.4	0.4	0.4	0.4	0.4	0.4	19.8	20.7	21.4	20.4	21.1	20.2	10.8	16.6	28.9	14.1	22.0	12.8
5.2	76.0	22.2	21.5	0.4	0.4	0.4	0.4	0.4	0.4	19.4	20.1	21.1	20.0	21.0	20.5	10.8	15.1	35.3	14.3	31.1	19.6
10.1	74.8	22.5	21.8	0.4	0.4	0.4	0.4	0.4	0.4	19.2	20.1	21.2	20.0	21.0	20.2	9.1	13.1	28.2	12.5	23.3	13.7
23.3	73.1	22.8	22.2	0.4	0.4	0.4	0.4	0.4	0.4	18.9	19.7	21.1	19.8	20.7	19.8	7.6	9.7	19.5	10.1	15.2	10.1
30.7	74.8	22.8	21.9	0.4	0.4	0.4	0.4	0.4	0.4	18.4	19.0	21.1	19.1	20.4	19.8	6.8	8.0	21.4	8.2	13.7	10.5
34.5	73.0	22.9	22.3	0.4	0.4	0.4	0.4	0.4	0.4	18.2	19.0	21.1	19.2	20.5	19.7	6.2	7.6	18.2	8.0	13.0	9.4
47.8	73.5	22.8	22.1	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.8	21.1	19.9	20.9	20.0	7.9	10.3	20.1	10.7	17.5	11.1
52.3	74.2	22.8	22.0	0.4	0.4	0.4	0.4	0.4	0.4	18.9	19.5	21.1	19.8	20.8	19.9	7.7	9.3	20.7	10.4	16.9	10.8
57.2	73.2	22.9	22.2	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.7	21.1	19.9	20.9	19.9	7.7	9.6	18.8	10.3	16.5	10.3
70.1	73.8	22.8	22.2	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.8	21.2	19.9	20.9	19.8	7.7	10.0	20.8	10.4	16.9	10.0
74.3	73.1	22.9	22.3	0.4	0.4	0.4	0.4	0.4	0.4	18.9	19.9	21.2	20.0	20.9	19.8	7.4	10.1	19.5	10.5	16.1	9.7
81.6	71.5	23.0	22.6	0.4	0.4	0.4	0.4	0.4	0.4	19.0	20.0	21.4	20.0	20.9	19.8	7.3	9.9	19.8	9.9	14.6	9.3
92.1	73.9	22.6	21.7	0.4	0.4	0.4	0.4	0.4	0.4	18.5	19.2	21.0	19.5	20.4	19.8	7.4	9.2	23.5	10.2	15.5	11.5
96.3	73.0	22.8	21.9	0.4	0.4	0.4	0.4	0.4	0.4	18.5	19.2	21.1	19.5	20.5	19.8	7.1	8.7	21.0	9.6	14.8	10.7
105.2	73.0	22.8	21.9	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.5	21.1	19.5	20.5	19.8	8.2	9.6	21.0	9.6	14.8	10.7
121.7	72.9	22.8	22.0	0.4	0.4	0.4	0.4	0.4	0.4	19.0	20.0	21.1	19.9	20.9	19.9	8.0	11.4	21.0	10.9	18.2	10.9
125.0	72.9	22.8	22.0	0.4	0.4	0.4	0.4	0.4	0.4	19.5	19.9	21.1	19.9	20.8	19.8	9.4	10.9	21.0	10.9	17.1	10.5
139.3	75.0	22.1	21.3	0.4	0.4	0.4	0.4	0.4	0.4	18.8	19.8	21.0	19.9	20.8	19.8	9.2	14.1	38.2	14.9	29.7	14.1
145.8	72.8	22.9	22.2	0.4	0.4	0.4	0.4	0.4	0.4	19.1	20.1	21.5	19.6	20.5	20.0	7.9	11.0	26.1	9.3	13.4	10.7
157.3	70.0	23.0	22.5	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.2	21.5	20.2	21.0	20.0	8.7	11.1	22.6	11.1	16.1	10.1
161.5	73.0	22.5	21.5	0.4	0.4	0.4	0.4	0.4	0.4	19.1	19.9	21.1	19.9	20.7	20.0	9.3	13.0	28.8	13.0	21.0	13.3
170.4	71.1	22.9	22.1	0.4	0.4	0.4	0.4	0.4	0.4	19.2	20.1	21.2	20.0	21.0	20.0	8.4	11.4	21.4	11.1	18.6	11.1
184.3	74.4	22.1	21.2	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.9	20.9	19.8	20.5	20.1	10.2	15.4	35.9	14.6	23.4	17.4
193.0	72.9	22.9	22.1	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.1	21.5	20.1	21.0	20.0	9.1	11.4	27.3	11.4	18.2	10.9
205.9	75.9	22.1	21.3	0.4	0.4	0.4	0.4	0.4	0.4	19.1	19.9	21.1	19.9	20.8	20.1	10.2	14.7	40.8	14.3	27.9	16.1
210.5	75.0	22.5	21.7	0.4	0.4	0.4	0.4	0.4	0.4	19.2	20.0	21.1	20.0	20.9	20.1	9.2	12.7	26.7	12.7	22.3	13.0
218.9	74.0	22.8	22.1	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.2	21.5	20.1	21.0	20.0	9.2	12.0	28.5	11.5	18.6	11.0

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
226.9	74.0	22.8	22.1	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.1	21.1	20.1	21.0	10.0	9.2	11.6	20.4	11.4	19.0	2.2
230.2	72.9	22.8	22.0	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.1	21.2	20.1	21.0	20.0	9.4	11.9	22.8	11.9	19.5	11.4
239.8	71.1	22.8	22.0	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.2	21.6	20.2	21.0	20.0	9.6	12.7	34.8	12.7	19.9	11.6

Table B-8: Membrane Productivity Experiment H

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.6	72.1	22.8	21.8	0.4	0.4	0.4	0.4	0.4	0.4	20.1	21.0	21.9	20.6	21.5	20.9	12.5	21.2	61.3	16.2	34.5	19.7
4.9	76.0	22.8	21.6	0.4	0.4	0.4	0.4	0.4	0.4	20.1	20.6	21.8	20.5	21.5	21.0	12.3	16.5	66.2	15.6	37.8	22.1
16.1	73.2	23.1	22.5	0.4	0.4	0.4	0.4	0.4	0.4	20.1	21.1	22.0	20.9	21.9	21.0	10.1	16.0	34.1	14.3	30.3	15.1
27.7	76.5	22.8	21.8	0.4	0.4	0.4	0.4	0.4	0.4	19.9	20.5	21.7	20.2	21.2	20.9	11.0	14.6	43.9	12.5	23.9	18.8
35.9	75.0	23.1	22.4	0.4	0.4	0.4	0.4	0.4	0.4	20.0	20.8	22.0	20.7	21.8	20.7	9.8	13.9	36.9	13.2	28.9	13.2
49.5	76.0	22.8	21.9	0.4	0.4	0.4	0.4	0.4	0.4	19.8	20.2	21.5	20.2	21.1	20.6	10.4	12.3	31.1	12.0	21.2	15.1
54.3	78.0	22.6	21.6	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.1	21.4	20.1	21.1	20.9	10.0	13.0	37.0	13.0	24.7	21.6
59.7	74.8	23.0	22.5	0.4	0.4	0.4	0.4	0.4	0.4	19.9	20.7	21.9	20.5	21.5	20.5	9.2	13.1	31.5	11.9	21.4	11.9
69.8	74.5	23.0	22.2	0.4	0.4	0.4	0.4	0.4	0.4	19.7	20.5	21.8	20.2	21.2	20.5	9.3	12.8	33.6	11.2	19.2	12.8
77.1	78.0	22.5	21.5	0.4	0.4	0.4	0.4	0.4	0.4	19.0	19.9	21.1	19.8	20.9	20.4	8.6	12.3	28.8	11.8	23.6	16.2
82.9	75.5	23.0	22.1	0.4	0.4	0.4	0.4	0.4	0.4	18.7	19.8	21.3	19.8	20.9	20.1	7.0	9.9	22.2	9.9	16.6	11.1
95.6	75.0	23.0	22.2	0.4	0.4	0.4	0.4	0.4	0.4	18.1	19.5	21.4	19.5	20.6	19.9	5.9	8.6	22.3	8.6	13.4	9.9
104.8	73.0	23.2	22.8	0.4	0.4	0.4	0.4	0.4	0.4	16.1	18.0	21.1	18.2	20.1	19.5	4.0	5.5	14.4	5.7	9.4	7.8
116.4	70.1	23.5	22.9	0.4	0.4	0.4	0.4	0.4	0.4	14.8	17.2	21.1	18.0	20.1	19.1	3.4	4.7	12.8	5.4	9.1	6.9
125.6	75.0	23.0	21.9	0.4	0.4	0.4	0.4	0.4	0.4	13.7	16.5	21.0	17.6	20.1	19.8	3.1	4.5	19.8	5.5	11.1	10.1
130.9	72.5	23.2	22.8	0.4	0.4	0.4	0.4	0.4	0.4	12.2	16.1	21.1	17.9	20.1	19.5	2.5	4.0	13.7	5.4	9.3	7.8
142.1	74.0	22.9	21.9	0.4	0.4	0.4	0.4	0.4	0.4	11.5	15.9	21.0	17.6	20.1	19.6	2.5	4.2	18.0	6.4	11.5	9.7
145.5	76.5	22.7	21.5	0.4	0.4	0.4	0.4	0.4	0.4	12.0	16.1	20.9	17.8	20.6	19.8	2.6	4.4	26.3	8.8	17.6	11.4
154.7	74.0	23.1	22.1	0.4	0.4	0.4	0.4	0.4	0.4	12.0	16.9	21.1	18.2	20.5	19.9	2.6	4.8	30.9	8.8	13.0	10.1
166.3	71.1	23.5	22.5	0.4	0.4	0.4	0.4	0.4	0.4	13.2	18.2	21.7	19.1	21.0	19.9	2.8	5.8	25.3	6.2	13.9	9.0
170.6	70.9	23.5	22.6	0.4	0.4	0.4	0.4	0.4	0.4	14.1	18.9	21.9	19.5	21.1	19.9	3.1	6.7	24.3	5.8	14.3	8.9
178.9	66.0	23.9	23.0	0.4	0.4	0.4	0.4	0.4	0.4	8.0	16.6	21.9	18.5	21.0	19.8	1.9	4.3	16.8	5.4	12.0	8.1
190.0	71.5	23.1	21.9	0.4	0.4	0.4	0.4	0.4	0.4	3.9	15.0	21.7	18.2	20.9	19.8	1.5	3.7	55.5	5.9	17.3	10.3
197.3	69.0	23.9	22.9	*0.0	0.4	0.4	0.4	0.4	0.4	n.a.	12.1	22.0	18.0	21.1	20.0	n.a.	2.5	21.9	4.8	12.4	8.3
203.1	67.0	23.9	23.1	*0.0	0.4	0.4	0.4	0.4	0.4	n.a.	8.0	22.1	17.8	21.1	19.8	n.a.	1.9	19.4	5.0	12.1	7.9
210.8	68.0	23.6	22.5	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	22.0	17.5	21.0	19.8	n.a.	n.a.	19.9	6.9	14.0	8.9
214.7	72.0	23.1	21.9	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	21.6	17.7	20.9	19.9	n.a.	n.a.	69.0	9.2	17.3	10.6

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
220.1	69.5	23.7	22.9	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	22.1	18.9	21.1	19.9	n.a.	n.a.	23.6	6.9	12.9	8.3
232.2	64.9	24.0	23.1	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	22.1	19.5	21.4	19.9	n.a.	n.a.	20.5	6.7	13.8	8.2
233.1	65.0	23.8	22.9	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	22.1	19.2	21.1	19.9	n.a.	n.a.	20.5	7.7	13.2	8.6
239.9	69.0	23.2	22.1	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	21.9	19.1	21.0	20.0	n.a.	n.a.	43.8	1.3	17.3	10.8
244.3	68.1	23.5	22.2	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	22.0	19.5	21.1	20.0	n.a.	n.a.	1.3	3.8	16.4	10.1

***Permeate valve was closed due to severe membrane fouling.**

Table B-9: Membrane Productivity Experiment I

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.05	59.5	22.9	18.5	0.4	0.4	0.4	0.4	0.4	0.4	18.6	19.1	20.1	19.1	20.5	19.1	15.0	19.7	52.5	19.7	158	19.1
7.08	68.0	22.9	18.5	0.4	0.4	0.4	0.4	0.4	0.4	18.3	19.0	20.0	19.0	20.1	19.5	12.0	16.9	41.1	16.9	48.0	24.0
13.10	69.0	22.9	18.5	0.4	0.4	0.4	0.4	0.4	0.4	18.1	18.9	20.0	18.9	20.0	18.9	10.8	15.8	40.7	15.8	40.7	15.8
24.90	71.5	22.0	17.5	0.4	0.4	0.4	0.4	0.4	0.4	17.1	17.9	19.5	17.9	19.0	18.1	10.5	15.0	111.0	15.0	37.0	16.3
27.10	72.5	21.8	17.3	0.4	0.4	0.4	0.4	0.4	0.4	17.1	17.9	19.1	17.9	19.0	18.1	11.2	16.6	61.0	16.6	49.9	18.9
32.81	70.5	22.0	17.9	0.4	0.4	0.4	0.4	0.4	0.4	17.2	18.1	19.5	18.0	19.1	18.0	10.2	15.2	62.3	14.4	33.0	14.4
46.15	71.5	20.9	16.9	0.4	0.4	0.4	0.4	0.4	0.4	16.1	16.9	18.0	17.0	18.0	17.1	9.9	34.7	30.8	14.6	30.8	15.4
51.25	74.9	20.1	16.1	0.4	0.4	0.4	0.4	0.4	0.4	15.8	16.5	17.7	16.5	17.5	17.1	11.6	22.3	66.9	16.7	44.6	26.8
58.25	72.0	20.2	16.4	0.4	0.4	0.4	0.4	0.4	0.4	15.7	16.5	17.7	16.5	17.5	16.8	10.6	15.3	46.0	15.3	34.5	18.4
71.30	68.0	19.2	15.5	0.4	0.4	0.4	0.4	0.4	0.4	14.8	15.2	16.5	15.5	16.2	14.9	11.3	33.9	33.9	15.6	24.0	11.8
77.61	67.5	19.0	15.2	0.4	0.4	0.4	0.4	0.4	0.4	13.7	14.4	16.0	14.8	15.7	14.2	8.5	15.2	26.3	12.6	20.7	10.0
82.70	67.1	18.1	14.6	0.4	0.4	0.4	0.4	0.4	0.4	12.5	13.1	15.0	13.8	14.8	13.3	7.6	14.9	21.5	11.4	18.8	9.5
89.7	66.5	18.0	14.1	0.4	0.4	0.4	0.4	0.4	0.4	12.1	12.7	14.8	13.2	14.2	12.6	7.4	9.9	23.4	10.3	15.8	8.5
91.9	64.0	19.5	15.4	0.4	0.4	0.4	0.4	0.4	0.4	14.1	15.1	16.7	15.2	16.2	12.1	9.0	6.3	40.1	13.1	24.0	5.6
99.2	63.0	17.2	13.6	0.4	0.4	0.4	0.4	0.4	0.4	11.4	12.7	14.5	13.1	14.0	12.1	7.6	86.7	33.7	13.2	21.7	9.2
102.7	70.0	17.5	13.2	0.4	0.4	0.4	0.4	0.4	0.4	10.6	12.0	14.5	12.6	13.8	12.1	5.9	8.3	33.2	10.3	18.2	8.7
108.1	72.0	17.8	13.2	0.4	0.4	0.4	0.4	0.4	0.4	8.8	10.8	14.3	11.9	13.3	11.9	4.1	5.9	23.0	7.7	12.5	7.7
113.5	68.5	18.1	14.1	0.4	0.4	0.4	0.4	0.4	0.4	4.3	9.0	14.7	11.2	12.9	11.1	2.4	4.0	20.5	5.8	9.0	5.7
125.9	67.5	17.8	13.8	0.4	0.4	0.4	0.4	0.4	0.4	0.9	7.1	14.2	10.2	12.5	10.5	1.9	3.3	18.1	5.2	8.8	5.5
131.3	66.8	18.0	13.8	*0.0	0.4	0.4	0.4	0.4	0.4	n.a.	5.1	14.9	10.0	12.8	10.2	n.a.	2.7	29.2	4.9	9.4	5.1
135.8	62.1	18.1	14.1	*0.0	0.4	0.4	0.4	0.4	0.4	n.a.	2.0	14.8	8.2	12.0	9.0	n.a.	2.2	23.6	3.9	7.5	4.3
140.1	64.0	17.2	13.2	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	14.2	9.1	13.2	9.0	n.a.	n.a.	30.8	4.9	15.2	4.9
144.3	62.5	17.9	14.0	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	14.5	8.5	13.6	8.3	n.a.	n.a.	21.1	4.1	13.0	4.0
151.6	63.0	17.9	13.9	*0.0	*0.0	0.4	0.4	0.4	0.4	n.a.	n.a.	14.5	4.0	13.2	5.7	n.a.	n.a.	22.08	2.5	11.4	3.0

***Permeate valve was closed due to severe membrane fouling.**

Table B-10: Membrane Productivity Experiment J

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.3	73.1	21.8	20.9	0.4	0.4	0.4	0.4	0.4	0.4	19.5	19.7	20.8	19.6	20.5	20.1	14.8	16.5	49.6	15.6	32.1	21.0
4.8	78.0	20.5	19.4	0.4	0.4	0.4	0.4	0.4	0.4	17.8	18.1	19.7	18.2	19.2	19.3	12.1	14.0	103.7	14.4	32.4	39.9
12.1	71.0	20.5	20.0	0.4	0.4	0.4	0.4	0.4	0.4	17.5	18.0	19.6	18.1	19.0	18.0	10.1	12.4	42.9	13.0	22.3	12.4
13.7	71.0	20.7	20.0	0.4	0.4	0.4	0.4	0.4	0.4	17.5	18.0	19.5	18.0	19.0	18.1	9.8	11.6	32.8	11.9	19.9	12.4
21.6	70.0	19.7	19.1	0.4	0.4	0.4	0.4	0.4	0.4	16.6	17.1	18.4	17.1	18.1	17.8	10.1	12.3	28.2	12.3	21.7	17.6
29.6	78.0	19.5	18.2	0.4	0.4	0.4	0.4	0.4	0.4	16.1	16.5	18.1	16.8	17.8	17.9	9.3	11.0	32.4	12.6	24.7	27.3
31.8	75.5	18.4	17.4	0.4	0.4	0.4	0.4	0.4	0.4	14.6	14.5	16.5	15.1	16.2	16.2	8.1	7.8	19.0	9.5	15.7	15.7
35.7	74.5	19.0	18.0	0.4	0.4	0.4	0.4	0.4	0.4	15.5	16.0	17.5	16.1	17.1	16.2	9.0	10.8	26.9	11.2	19.2	11.7
41.8	79.0	18.2	17.2	0.4	0.4	0.4	0.4	0.4	0.4	15.1	15.5	17.0	15.6	16.8	16.5	9.9	11.7	36.6	12.2	28.5	21.4
45.7	72.1	14.0	13.5	0.4	0.4	0.4	0.4	0.4	0.4	11.1	11.5	12.9	12.0	12.8	12.6	10.4	12.3	32.4	15.8	29.0	24.0
54.3	71.1	18.9	18.2	0.4	0.4	0.4	0.4	0.4	0.4	16.1	16.6	17.5	16.6	17.2	16.7	11.4	14.3	26.5	14.3	20.6	15.1
59.8	75.0	18.5	18.0	0.4	0.4	0.4	0.4	0.4	0.4	14.7	15.2	17.0	15.6	16.5	15.5	7.5	8.8	21.4	10.1	15.3	9.7
64.8	69.9	19.2	18.5	0.4	0.4	0.4	0.4	0.4	0.4	14.8	15.4	17.1	15.9	16.6	15.1	7.0	8.2	16.1	9.6	12.5	7.5
76.0	69.9	18.4	17.2	0.4	0.4	0.4	0.4	0.4	0.4	13.2	14.0	16.1	14.8	15.4	14.2	6.1	7.4	16.1	9.4	11.8	7.8
79.5	72.9	22.1	20.9	0.4	0.4	0.4	0.4	0.4	0.4	16.9	17.9	19.9	18.2	19.1	18.5	5.9	7.6	17.1	8.3	11.4	9.1
85.6	70.0	23.1	22.1	0.4	0.4	0.4	0.4	0.4	0.4	17.9	18.9	21.0	19.5	20.1	19.0	6.0	7.6	17.6	9.1	11.3	7.8
89.0	69.0	23.0	22.3	0.4	0.4	0.4	0.4	0.4	0.4	17.6	18.5	20.8	19.3	20.0	18.5	5.6	6.9	15.4	8.5	10.8	6.9
100.2	72.9	20.6	19.8	0.4	0.4	0.4	0.4	0.4	0.4	15.2	16.1	18.2	16.6	17.5	16.9	5.4	6.6	13.7	7.6	10.1	8.3
100.7	75.1	16.6	15.6	0.4	0.4	0.4	0.4	0.4	0.4	11.8	12.1	14.5	13.2	14.0	13.9	6.2	6.7	16.7	9.2	12.4	12.1

Table B-11: Membrane Productivity Experiment K

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
2.8	76.8	22.9	21.6	0.45	0.50	0.55	0.60	0.65	0.70	19.9	19.9	21.1	19.5	20.1	19.2	12.6	14.0	30.1	14.3	19.8	15.1
5.7	76.5	23.3	22.1	0.45	0.50	0.55	0.60	0.65	0.70	20.0	20.1	21.5	19.9	20.4	19.2	11.0	12.4	30.2	14.1	18.6	13.2
12.7	71.0	24.0	23.0	0.45	0.50	0.55	0.60	0.65	0.70	20.5	20.5	21.9	20.1	20.6	19.0	10.6	11.7	24.4	12.4	15.8	10.9
17.4	78.1	23.5	22.1	0.45	0.50	0.55	0.60	0.65	0.70	20.2	20.2	21.6	20.0	20.8	19.5	11.3	12.6	30.3	14.0	21.3	13.8
22.2	75.1	23.8	22.5	0.45	0.50	0.55	0.60	0.65	0.70	20.2	20.2	21.9	20.0	20.6	19.2	10.2	11.3	29.4	12.7	17.0	11.8
26.6	73.0	23.5	22.7	0.45	0.50	0.55	0.60	0.65	0.70	20.0	20.1	21.2	19.9	20.0	18.6	9.9	11.2	19.8	12.8	14.3	10.6
34.9	75.0	23.2	22.1	0.45	0.50	0.55	0.60	0.65	0.70	19.8	19.7	21.1	19.2	19.8	19.0	10.6	11.3	23.7	11.6	15.3	12.8

Table B-12: Membrane Productivity Experiment L

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
12.2	73.5	22.6	21.6	0.4	0.4	0.4	0.4	0.4	0.4	20.0	20.4	21.5	20.5	21.5	20.1	12.9	16.0	45.3	17.0	45.3	13.6
12.2	78.0	22.5	21.4	0.4	0.4	0.4	0.4	0.4	0.4	19.9	20.1	21.4	20.2	21.1	20.7	12.6	14.0	47.1	14.8	30.5	20.7
15.7	81.0	22.2	21.2	0.4	0.4	0.4	0.4	0.4	0.4	19.5	20.0	21.2	20.0	21.0	20.5	11.4	14.3	50.2	14.8	35.9	20.9
26.8	72.9	23.0	22.2	0.4	0.4	0.4	0.4	0.4	0.4	20.0	20.6	22.0	20.7	21.5	20.3	10.7	14.0	45.6	14.8	26.0	12.2
37.3	76.0	23.1	22.2	0.4	0.4	0.4	0.4	0.4	0.4	20.1	20.5	22.0	20.3	21.6	20.5	10.2	12.3	37.8	11.0	25.2	12.3
42.4	76.1	23.0	22.0	0.4	0.4	0.4	0.4	0.4	0.4	20.0	20.3	21.8	20.5	21.5	20.5	10.6	12.0	37.8	13.2	26.4	13.2
47.4	72.9	23.1	22.6	0.4	0.4	0.4	0.4	0.4	0.4	20.2	20.9	22.0	21.0	21.8	20.5	10.3	14.0	32.2	14.8	26.0	11.6
60.0	79.0	23.1	22.0	0.4	0.4	0.4	0.4	0.4	0.4	20.1	20.5	22.0	20.6	21.5	20.9	10.5	12.5	46.6	13.1	24.4	15.5
66.0	75.9	23.5	22.5	0.4	0.4	0.4	0.4	0.4	0.4	20.5	21.0	22.2	21.0	22.0	21.0	10.6	13.2	33.1	13.2	26.5	13.2
71.4	74.5	23.5	22.7	0.4	0.4	0.4	0.4	0.4	0.4	20.5	21.0	22.2	21.0	22.0	21.0	10.3	12.8	29.9	12.8	24.4	12.8
83.5	75.0	23.2	22.2	0.4	0.4	0.4	0.4	0.4	0.4	20.2	20.9	22.1	21.0	21.9	20.9	10.7	14.9	44.6	15.3	33.4	14.9
91.1	73.1	23.2	22.5	0.4	0.4	0.4	0.4	0.4	0.4	20.5	21.0	22.1	21.1	22.0	20.9	11.6	14.8	34.1	15.2	30.3	14.0
106.0	79.0	24.0	23.0	0.4	0.4	0.4	0.4	0.4	0.4	21.1	21.8	22.9	21.7	22.5	22.1	10.7	15.1	42.7	14.2	25.6	18.3
112.4	77.5	23.1	22.2	0.4	0.4	0.4	0.4	0.4	0.4	20.5	21.0	22.0	21.0	21.8	21.5	12.3	16.0	41.7	16.0	31.6	23.2
117.5	73.0	23.5	22.9	0.4	0.4	0.4	0.4	0.4	0.4	20.5	21.1	22.1	21.1	22.0	20.8	10.1	13.0	24.8	12.7	22.8	11.4
130.8	80.5	22.8	21.5	0.4	0.4	0.4	0.4	0.4	0.4	20.0	20.2	21.8	20.5	21.5	20.9	11.7	12.9	72.1	15.3	38.8	20.2
134.3	78.9	23.1	22.0	0.4	0.4	0.4	0.4	0.4	0.4	20.1	20.5	22.0	20.8	21.8	21.0	10.4	12.7	48.9	14.9	35.4	16.3

Table B-13: Membrane Productivity Experiment M

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.4	74.0	23.9	23.0	0.45	0.50	0.55	0.60	0.65	0.70	21.0	21.0	22.1	20.2	21.0	20.2	12.4	13.8	26.5	12.5	17.9	14.6
7.7	81.0	23.9	22.7	0.45	0.50	0.55	0.60	0.65	0.70	19.5	19.7	21.2	16.9	19.5	18.0	7.4	8.7	16.4	5.9	10.7	8.2
15.5	74.0	24.2	23.7	0.45	0.50	0.55	0.60	0.65	0.70	19.4	19.2	21.1	14.4	17.9	15.9	6.7	7.1	12.8	4.2	7.3	5.9
26.1	76.0	23.9	22.8	0.45	0.50	0.55	0.60	0.65	0.70	18.5	17.2	20.2	12.8	15.5	14.2	6.1	5.4	11.6	3.8	5.5	5.1
29.9	77.9	23.8	22.5	0.45	0.50	0.55	0.60	0.65	0.70	18.1	16.9	20.1	12.0	14.9	13.8	5.8	5.2	11.5	3.5	5.1	4.9
38.7	72.0	24.2	23.3	0.45	0.50	0.55	0.60	0.65	0.70	17.1	15.1	19.8	17.0	18.8	9.9	4.7	4.0	9.6	6.1	9.1	3.5
50.2	76.1	26.0	25.0	0.45	0.50	0.55	*0.0	*0.0	*0.0	19.6	17.1	22.0	n.a.	n.a.	n.a.	5.0	3.9	10.4	n.a.	n.a.	n.a.
53.7	78.9	23.5	22.4	0.45	0.50	0.55	*0.0	*0.0	*0.0	14.2	8.5	19.6	n.a.	n.a.	n.a.	3.3	2.2	10.5	n.a.	n.a.	n.a.
59.3	74.0	24.1	23.5	n.a.	n.a.	n.a.	*0.0	*0.0	*0.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
75.0	78.0	33.9	32.0	n.a.	n.a.	n.a.	*0.0	*0.0	*0.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
79.4	78.9	24.5	23.6	0.45	0.50	0.55	*0.0	*0.0	*0.0	16.0	8.5	11.1	n.a.	n.a.	n.a.	3.6	2.1	2.7	n.a.	n.a.	n.a.

***Permeate valve closed due to severe membrane fouling.**

Table B-14: Membrane Productivity Experiment N

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.0	76.5	21.1	20.5	0.45	0.50	0.55	0.60	0.65	0.70	18.6	18.8	19.5	18.5	19.2	19.0	13.6	16.7	28.4	17.4	27.2	26.0
6.2	82.0	25.1	24.1	0.45	0.50	0.55	0.60	0.65	0.70	22.5	22.5	23.5	22.0	23.1	22.7	13.5	15.0	31.8	14.5	27.4	23.2
15.4	74.0	23.0	22.0	0.45	0.50	0.55	0.60	0.65	0.70	20.1	19.9	21.0	19.3	20.5	19.4	12.4	13.0	24.8	12.7	22.0	15.3
21.4	80.0	22.8	21.8	0.45	0.50	0.55	0.60	0.65	0.70	20.0	19.9	21.0	19.0	20.2	19.2	12.4	13.2	26.8	11.5	19.6	14.3
34.8	77.0	23.0	21.9	0.45	0.50	0.55	0.60	0.65	0.70	19.8	19.5	20.8	18.9	20.1	19.1	11.1	11.1	21.8	11.1	17.7	13.5
39.4	81.0	22.2	21.1	0.45	0.50	0.55	0.60	0.65	0.70	19.0	19.0	20.1	18.2	19.9	18.9	10.8	12.0	22.6	11.0	23.6	16.1
48.7	78.0	22.5	21.5	0.45	0.50	0.55	0.60	0.65	0.70	19.4	19.1	20.1	18.2	19.9	18.7	11.2	11.2	18.8	9.7	20.1	13.7
63.3	81.2	22.1	21.1	0.45	0.50	0.55	0.60	0.65	0.70	19.1	19.0	20.0	18.0	19.6	19.0	11.1	12.0	21.5	14.7	20.4	16.9
74.8	76.0	23.5	22.8	0.45	0.50	0.55	0.60	0.65	0.70	20.0	20.0	21.0	19.1	20.8	19.0	9.5	10.5	16.9	8.7	18.3	11.2
84.4	80.0	23.2	22.1	0.45	0.50	0.55	0.60	0.65	0.70	19.9	19.9	20.9	18.6	20.2	19.0	10.5	11.4	20.2	9.5	17.0	12.2
97.9	78.0	23.1	22.0	0.45	0.50	0.55	0.60	0.65	0.70	19.7	19.6	20.5	18.5	20.2	18.8	10.3	11.1	17.6	9.7	18.1	12.2
108.9	77.0	22.1	21.1	0.45	0.50	0.55	0.60	0.65	0.70	18.5	18.5	19.8	17.5	19.2	17.1	9.7	10.7	20.6	9.7	18.1	10.2

Table B-15: Membrane Productivity Experiment O

Run Hour	Temp. (°F)	Feed (psi)	Conc. (psi)	Permeate Flow (GPM)						Permeate Pressure (psi)						MTC (GFD/psi)					
				P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.1	74.9	23.1	22.4	0.45	0.50	0.55	0.60	0.65	0.70	20.7	20.9	21.5	20.2	21.1	20.0	14.9	18.3	30.1	15.9	26.8	17.2
5.6	82.4	23.5	22.2	0.45	0.50	0.55	0.60	0.65	0.70	20.5	20.5	21.8	20.0	21.2	20.1	12.0	13.3	33.2	13.1	24.7	15.9
14.2	74.5	23.0	22.1	0.45	0.50	0.55	0.60	0.65	0.70	19.5	19.5	20.5	18.4	19.5	17.5	9.9	11.0	18.0	9.7	14.3	9.3
21.3	83.5	23.4	22.1	0.45	0.50	0.55	0.60	0.65	0.70	20.1	20.0	21.2	19.1	20.9	19.8	10.3	11.2	22.0	10.0	21.8	14.6
30.9	76.1	23.5	22.4	0.45	0.50	0.55	0.60	0.65	0.70	20.0	19.9	21.0	18.4	20.2	18.0	10.1	10.8	18.6	8.7	15.6	9.3
42.2	78.9	22.1	21.1	0.45	0.50	0.55	0.60	0.65	0.70	18.7	18.5	19.8	17.0	19.0	15.6	10.0	10.4	19.6	8.4	16.0	7.5
52.0	74.1	23.8	22.9	0.45	0.50	0.55	0.60	0.65	0.70	20.1	20.2	21.5	19.0	20.9	18.0	9.3	10.7	20.1	9.3	17.9	8.8
61.8	81.0	23.4	22.1	0.45	0.50	0.55	0.60	0.65	0.70	20.1	20.0	21.2	18.6	21.0	18.0	10.6	11.5	22.6	9.1	23.6	9.3
71.8	76.0	23.0	22.1	0.45	0.50	0.55	0.60	0.65	0.70	20.0	20.0	21.0	18.6	20.8	17.5	11.8	13.1	23.9	10.1	24.9	9.2
85.2	81.0	23.2	22.1	0.45	0.50	0.55	0.60	0.65	0.70	20.1	20.1	21.1	19.0	20.7	18.1	11.0	12.2	22.6	10.4	21.2	9.7
96.7	77.0	23.0	22.2	0.45	0.50	0.55	0.60	0.65	0.70	20.0	20.0	20.9	18.9	20.2	18.0	11.3	12.6	21.2	10.6	17.7	10.0
106.7	80.2	23.0	22.0	0.45	0.50	0.55	0.60	0.65	0.70	19.6	19.5	20.5	18.1	19.8	17.0	9.8	10.5	17.4	8.6	15.0	8.1

APPENDIX C: WATER QUALITY ANALYSIS DATA

Table C-1: Raw pH Data

Exp. ID	Date	Feed	P1	P2	P3	P4	P5	P6	Avg. Permeate
B	9/13/99	6.7	6.8	6.8	6.8	6.9	6.9	6.9	6.8
B	9/16/99	6.8	7.0	7.1	7.1	7.1	7.1	7.1	7.1
B	9/17/99	6.9	6.9	6.9	7.0	7.0	7.0	7.0	7.0
B	9/18/99	6.7	6.8	6.9	6.9	6.9	6.9	6.9	6.9
B	9/19/99	7.3	7.2	7.3	7.3	7.3	7.3	7.3	7.3
B	9/20/99	7.2	7.4	7.4	7.5	7.4	7.5	7.4	7.4
B	9/21/99	7.1	7.0	7.1	7.1	7.1	7.1	7.1	7.1
B	9/22/99	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
B	9/23/99	6.9	6.9	6.9	7.0	7.0	7.0	7.1	7.0
B	9/24/99	7.1	7.0	7.1	7.1	7.1	7.1	7.1	7.1
B	9/25/99	7.1	7.1	7.2	7.3	7.2	7.2	7.2	7.2
B	9/26/99	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
C	9/28/99	7.2	7.2	7.2	7.3	7.3	7.3	7.3	7.2
C	10/1/99	7.2	7.1	7.3	7.3	7.3	7.3	7.3	7.3
C	10/2/99	7.1	7.2	7.2	7.2	7.2	7.2	7.2	7.2
C	10/3/99	6.8	6.9	6.9	6.9	6.9	6.9	6.9	6.9
C	10/4/99	7.1	7.1	7.1	7.1	7.1	7.1	7.2	7.1
E	11/8/99	7.3	7.5	7.6	7.5	7.6	7.6	7.5	7.5
E	11/9/99	6.7	7.1	7.2	7.2	7.2	7.2	7.2	7.2
E	11/10/99	6.8	7.0	7.1	7.1	7.0	7.0	7.1	7.0
E	11/11/99	7.0	7.1	7.1	7.1	7.2	7.1	7.1	7.1
E	11/12/99	6.7	7.0	7.0	7.0	7.0	7.1	7.0	7.0
E	11/13/99	7.0	n.a	7.1	7.1	7.2	7.1	n.a.	7.1
E	11/14/99	7.1	n.a.	7.2	7.2	7.2	7.1	n.a.	7.2
F	11/29/99	6.8	6.7	6.8	6.7	6.7	6.7	6.6	6.7
F	11/30/99	6.7	7.0	7.1	7.2	7.2	7.2	7.2	7.2
F	12/1/99	7.6	7.6	7.5	7.6	7.5	7.5	7.3	7.5
F	12/3/99	7.3	7.3	7.4	7.3	7.3	7.4	7.4	7.4
F	12/4/99	7.3	7.3	7.3	7.3	7.3	6.8	7.2	7.2
F	12/5/99	3.9	6.8	7.0	7.2	7.1	7.1	7.1	7.1
F	12/6/99	7.2	7.1	7.2	7.1	7.1	7.5	7.4	7.2
F	12/7/99	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
F	12/8/99	7.5	7.5	7.5	7.6	7.5	7.6	7.6	7.6
F	12/9/99	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
G	12/13/99	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
G	12/14/99	7.6	7.5	7.4	7.5	7.5	7.4	7.5	7.5
G	12/20/99	6.8	6.8	6.8	6.9	6.9	6.9	6.6	6.8
G	12/21/99	6.7	6.8	6.9	6.9	6.9	6.9	6.9	6.9
G	12/24/99	7.0	6.9	7.0	7.1	7.1	7.1	7.1	7.1

***Water Quality Analysis was not performed for experiments A, D, and K.**

Exp. ID	Date	Feed	P1	P2	P3	P4	P5	P6	Avg. Permeate
H	1/8/00	7.3	7.4	7.2	7.3	7.3	7.3	7.4	7.3
H	1/9/00	6.9	7.1	7.2	7.2	7.2	7.2	7.2	7.2
H	1/10/00	7.3	7.3	7.2	7.3	7.4	7.3	7.3	7.3
H	1/11/00	7.0	7.1	7.2	7.2	7.2	7.2	7.2	7.2
H	1/12/00	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
H	1/13/00	7.2	7.2	7.3	7.4	7.4	7.4	7.4	7.6
H	1/14/00	6.8	6.9	7.0	7.1	7.0	7.0	7.0	7.4
H	1/15/00	6.8	n.a.	6.9	6.8	6.9	6.9	7.0	7.0
H	1/16/00	6.8	n.a.	n.a.	6.9	7.1	7.1	7.1	6.9
H	1/17/00	6.9	n.a.	n.a.	7.1	7.1	7.2	7.2	7.1
I	1/28/00	7.1	7.0	7.0	6.9	6.9	6.9	6.8	7.2
I	1/29/00	7.0	7.1	7.1	7.1	7.1	7.2	7.1	7.1
I	1/30/00	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.1
I	2/1/00	6.7	7.0	7.0	7.0	7.0	7.1	7.1	7.0
I	2/4/00	7.0	7.1	7.1	7.1	7.0	7.1	7.1	7.1
I	2/5/00	6.8	6.9	6.9	7.0	7.0	7.1	7.0	7.0
J	2/17/00	7.0	7.0	7.0	7.1	7.1	7.0	7.1	7.1
J	2/18/00	7.0	7.1	7.1	7.1	7.1	7.1	7.1	7.1
J	2/20/00	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
J	2/21/00	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
J	2/22/00	6.7	6.9	6.8	6.8	6.8	6.8	6.8	6.8
L	3/15/00	6.4	6.5	6.6	6.6	6.6	6.6	6.6	6.6
L	3/16/00	6.4	6.5	6.5	6.5	6.5	6.5	6.5	6.5
L	3/17/00	6.8	6.9	6.9	6.8	6.9	6.9	6.9	6.9
L	3/18/00	6.9	7.0	7.0	7.0	7.0	6.9	6.9	n.a.
M	3/20/00	6.8	6.8	6.8	6.8	6.8	6.5	6.7	6.7
M	3/21/00	6.8	6.8	6.6	6.7	6.8	6.8	6.8	6.7
M	3/22/00	6.9	6.9	6.0	7.0	6.8	6.9	5.9	6.6
M	3/23/00	6.9	7.0	7.0	7.0	6.6	6.7	7.0	6.9
M	3/24/00	6.9	6.9	6.9	6.9	n.a.	n.a.	n.a.	6.9
M	3/25/00	6.9	6.7	6.9	6.5	n.a.	n.a.	n.a.	6.7
N	4/25/00	7.0	7.0	7.1	7.1	7.1	7.1	6.9	7.1
N	4/26/00	7.0	7.1	7.1	7.1	7.0	7.1	7.1	7.1
N	4/27/00	7.1	7.2	7.2	7.3	7.2	7.2	7.2	7.2
N	4/30/00	7.2	7.2	7.2	7.2	7.3	7.2	7.3	7.2
N	5/1/00	7.0	7.2	7.2	7.2	7.2	7.3	7.2	7.2
O	5/5/00	7.1	7.2	7.2	7.2	7.2	7.1	7.2	7.2
O	5/6/00	7.1	7.1	7.1	7.1	7.1	7.2	7.2	7.1
O	5/7/00	7.1	7.2	7.1	7.2	7.2	7.1	7.2	7.2
O	5/8/00	7.1	7.2	7.2	7.2	7.2	7.1	7.1	7.2
O	5/9/00	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.1

Table C-2: Raw Turbidity and Rejection Data

Exp. ID	Date	Feed (NTU)	P1 (NTU)	P2 (NTU)	P3 (NTU)	P4 (NTU)	P5 (NTU)	P6 (NTU)	Avg. Permeate (NTU)	Rejection %
B	9/13/99	1.6	0.1	0.2	0.3	0.2	0.1	0.2	0.18	88.5
B	9/16/99	1.4	0.74	0.11	0.4	0.27	0.22	0.14	0.31	77.6
B	9/17/99	0.7	0.1	0.07	0.05	0.09	0.03	0.07	0.07	90.2
B	9/18/99	0.42	0.04	0.13	0.06	0.03	0.03	0.02	0.05	87.7
B	9/19/99	0.43	0.07	0.04	0.04	0.03	0.07	0.06	0.05	88.0
B	9/20/99	0.35	0.13	0.06	0.06	0.05	0.07	0.09	0.08	78.1
B	9/21/99	0.57	0.15	0.07	0.13	0.04	0.05	0.1	0.09	84.2
B	9/22/99	0.56	0.05	0.07	0.04	0.04	0.1	0.02	0.05	90.5
B	9/23/99	0.62	0.04	0.04	0.03	0.04	0.03	0.1	0.05	92.5
B	9/24/99	0.6	0.04	0.04	0.03	0.01	0.04	0.02	0.03	95.0
B	9/25/99	0.98	0.06	0.02	0.04	0.04	0.01	0.01	0.03	96.9
B	9/26/99	0.8	0.07	0.07	0.08	0.05	0.01	0.01	0.05	94.0
C	9/28/99	1.11	0.22	0.08	0.03	0.22	0.01	0.02	0.10	91.3
C	10/1/99	0.85	0.05	0.06	0.17	0.04	0.07	0.06	0.08	91.2
C	10/2/99	1.15	0.1	0.06	0.03	0.07	0.02	0.05	0.06	95.2
C	10/3/99	0.68	0.03	n.a.	0.02	n.a	n.a.	n.a.	0.03	96.3
C	10/4/99	0.55	n.a.	0.04	0.09	0.07	0.01	0.06	0.05	90.2
E	11/8/99	1.15	0.44	0.74	0.27	0.36	0.4	0.21	0.40	64.9
E	11/9/99	1.25	0.09	0.13	0.07	0.07	0.07	0.07	0.08	93.3
E	11/10/99	1.4	0.07	0.08	0.08	0.08	0.07	0.08	0.08	94.5
E	11/11/99	0.94	0.085	0.09	0.07	0.08	0.07	0.06	0.08	91.9
E	11/12/99	0.96	0.06	0.08	0.07	0.07	0.075	0.06	0.07	92.8
E	11/13/99	0.725	n.a.	0.05	0.08	0.06	0.07	n.a.	0.07	91.0
E	11/14/99	0.87	n.a.	0.085	0.06	0.06	0.06	n.a.	0.07	92.4
E	11/15/99	1.515	n.a.	0.07	0.03	0.05	0.06	n.a.	0.05	96.5
F	11/29/99	1.08	0.11	0.07	0.07	0.08	0.08	0.07	0.08	92.6
F	11/30/99	1.4	0.74	0.11	0.4	0.27	0.22	0.14	0.31	77.6
F	12/1/99	1.35	0.05	0.06	0.05	0.06	0.06	0.06	0.06	95.8
F	12/3/99	0.68	0.04	0.05	0.04	0.05	0.04	0.05	0.05	93.4
F	12/4/99	0.73	0.04	0.04	0.04	0.04	0.04	0.05	0.04	94.3
F	12/5/99	0.73	0.04	0.04	0.04	0.06	0.04	0.04	0.04	94.1
F	12/6/99	10.2	0.05	0.04	0.05	0.05	0.05	0.05	0.05	99.5
F	12/7/99	3.7	0.05	0.05	0.05	0.05	0.04	0.05	0.05	98.7
F	12/8/99	2.1	0.05	0.06	0.05	0.06	0.05	0.06	0.06	97.4
F	12/9/99	0.84	0.05	0.05	0.05	0.05	0.05	0.04	0.05	94.2
G	12/13/99	1.325	0.05	0.05	0.05	0.05	0.05	0.05	0.05	96.2
G	12/14/99	1.7	0.08	0.05	0.06	0.07	0.05	0.06	0.06	96.4
G	12/15/99	0.7	0.05	0.13	0.305	0.07	0.12	0.06	0.12	82.5
G	12/16/99	0.87	0.04	0.05	0.04	0.04	0.05	0.05	0.05	94.8

***Water Quality Analysis was not performed for experiments A, D, and K.**

Exp. ID	Date	Feed (NTU)	P1 (NTU)	P2 (NTU)	P3 (NTU)	P4 (NTU)	P5 (NTU)	P6 (NTU)	Avg. Permeate (NTU)	Rejection %
G	12/17/99	0.73	0.06	0.07	0.07	0.07	0.06	0.07	0.07	90.9
G	12/18/99	1.34	0.08	0.06	0.07	0.07	0.06	0.04	0.06	95.3
G	12/19/99	0.76	0.05	0.05	0.05	0.28	0.11	0.08	0.10	86.4
G	12/20/99	1.59	0.06	0.05	0.06	0.05	0.05	0.06	0.06	96.5
H	1/8/00	0.92	0.08	0.05	0.06	0.07	0.05	0.06	0.06	93.3
H	1/9/00	0.84	0.05	0.13	0.305	0.07	0.12	0.06	0.12	85.4
H	1/10/00	1.02	0.04	0.05	0.04	0.04	0.05	0.05	0.05	95.6
H	1/11/00	1.11	0.06	0.07	0.07	0.07	0.06	0.07	0.07	94.0
H	1/12/00	0.94	0.08	0.06	0.07	0.07	0.06	0.04	0.06	93.3
H	1/13/00	0.6	0.05	0.05	0.05	0.28	0.11	0.08	0.10	82.8
H	1/14/00	0.54	0.06	0.05	0.06	0.05	0.05	0.06	0.06	89.8
H	1/15/00	1.24	0.06	0.05	0.05	0.06	0.06	0.05	0.06	95.6
H	1/16/00	0.37	0.1	0.13	0.13	0.07	0.06	0.06	0.09	75.2
H	1/17/00	0.61	0.12	0.125	0.1035	0.146	0.09	0.098	0.11	81.4
I	1/28/00	1.34	0.5	0.08	0.39	0.06	0.45	1.01	0.42	69.0
I	1/29/00	1.105	0.05	0.04	0.04	0.04	0.05	0.04	0.04	96.1
I	1/30/00	1.035	0.05	0.04	0.04	0.04	0.04	0.04	0.04	96.0
I	2/1/00	2.3	0.04	0.05	0.05	0.05	0.05	0.05	0.05	97.9
I	2/4/00	3.2	0.06	0.05	0.05	0.05	0.04	0.05	0.05	98.4
I	2/5/00	0.985	n.a.	0.04	0.04	0.04	0.04	0.04	0.04	95.9
I	2/7/00	1.525	n.a.	n.a.	0.04	0.04	0.04	0.04	0.04	97.4
J	2/17/00	3.7	0.05	0.04	0.05	0.045	0.04	0.04	0.04	98.8
J	2/18/00	2.7	0.06	0.05	0.05	0.04	0.05	0.05	0.05	98.1
J	2/20/00	3.8	0.08	0.04	0.04	0.04	0.04	0.04	0.05	98.8
J	2/21/00	3.8	0.06	0.05	0.05	0.05	0.05	0.05	0.05	98.6
J	2/22/00	9.5	0.05	0.05	0.065	0.05	0.09	0.06	0.06	99.4
L	3/15/00	8.1	0.095	0.05	0.06	0.1	0.05	0.07	0.07	99.1
L	3/16/00	5.4	0.07	0.09	0.06	0.05	0.06	0.06	0.07	98.8
L	3/17/00	6.15	0.08	0.06	0.05	0.07	0.06	0.06	0.06	99.0
L	3/18/00	5.3	0.06	0.05	0.04	0.05	0.05	0.06	0.05	99.0
M	3/22/00	16.05	0.12	0.1	0.09	0.1	0.15	0.08	0.11	99.3
M	3/23/00	4.015	0.04	0.04	0.05	0.04	0.04	0.04	0.04	99.0
M	3/24/00	3.25	0.06	0.04	0.04	n.a.	n.a.	n.a.	0.05	98.6
M	3/25/00	1.545	0.05	0.04	0.05	n.a.	n.a.	n.a.	0.05	97.0
N	4/25/00	14.6	0.05	0.03	0.04	0.04	0.05	0.37	0.10	99.3
N	4/26/00	3.3	0.08	0.12	0.3	0.06	0.28	0.09	0.16	95.3
N	4/27/00	3.35	0.05	0.04	0.04	0.04	0.04	1.35	0.26	92.2
N	4/29/00	6.35	0.05	0.04	0.04	0.04	0.62	0.07	0.14	97.7
N	4/30/00	3.3	0.04	0.07	0.04	0.04	1.355	0.05	0.27	91.9

Exp. ID	Date	Feed (NTU)	P1 (NTU)	P2 (NTU)	P3 (NTU)	P4 (NTU)	P5 (NTU)	P6 (NTU)	Avg. Permeate (NTU)	Rejection %
N	5/1/00	3.5	0.05	0.05	0.05	0.04	0.04	2.9	0.52	85.1
O	5/4/00	5.4	0.06	0.04	0.04	0.04	0.04	1.935	0.36	93.3
O	5/5/00	2.3	0.07	0.04	0.04	0.04	0.06	0.54	0.13	94.3
O	5/6/00	1.49	0.05	0.05	0.06	0.14	0.05	0.06	0.07	95.4
O	5/7/00	1.6	0.04	0.04	0.04	0.135	0.04	0.09	0.06	96.0
O	5/8/00	2.2	0.05	0.03	0.04	0.04	0.03	0.03	0.04	98.3
O	5/9/00	13.6	0.05	0.09	0.03	0.03	0.04	0.05	0.05	99.6

Sample Calculation of Turbidity Rejection using Exp. O (5/9/00) data:

$$\%\,\mathrm{Re}\,jection = \frac{Feed - Avg.Permeate}{Feed} \times 100\% = \frac{13.6 - .05}{13.6} \times 100\% = 99.6\%$$

Table C-3: Raw Particle Count and Rejection Data

Exp. ID	Date	Feed (counts/ml)	P1 (counts/ml)	P2 (counts/ml)	P3 (counts/ml)	P4 (counts/ml)	P5 (counts/ml)	P6 (counts/ml)	Avg. Permeate (counts/ml)	Rejection %
B	9/13/99	3964	1364	553	294	725	189	122	541	86.3
B	9/16/99	3442	1008	182	596	388	316	186	446	87.0
B	9/17/99	1668	943	139	236	619	315	191	407	75.6
B	9/18/99	1158	368	172	294	278	285	183	263	77.3
B	9/19/99	1178	860	315	424	380	270	309	427	63.8
B	9/20/99	1475	1186	337	354	286	265	209	439	70.2
B	9/21/99	2026	592	426	1019	330	301	336	501	75.3
B	9/22/99	1420	596	213	447	276	337	276	358	74.8
B	9/23/99	1618	664	256	255	447	264	360	374	76.9
B	9/24/99	1137	646	323	407	204	249	383	369	67.6
B	9/25/99	1519	634	251	494	197	147	151	312	79.4
B	9/26/99	1206	n.a.	403	760	419	210	362	431	64.2
C	9/28/99	2932	1290	692	431	1291	279	893	717	69.6
C	10/1/99	1393	725	187	215	733	255	328	343	76.5
C	10/2/99	2047	1754	336	307	343	221	313	304	84.7
C	10/3/99	5533	520	174	140	448	113	189	213	96.6
C	10/4/99	978	n.a	490	450	221	92	230	296	76.5
E	11/8/99	9006	295	306	691	654	981	443	562	93.8
E	11/9/99	5153	382	425	245	201	230	388	312	94.0
E	11/10/99	4831	201	192	144	337	168	158	200	95.9
E	11/11/99	3423	244	366	60	348	203	152	229	93.3
E	11/12/99	2808	124	95	136	148	106	n.a.	122	95.7
E	11/13/99	2169	n.a.	269	224	274	139	n.a.	227	89.6
E	11/14/99	3001	n.a.	260	181	218	201	n.a	215	92.8

***Water Quality Analysis was not performed for experiments A, D, and K.**

Exp. ID	Date	Feed (counts/ml)	P1 (counts/ml)	P2 (counts/ml)	P3 (counts/ml)	P4 (counts/ml)	P5 (counts/ml)	P6 (counts/ml)	Avg. Permeate (counts/ml)	Rejection %
E	11/15/99	6733	n.a.	394	68	88	56	n.a.	152	97.7
F	11/29/99	3951	291	171	442	210	180	577	312	92.1
F	11/30/99	2684	296	248	72	56	77	347	183	93.2
F	12/1/99	3314	86	39	19	105	95	112	76	97.7
F	12/3/99	2061	40	51	33	156	40	152	79	96.2
F	12/4/99	2128	46	48	96	42	172	60	77	96.4
F	12/5/99	3784	39	54	65	45	50	21	46	98.8
F	12/6/99	3697	40	29	40	59	28	25	37	99.0
F	12/7/99	3975	71	29	30	64	78	74	58	98.5
F	12/8/99	3654	89	27	23	65	38	29	45	98.8
F	12/9/99	2198	36	42	26	58	148	39	58	97.4
G	12/13/99	2839	132	81	152	71	33	32	83	97.1
G	12/14/99	3164	51	15	47	164	58	70	68	97.9
G	12/15/99	3575	36	52	103	56	49	40	56	98.4
G	12/16/99	2862	92	37	45	36	83	128	70	97.5
G	12/17/99	2178	44	26	42	41	59	50	44	98.0
G	12/18/99	3118	73	45	46	189	68	186	101	96.7
G	12/19/99	1378	43	80	44	122	799	442	255	81.5
G	12/20/99	3270	90	14	67	65	64	74	62	98.1
G	12/21/99	2389	51	18	24	53	54	20	37	98.5
G	12/24/99	3528	72	55	50	140	165	19	83	97.6
H	1/7/00	3757	132	81	152	71	33	32	83	97.8
H	1/8/00	1792	51	15	47	164	58	70	68	96.2
H	1/9/00	2075	36	52	103	56	49	40	56	97.3
H	1/10/00	2491	92	37	45	36	83	128	70	97.2

Exp. ID	Date	Feed (counts/ml)	P1 (counts/ml)	P2 (counts/ml)	P3 (counts/ml)	P4 (counts/ml)	P5 (counts/ml)	P6 (counts/ml)	Avg. Permeate (counts/ml)	Rejection %
H	1/11/00	2402	44	26	42	41	59	50	44	98.2
H	1/12/00	1602	73	45	46	189	68	186	101	93.7
H	1/13/00	1138	43	80	44	122	799	442	255	77.6
H	1/14/00	992	90	14	67	65	64	74	62	93.7
H	1/15/00	801	51	18	24	53	54	20	37	95.4
H	1/16/00	928	72	55	50	140	165	19	83	91.0
I	1/28/00	2827	512	197	554	67	168	228	288	89.8
I	1/29/00	3072	76	43	23	39	50	124	59	98.1
I	1/30/00	2795	65	50	42	30	40	50	46	98.4
I	2/1/00	5388	103	46	41	43	40	54	55	99.0
I	2/4/00	6833	145	44	85	42	63	183	94	98.6
I	2/5/00	3526	n.a.	62	59	58	56	66	60	98.3
I	2/7/00	3723	n.a.	n.a.	100	170	68	129	117	96.9
J	2/18/00	3862	47	54	70	39	36	134	63	98.4
J	2/20/00	6900	197	31	60	56	36	56	73	98.9
J	2/21/00	5788	91	182	63	56	43	63	83	98.6
J	2/22/00	9074	34	81	72	34	39	56	53	99.4
L	3/15/00	9719	110	118	71	91	47	66	84	99.1
L	3/16/00	8774	100	46	81	51	55	129	77	99.1
L	3/17/00	8958	93	78	67	129	82	157	101	98.9
L	3/18/00	8677	49	58	40	74	118	32	62	99.3
L	3/20/00	9713	41	50	55	56	56	101	60	99.4
L	3/21/00	9334	52	74	64	69	141	147	91	99.0
M	3/22/00	4241	147	243	159	137	180	245	185	95.6
M	3/23/00	7717	37	31	34	31	41	54	38	99.5

Exp. ID	Date	Feed (counts/ml)	P1 (counts/ml)	P2 (counts/ml)	P3 (counts/ml)	P4 (counts/ml)	P5 (counts/ml)	P6 (counts/ml)	Avg. Permeate (counts/ml)	Rejection %
M	3/24/00	7681	39	45	57	n.a.	n.a.	n.a.	47	99.4
M	3/25/00	3904	122	30	75	n.a.	n.a.	n.a.	76	98.1
N	4/25/00	9549	222	56	92	48	54	1243	286	97.0
N	4/26/00	6315	72	139	201	82	104	143	124	98.0
N	4/29/00	7019	36	62	63	40	905	115	204	97.1
N	4/30/00	6360	42	49	65	51	1765	68	340	94.7
N	5/1/00	7082	38	79	43	45	45	2319	428	94.0
O	5/4/00	6100	105	134	105	25	45	2239	442	92.8
O	5/5/00	3382	201	40	85	44	65	1195	272	92.0
O	5/6/00	2779	96	105	52	1221	65	133	279	90.0
O	5/7/00	2932	61	57	66	926	41	63	202	93.1
O	5/8/00	4213	60	28	92	85	41	24	55	98.7
O	5/9/00	8429	102	654	46	41	32	122	166	98.0

Sample Calculation of Particle Rejection using Exp. N (5/1/00) data:

$$\%\,\mathrm{Re}\,jection = \frac{Feed - Avg.Permeate}{Feed} \times 100\% = \frac{7082 - 428}{7082} \times 100\% = 94.0\%$$

Table C-4: Raw UV_{254} and Rejection Data

Exp. ID	Date	Feed (cm^{-1})	P1 (cm^{-1})	P2 (cm^{-1})	P3 (cm^{-1})	P4 (cm^{-1})	P5 (cm^{-1})	P6 (cm^{-1})	Avg. Permeate (cm^{-1})	Rejection %
B	9/13/99	0.2071	n.a.	0.2001	0.2075	0.2065	0.2054	0.2049	0.2049	1.1
B	9/20/99	0.2311	0.2234	0.2236	0.2263	0.2229	0.2262	0.2245	0.2247	2.8
B	9/26/99	0.2217	0.1922	0.2060	0.2122	0.2131	0.2111	0.2069	0.2099	5.3
C	9/28/99	0.2178	0.2056	0.2128	0.2125	0.2149	0.2008	0.2103	0.2103	3.5
E	11/13/99	0.1967	n.a.	0.1736	0.1788	0.1863	0.1911	n.a.	0.1825	7.2
F	11/30/99	0.2009	0.2005	0.1975	0.1996	0.2034	0.2028	0.2036	0.2012	-0.2
F	12/4/99	0.1896	0.1902	0.1921	0.1961	0.1941	0.1943	0.1944	0.1935	-2.1
F	12/9/99	0.1933	0.1945	0.1972	0.1958	0.1939	0.1934	0.1931	0.1947	-0.7
G	12/13/99	0.2155	0.2004	0.2024	0.2040	0.2053	0.2065	0.2047	0.2039	5.4
G	12/18/99	0.2578	0.2468	0.2518	0.2527	0.2540	0.2503	0.2532	0.2515	2.5
G	12/24/99	0.2504	0.2409	0.2491	0.2522	0.2411	0.2444	0.2524	0.2467	1.5
H	1/7/00	0.2023	0.2017	0.1977	0.2114	0.2064	0.1981	0.2012	0.2028	-0.2
H	1/12/00	0.1940	0.1951	0.1903	0.1956	0.1922	0.1938	0.1935	0.1934	0.3
H	1/17/00	0.1502	n.a.	n.a.	0.1922	0.1938	0.1930	0.1895	0.1921	-27.9
I	1/28/00	0.1872	0.1813	0.1864	0.1826	0.1869	0.1835	0.1776	0.1831	2.2
I	2/7/00	0.2037	n.a.	n.a.	0.1917	0.1785	0.1926	0.1792	0.1855	8.9
J	2/17/00	0.1865	0.1781	0.1801	0.1780	0.1802	0.1802	0.1822	0.1798	3.6
J	2/22/00	0.1854	0.1832	0.1811	0.1809	0.1787	0.1849	0.1830	0.1820	1.9
L	3/15/00	0.2117	0.2056	0.2078	0.2054	0.2111	0.2145	0.2135	0.2097	1.0
L	3/21/00	0.2005	0.1959	0.1968	0.1913	0.1969	0.1977	0.1948	0.1956	2.5
M	3/22/00	0.2160	0.2222	0.2218	0.2097	0.2133	0.2226	0.2175	0.2178	-0.9
M	3/25/00	0.1931	0.1805	0.1805	0.1779	n.a.	n.a.	n.a.	0.1796	7.0
N	4/25/00	0.1447	0.1409	0.1460	0.1457	0.1491	0.1553	0.1740	0.1518	-4.9

***Water Quality Analysis was not performed for experiments A, D, and K.**

Exp. ID	Date	Feed (cm^{-1})	P1 (cm^{-1})	P2 (cm^{-1})	P3 (cm^{-1})	P4 (cm^{-1})	P5 (cm^{-1})	P6 (cm^{-1})	Avg. Permeate (cm^{-1})	Rejection %
N	5/1/00	0.1936	0.1883	0.1880	0.1858	0.1878	0.1897	0.2011	0.1901	1.8
O	5/4/00	0.2030	0.1953	0.1969	0.1966	0.1962	0.1945	0.2264	0.2010	1.0
O	5/9/00	0.1884	0.1671	0.1667	0.1752	0.1766	0.1763	0.1715	0.1722	8.6

Sample Calculation of UV_{254} Rejection using Exp. J (2/17/00) data:

$$\%\,\mathrm{Re}\,jection = \frac{Feed - Avg.Permeate}{Feed} \times 100\% = \frac{.1865 - .1798}{.1865} \times 100\% = 3.6\%$$

Table C-5: Raw TOC and Rejection Data

Exp. ID	Date	Feed (mg/l)	P1 (mg/l)	P2 (mg/l)	P3 (mg/l)	P4 (mg/l)	P5 (mg/l)	P6 (mg/l)	Avg. Permeate (mg/l)	Rejection %
B	9/13/99	8.8	n.a.	9.0	9.1	8.9	9.0	9.2	9.0	-2.0
B	9/20/99	9.5	9.0	8.0	9.0	8.9	9.0	9.3	8.7	8.5
B	9/26/99	8.2	8.4	8.8	9.0	8.9	8.9	9.3	8.9	-8.9
C	9/28/99	6.1	3.9	7.3	9.4	8.4	8.6	8.3	8.4	-38.7
E	11/8/99	n.a.	7.1	6.2	10.3	7.2	6.1	5.7	7.5	n.a
E	11/13/99	5.2	n.a.	5.4	5.4	5.4	5.1	5.2	5.3	-2.8
F	11/30/99	9.0	8.9	8.9	8.8	9.1	9.1	9.1	9.0	0.2
F	12/4/99	8.9	8.5	8.4	8.7	8.4	8.6	8.5	8.5	4.5
F	12/9/99	9.5	9.5	9.4	9.5	9.1	9.2	9.0	9.3	2.0
G	12/13/99	8.5	8.3	8.1	8.0	8.0	8.2	8.7	8.1	5.1
G	12/18/99	n.a.	n.a.	n.a.	8.6	8.7	8.4	8.6	8.5	n.a
G	12/24/99	8.6	8.2	8.5	8.3	8.2	8.6	8.3	8.4	1.8
H	1/7/00	7.7	9.5	8.8	8.3	8.1	8.1	7.9	8.3	-7.8
H	1/12/00	7.2	7.2	7.0	7.2	7.5	7.1	7.2	7.2	-0.4
H	1/17/00	5.2	n.a.	n.a.	7.1	6.9	7.0	7.1	7.0	-36.2
I	1/28/00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
I	2/7/00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
J	2/13/00	n.a.	6.4	6.4	7.2	6.3	6.2	6.2	6.5	n.a.
J	2/17/00	7.6	9.6	7.4	7.3	7.5	7.3	7.3	7.4	3.0
J	2/22/00	7.2	7.2	7.5	7.4	7.6	7.6	7.5	7.5	-4.2
L	3/14/00	9.4	8.6	8.9	8.8	9.1	9.1	9.2	9.0	4.3
L	3/21/00	7.9	7.7	7.8	7.6	7.9	7.8	7.4	7.8	2.2
M	3/22/00	7.9	8.6	9.3	7.6	7.8	8.0	9.6	8.2	-3.7

***Water Quality Analysis was not performed for experiments A, D, and K.**

Exp. ID	Date	Feed (mg/l)	P1 (mg/l)	P2 (mg/l)	P3 (mg/l)	P4 (mg/l)	P5 (mg/l)	P6 (mg/l)	Avg. Permeate (mg/l)	Rejection %
M	3/25/00	8.4	6.8	7.1	6.8	n.a.	n.a.	n.a.	7.0	17.2
N	4/25/00	7.3	7.3	7.4	7.5	7.7	7.5	7.7	7.5	-3.8
N	5/1/00	7.6	7.6	7.5	7.3	7.3	7.5	7.8	7.4	3.0
O	5/4/00	7.8	7.3	7.3	7.4	7.4	7.3	7.5	7.4	6.1
O	5/9/00	7.5	6.8	n.a	7.0	7.0	7.2	6.9	7.1	5.1

Sample Calculation of TOC Rejection using Exp. F (12/14/99) data:

$$\%\,\mathrm{Re}\,jection = \frac{Feed - Avg.Permeate}{Feed} \times 100\% = \frac{8.9 - 8.5}{8.9} \times 100\% = 4.5\%$$

Table C-6: Raw HPC and Rejection Data

Exp. ID	Date	Feed (CFU/ml)	P1 (CFU/ml)	P2 (CFU/ml)	P3 (CFU/ml)	P4 (CFU/ml)	P5 (CFU/ml)	P6 (CFU/ml)	Avg. Permeate (CFU/ml)	LRV
B	9/13/99	1.60E+05	2.50E+05	4.90E+05	7.90E+05	6.00E+04	1.30E+05	9.60E+05	4.47E+05	-0.4
B	9/23/99	2.50E+06	2.00E+01	6.00E+01	7.20E+02	2.60E+03	6.00E+04	8.50E+04	2.47E+04	2.0
C	9/28/99	1.60E+06	4.40E+01	1.20E+01	5.00E+00	4.90E+01	1.80E+01	2.00E+00	2.17E+01	4.9
E	11/8/99	1.90E+05	1.40E+03	9.40E+02	7.60E+02	1.70E+03	1.80E+03	2.50E+03	1.52E+03	2.1
F	11/29/99	1.10E+07	6.00E+03	9.00E+03	1.30E+04	3.00E+03	8.00E+03	5.00E+03	7.33E+03	3.2
F	12/9/99	5.00E+05	2.80E+02	2.90E+02	5.90E+02	5.40E+02	5.00E+02	4.00E+02	4.33E+02	3.1
G	12/13/99	4.00E+05	5.60E+02	5.00E+03	3.00E+03	3.00E+03	7.00E+03	1.84E+03	3.40E+03	2.1
H	1/7/00	2.80E+06	2.30E+03	1.10E+03	9.00E+02	1.60E+03	9.10E+02	6.60E+02	1.25E+03	3.4
H	1/17/00	4.30E+04	n.a.	n.a.	2.00E+01	2.00E+01	3.00E+01	2.70E+02	8.50E+01	2.7
I	1/24/00	3.20E+05	1.80E+03	6.40E+03	3.00E+02	1.20E+02	1.70E+03	1.50E+03	1.97E+03	2.2
I	2/7/00	1.10E+05	n.a.	n.a.	7.00E+01	4.00E+00	9.00E+02	6.70E+02	4.11E+02	2.4
J	2/17/00	1.30E+06	2.00E+03	7.60E+03	1.80E+03	1.70E+03	1.00E+03	1.30E+03	2.57E+03	2.7
J	2/22/00	9.10E+05	3.00E+01	4.00E+01	1.10E+02	8.00E+01	9.00E+01	4.40E+03	7.92E+02	3.1
L	3/15/00	1.10E+06	9.00E+02	1.90E+03	4.70E+04	7.00E+02	5.00E+03	1.80E+04	1.23E+04	2.0
M	3/22/00	8.70E+05	7.60E+02	4.20E+03	1.40E+03	7.20E+02	8.70E+02	5.70E+02	1.42E+03	2.8
N	4/25/00	5.00E+05	1.70E+02	2.30E+03	2.80E+03	2.00E+03	2.10E+03	3.00E+03	2.06E+03	2.4
O	5/4/00	5.20E+05	2.60E+02	7.90E+02	5.90E+02	2.70E+02	9.50E+02	5.40E+02	5.67E+02	3.0

***Water Quality Analysis was not performed for experiments A, D, and K**

Sample Calculation of HPC LRV using Exp. C (9/28/99) data:

$$LRV = -\log_{10}\left(\frac{Avg.permeate}{Feed}\right) = -\log_{10}\left(\frac{2.17E+01}{1.60E+06}\right) = 4.9$$

Table C-7: Raw Coliform and Rejection Data

Exp. ID	Date	Feed (CFU/100ml)	P1 (CFU/100ml)	P2 (CFU/100ml)	P3 (CFU/100ml)	P4 (CFU/100ml)	P5 (CFU/100ml)	P6 (CFU/100ml)	Avg. Permeate (CFU/100ml)	LRV
B	9/13/99	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC	n.a.
B	9/23/99	6.30E+03	0.00E+00	0.00E+00	0.00E+00	4.00E+02	8.00E+02	1.10E+03	3.83E+02	1.2
C	9/28/99	TNTC	3.00E+00	3.00E+00	1.00E+00	1.00E+00	1.00E+00	0.00E+00	1.50E+00	*6.1
E	11/8/99	4.00E+02	2.00E+00	6.00E+00	5.00E+00	6.00E+00	7.00E+00	7.00E+00	5.50E+00	1.9
F	11/29/99	2.00E+02	1.00E+00	5.00E+00	neg.	neg.	3.00E+00	neg.	3.00E+00	1.8
F	12/9/99	2.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**inf.
G	12/13/99	2.00E+05	0.00E+00	0.00E+00	1.00E+03	0.00E+00	1.00E+03	2.00E+03	6.67E+02	2.5
H	1/7/00	2.00E+06	0.00E+00	0.00E+00	1.00E+04	0.00E+00	0.00E+00	0.00E+00	1.67E+03	3.1
H	1/17/00	1.00E+05	n.a.	n.a.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**inf.
I	1/24/00	3.00E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**inf.
I	2/7/00	3.00E+05	n.a.	n.a.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**inf.
J	2/17/00	1.00E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**inf.
J	2/22/00	2.00E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.00E+02	3.33E+01	4.8
L	3/15/00	2.00E+03	0.00E+00	0.00E+00	2.00E+00	0.00E+00	0.00E+00	0.00E+00	3.33E-01	3.8
M	3/22/00	1.00E+03	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.67E-01	3.8
N	4/25/00	2.00E+03	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	1.67E-01	4.1

***Water Quality Analysis was not performed for experiments A, D, K and O. **Infinite rejection.**

Sample Calculation of Total Coliform LRV using Exp. N (4/25/00) data:

$$LRV = -\log_{10}\left(\frac{Avg.permeate}{Feed}\right) = -\log_{10}\left(\frac{1.67E-01}{2.00E+03}\right) = 4.1$$

APPENDIX D: CLEAN WATER FLUX PROFILES

Table D-1: Pre-Experimental Clean Water MTC Values

Exp. ID	MTC Values Based On Clean Water Flux Profiles						% Recovery of New Membrane MTC					
	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
New	13.5	18.1	20.2	17.3	19.7	20.0	100%	100%	100%	100%	100%	100%
A	12.3	16.1	19.7	15.7	19.3	17.9	91%	89%	97%	91%	98%	90%
B	8.0	9.7	11.8	9.8	10.7	9.5	59%	54%	58%	57%	54%	47%
C	8.5	10.6	12.8	10.5	11.4	9.2	63%	59%	63%	61%	58%	46%
D	16.8	15.4	16.0	15.0	10.1	15.7	124%	85%	79%	86%	51%	78%
E	15.1	17.3	17.0	15.0	20.9	12.5	112%	96%	84%	87%	106%	63%
F	13.3	15.3	22.1	14.5	17.5	18.8	99%	85%	109%	84%	88%	94%
G	12.0	15.1	21.5	14.7	17.1	15.6	89%	83%	107%	85%	86%	78%
H	16.3	20.0	32.5	20.7	26.5	23.0	121%	111%	161%	120%	134%	115%
I	13.2	16.0	15.0	17.9	21.8	13.8	98%	89%	74%	103%	111%	69%
J	14.7	17.6	31.5	17.9	24.9	18.1	109%	98%	156%	103%	126%	91%
K	12.3	16.2	25.9	16.6	20.6	16.6	91%	90%	128%	96%	104%	83%
L	13.8	16.8	25.3	16.8	21.3	16.2	102%	93%	125%	97%	108%	81%
M	13.6	14.6	25.1	15.9	16.4	14.7	101%	81%	124%	92%	83%	74%
N	14.5	16.7	25.8	19.8	27.3	15.9	107%	93%	128%	114%	138%	80%
O	14.6	16.4	21.2	15.1	21.4	14.3	108%	91%	105%	87%	108%	71%

Sample Calculation of % Recovery of New MTC value using Experiment A (Membrane #1) data:

$$\%\,\text{Recovery} = \frac{MTC_{pre-\exp(A)}}{MTC_{new}} = \frac{12.3 GFD/psi}{13.5 GFD/psi} \times 100 = 91\%$$

APPENDIX E: MULTIPLE LINEAR REGRESSION STATISTICS

Table E-1: Summary Output and ANOVA Results for Model A1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.829177403
R Square	0.687535165
Adjusted R Square	0.647359106
Standard Error	0.159500421
Observations	61

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	3.134768394	0.626954	24.64403	6.20422E-13
Residual	56	1.424661513	0.02544		
Total	61	4.559429906			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X1	-1.13E-02	0.002461655	-4.605693	2.41E-05	-0.01626891	-0.00640634
X2	1.57E-06	1.51633E-07	10.34051	1.34E-14	1.26421E-06	1.87172E-06
X3	7.34E-02	0.014591979	5.028104	5.42E-06	0.044138756	0.10260121
X4	4.49E-11	5.78095E-11	0.777058	0.440394	-7.08849E-11	1.60728E-10
X6	-2.33E-02	0.003190946	-7.302199	1.1E-09	-0.029693153	-0.0169087

Table E-2: Summary Output and ANOVA Results for Model A2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.827143285
R Square	0.684166014
Adjusted R Square	0.649999313
Standard Error	0.158945148
Observations	61

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	3.119406983	0.779852	30.86864022	1.39282E-13
Residual	57	1.440022923	0.025264		
Total	61	4.559429906			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X1	-1.01E-02	0.001915094	-5.295951	1.97805E-06	-0.013977159	-0.006307
X2	1.55E-06	1.49236E-07	10.38279	9.3203E-15	1.25065E-06	1.85E-06
X3	6.68E-02	0.011810106	5.652353	5.29723E-07	0.043105552	0.090404
X6	-2.22E-02	0.002879283	-7.727144	1.95364E-10	-0.028014305	-0.016483

Table E-3: Summary Output and ANOVA Results for Model B1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.867836738
R Square	0.753140604
Adjusted R Square	0.660568331
Standard Error	0.01329166
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	0.008623922	0.00143732	8.135703889	0.000378496
Residual	16	0.002826691	0.000176668		
Total	22	0.011450613			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Rm0	6.99E-02	0.005103671	13.69634411	2.96E-10	0.059082337	0.08072093
X1	6.91E-04	0.001851063	0.373095508	7.14E-01	-0.003233455	0.004614701
X2	-1.40E-07	3.20279E-08	-4.378121971	4.68E-04	-2.08118E-07	-7.23259E-08
X3	3.09E-03	0.004801313	0.644344661	5.28E-01	-0.007084626	0.013272026
X4	-4.89E-10	1.17065E-09	-0.417691273	6.82E-01	-2.97064E-09	1.9927E-09
X5	1.09E-04	9.77684E-05	1.114109896	2.82E-01	-9.8335E-05	0.000316185
X6	-3.13E-03	0.005238733	-0.597007179	5.59E-01	-0.014233176	0.007978054

Table E-4: Summary Output and ANOVA Results for Model B2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.866598479
R Square	0.750992924
Adjusted R Square	0.677755548
Standard Error	0.012950775
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	0.008599329	0.00172	10.25423	0.000115682
Residual	17	0.002851284	0.000168		
Total	22	0.011450613			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Rm0	6.96E-02	0.004923877	14.14236	7.85E-11	0.059246759	0.080023735
X2	-1.45E-07	2.88366E-08	-5.021036	1.05E-04	-2.0563E-07	-8.39497E-08
X3	3.98E-03	0.004069394	0.97738	3.42E-01	-0.004608337	0.012563028
X4	-1.57E-10	7.41482E-10	-0.211849	8.35E-01	-1.72147E-09	1.40731E-09
X5	8.41E-05	6.98494E-05	1.204329	2.45E-01	-6.32479E-05	0.000231491
X6	-1.45E-03	0.002622156	-0.553219	5.87E-01	-0.0069829	0.004081647

Table E-5: Summary Output and ANOVA Results for Model B3

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.866219108
R Square	0.750335542
Adjusted R Square	0.694854552
Standard Error	0.012602493
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	0.008591802	0.002148	13.52419	2.92201E-05
Residual	18	0.002858811	0.000159		
Total	22	0.011450613			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Rm0	6.94E-02	0.004674576	14.8476	1.53E-11	0.059585323	0.079227178
X2	-1.42E-07	2.36724E-08	-5.977827	1.18E-05	-1.91243E-07	-9.17755E-08
X3	3.13E-03	0.000680136	4.599163	2.23E-04	0.001699144	0.004556972
X5	6.97E-05	1.58753E-05	4.392557	3.51E-04	3.63805E-05	0.000103086
X6	-9.02E-04	0.000414294	-2.178393	4.29E-02	-0.001772896	-3.20953E-05

APPENDIX F: MODEL VERIFICATION STATISTICS

Table F-1: Model A2 Verification of Element Two Operational Data

SUMMARY OUTPUT

Regression Statistics	
Multiple R	65535
R Square	-0.19686782
Adjusted R Square	-0.213816973
Standard Error	0.138817081
Observations	60

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	-0.187010664	-0.187010664	-9.704665132	#NUM!
Residual	59	1.136940744	0.019270182		
Total	60	0.94993008			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
R_T actual	0.534063636	0.068959847	7.744559491	1.48084E-10	0.396075156	0.672052115

Table F-2: Model A2 Verification of Element Six Operational Data

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.847284595
R Square	0.717891185
Adjusted R Square	0.700942032
Standard Error	0.156358251
Observations	60

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.67058752	3.67058752	150.1391578	9.85557E-18
Residual	59	1.442426259	0.024447903		
Total	60	5.113013779			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
R_T actual	0.968556311	0.063587351	15.23190219	4.139E-22	0.841318182	1.09579444

Table F-3: Model A2 t-Test Results of Element Six Operational Data

t-Test: Paired Two Sample for Means

	R_T *actual*	R_T *predicted*
Mean	0.182646791	0.18757228
Variance	0.08666125	0.066249635
Observations	60	60
Pearson Correlation	0.847284917	
Hypothesized Mean Difference	0	
df	59	
t Stat	-0.2436924	
P(T<=t) one-tail	0.404157216	
t Critical one-tail	1.671091923	
P(T<=t) two-tail	0.808314431	
t Critical two-tail	2.000997483	

Table F-4: Model B3 Verification of Element Two Operational Data

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.875943058
R Square	0.767276242
Adjusted R Square	0.721821696
Standard Error	0.011551716
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.009678916	0.009678916	72.53267753	2.97677E-08
Residual	22	0.002935727	0.000133442		
Total	23	0.012614643			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
R_T actual	0.979603412	0.026668275	36.73291195	3.0703E-21	0.924296735	1.03491009

Table F-5: Model B3 Verification of Element Six Operational Data

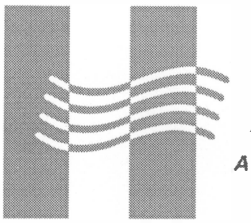
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.764804917
R Square	0.58492656
Adjusted R Square	0.539472015
Standard Error	0.017678938
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.009689724	0.009689724	31.00266868	1.58848E-05
Residual	22	0.006875986	0.000312545		
Total	23	0.01656571			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
R_T actual	0.898854041	0.038930463	23.0887067	6.4938E-17	0.818117115	0.979590966



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Hydranautics Testing
at San Luis Rey Wastewater Treatment Plant
Oceanside, California
December 1999 – February 2000

Final Report

Contract No. 98-FC-81-0060

RS30-4S at San Luis Rey WWTP, Oceanside, CA
Operating on Secondary Treated Wastewater
December 1999 – February 2000

Testing Objectives

The goal of this testing was to obtain stable operating data on secondary treated wastewater and compare the performance of RS30-4S to HYDRAcap, running side by side on the same feed.

Test Conditions

Testing started December 6th, 1999 with two brand new RS30-4S backwashable spiral UF membrane elements. Both elements were bubble tested prior to installation into the pilot unit. In order to simulate the intended process configuration, the pilot unit was reconfigured to remove filtrate from the bottom of the pressure vessel. First 36 hours of operation were on Oceanside City water to establish original filtrate flow profile data. Test conditions for both tap water and intended process water are listed in Table 1.

Table 1. Operating Conditions.

	Tap water	**Waste Water**
Element Type	RS30-4S	RS30-4S
Element Size	4" diameter	4" diameter
Membrane Area	80 sq. ft per element	80 sq. ft per element
Number of Elements	2	2
Target Operating Flux	26.75	26.75 gfd
Total Filtrate Recovery	90%	90% (80% after 05Jan00)
Backwash Flux	35 gfd	35 gfd
Backwash Pressure		17 psi
Backwash Frequency	10 min	10 min
Total Backwash Duration	61 sec	61 sec
Forward Flush Duration	9 sec	9 sec
Backwash Top Duration	0	0 sec
Backwash Bottom Duration	20	20sec
Backwash Top/Bottom Duration	0	0 sec
Soak	20 sec	20 sec
Rinse	12 sec	12 sec
Backwash Effluent Free Chlorine		1.0 to 3.5 ppm
NaOCl dosing rate		250 ppm
Prefilter Micron Rating	50	50
NaOCl Concentration in Sump	12.5 %	12.5 %

Description of RS30-4S Pilot Unit Layout/Operation

The secondary wastewater is pumped up from the intake location via a submersible pump to the pilot unit, located about 20 ft away. The unit has two RS30-4S membrane modules connected in parallel, each in its own pressure vessel. One of the pressure vessels is fiberglass to allow visual inspection of the membrane module as needed.

vessel. One of the pressure vessels is fiberglass to allow visual inspection of the membrane module as needed. Both modules are vertically mounted. An 80um prefilter prevents larger particles from getting into the modules and plugging up spaces between membrane leaves. Also included are: one feed and one backwash pump, actuated valves, a control panel with PLC to control backwash frequency and duration, filtrate holding tank, chlorine metering pump and week storage tank. Flow and pressure are monitored with flow meters and pressure gauges. Feed and filtrate turbidity is measured by inline turbidity meters. Figure 1 shows a photograph this pilot unit.

The following is a description of steps involved in pilot operation:

Processing: Feed water from the intake location via transfer pump is introduced through the prefilter into the pressure vessel, where it goes through the membrane and is taken out of the filtrate line. System operates in direct flow mode, meaning there is no concentrate stream. All the feed water introduced into the pressure vessel leaves as product.

Forward Flush: High turbidity concentrate in the pressure vessel is replaced with high velocity feed water. No filtrate is made during this step. The purpose of this step is to remove particulate matter off the surface of the membrane. Replacing high turbidity concentrate in the vessel with feedwater also helps reduce chlorine consumption in the next step.

Backwash Bottom: Filtrate water from the filtrate tank via backwash pump goes through the filtrate side to the feed side of the membrane module and then to drain (Backwash effluent is removed from the bottom of the pressure vessel). Chlorine is dosed into the filtrate by the dosing pump. By

Soak: All the valves are closed. Chlorinated filtrate water is in the pressure vessel. The purpose of this step is to allow a longer contact time for chlorine to take effect.

Rinse: Same as backwash, except without chlorine dosing.

Figure1.

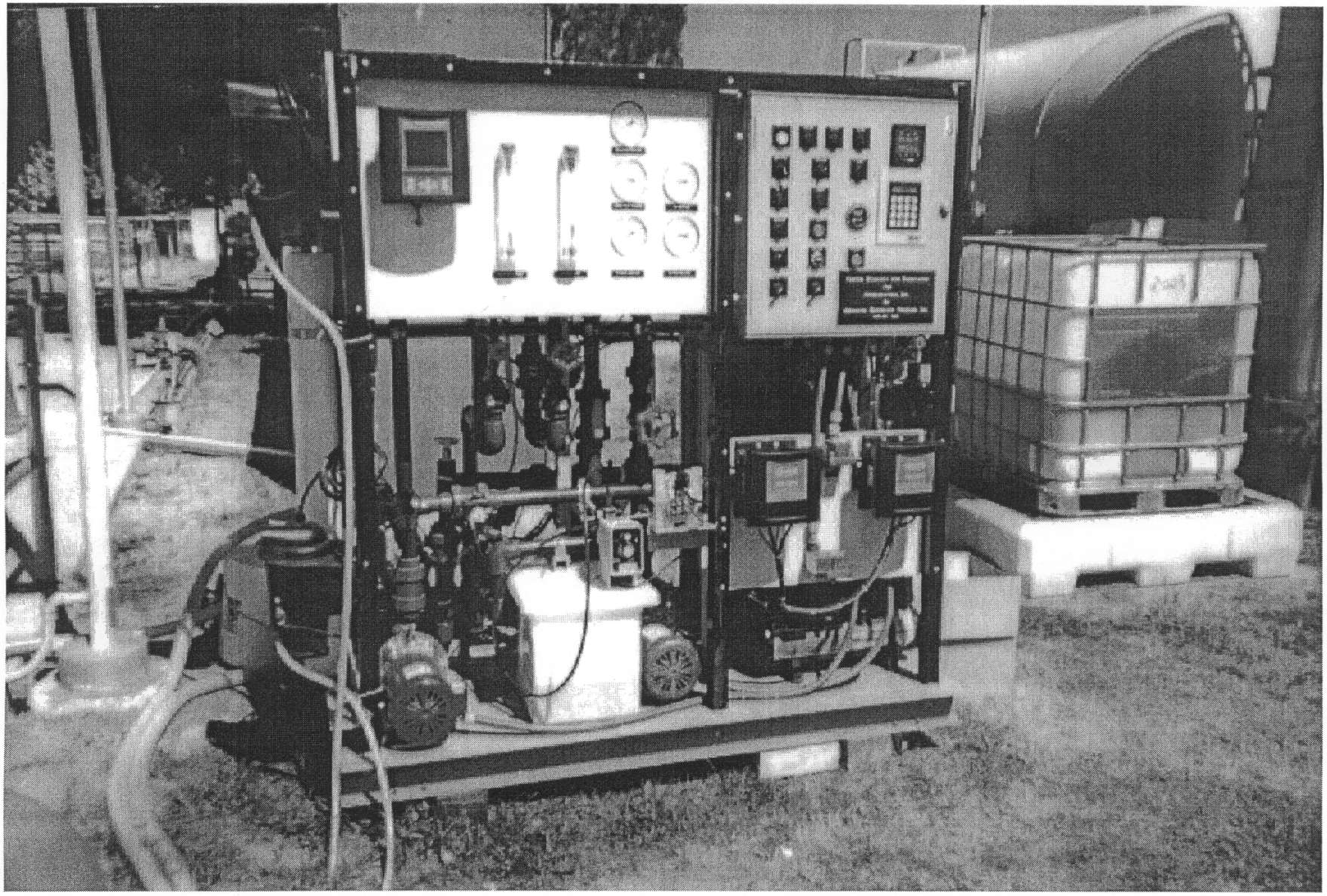


Table 2 contains process water analysis.

Table 2. San Luis Rey WWTP Secondary Effluent (collected 03/03/99)

Analyte	Units	Result
Chloride	mg/L	268
Nitrite as N		<0.30
Nitrate as N		11.1
Sulfate		234
Boron		0.472
Calcium		83.0
Iron		0.04
Magnesium		28.6
Manganese		.033
Phosphorous		.622
Potassium		14.4
Silicon		6.10
Sodium		184
% Volatile Suspended Solids	%	98
Carbonaceous BOD – 5 day	mg/L	5
Chlorine presence/absence	---	Present
Conductivity	umhos/cm	1630
Fluoride	mg/L	0.42
Methylene Blue Active Substance		.09
Ammonia in WW		10.8
pH	pH	6.91
Total Alkalinity	mg/L as $CaCO_3$	115
Total Dissolved Solids	mg/L	974
Total Suspended Solids		6.3
Volatile Suspended Solids		6.2

RS30-4S Cleaning Procedure

Cleaning procedure used was developed during previous series of RS30-4S tests at Oceanside. Since most of the foulants encountered in secondary treated wastewater are of the organic nature, high pH solution does most of the work in cleaning the membrane. Low pH solution cannot be eliminated, though, because high pH solution is not as effective by itself, as opposed to when it is preceded by low pH. It is likely that the removal of inorganic foulants by low pH solution loosens up organic constituents of fouling and prepares the way for high pH cleaner.

Cleaning procedure remained the same for all the cleanings. Cleanings were done in a backwash mode with all other steps set to zero. Regular backwash flux equal to 1.5 x product flux was used. 50 gal of 2% citric acid solution in tap water followed by 100 gal of 0.25% NaOH with 250 ppm sodium hypochlorite dosing were the two steps involved in cleaning. In between low and high pH cleanings the modules were rinsed with clean city water, also in a backwash mode.

RS30-4S Integrity Test

Integrity test for this pilot unit was developed based on the various tests performed on one of the elements (RS30-4S 9042033). The results are summarized in Test Report TS-99-05 of 29Nov99. The theory behind the pressure hold test is that wet membrane should not be permeable to air due to the surface tension forces of water inside the membrane pores. If the pores are small enough, the water in the pores should keep the air from escaping. By measuring the air escape rate, the actual pore size can be calculated. Knowing the pore size, molecular weight cutoff (MWCO) is set as the size of the smallest particle 90% of which is going to be rejected by the membrane.

Currently, the integrity test consists of bubble testing of elements involved prior to installation, inline pressure hold test, and, if necessary, air passage rate measurement to determine membrane pore size and virus rejection characteristics. During the bubble test core tube of submerged element is pressurized with air to 5 psi. The bubble streams observed should become weaker and disappear with time. Pressure change over 3 min. of time should not be greater than 1 psi. Both of RS30-4S elements involved in this testing had passed successfully.
Inline pressure hold test involves pressurising the filtrate side with air to 5 psi and monitoring pressure decay over 3 minutes. As long as the pressure is greater than 3 psi at the end of 3 min, good integrity is assumed. Together, elements used in this test failed pressure hold test at the end of testing at Oceanside.
Air passage rate is measured by keeping the pressure on the feed side of a module at 5 psi and capturing the air that escapes out of the filtrate side. This test is done offline on separate equipment. All the tests require that the elements are thoroughly wetted.

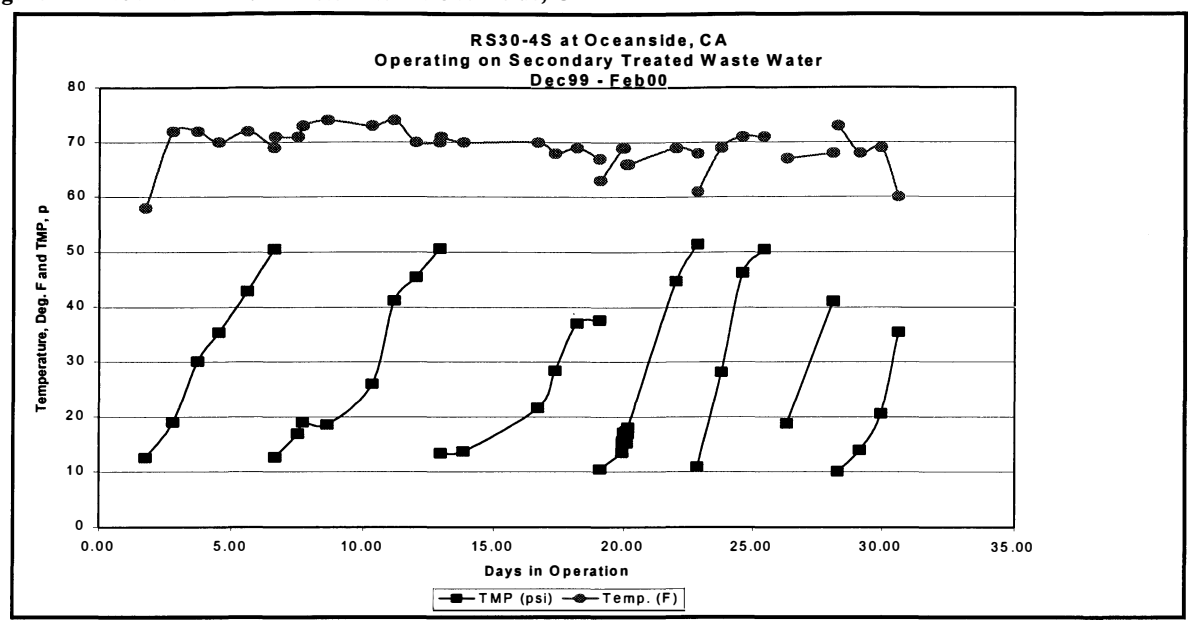
Schedule of Events

06Dec99 – Start of operation with city water feed
13Dec99 – Start operation on wastewater
21Dec99 – Cleaning
29Dec99 – Cleaning
05Jan00 – Cleaning. Recovery set at 80% to match HYDRAcap unit.
06Jan00 – Low feed pressure. Cleaning attempted.
07Jan00 – Unit found shut down due to low feed pressure. Prefilter clogging seems to be the problem. Prefilter cleaned. Another cleaning attempted.
11Jan00 – Cleaning
14Jan00 – Cleaning
24Jan00 – Cleaning
01Feb00 – Cleaning
04Feb00 – End of testing at Oceanside

RS30-4S Results

During operation it was necessary to clean the unit every five to seven days to maintain the desired flux rate. Transmembrane pressure and its corresponding temperature data are in Figure 2.

Figure 2. RS30-4S TMP on Wastewater at Oceanside, CA.



Turbidity of the filtrate was greater than desired, but when compared with the feedwater turbidity the reduction was still significant. Please refer to Figure 3 for further detail.

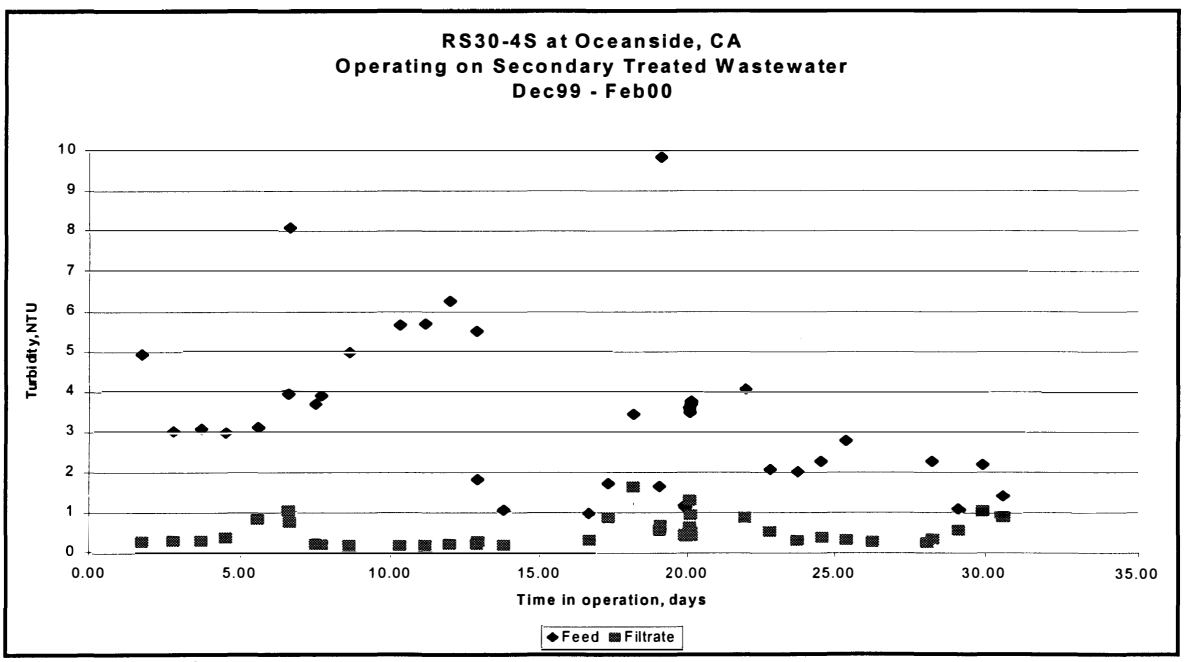


Figure 3. Turbidity of RS30-4S Feed and Filtrate at Oceanside, CA.

After each cleaning, transmembrane pressures were recorded at 2, 3, 4, 6, and 8 gpm of filtrate flow. The results were compared with those of a brand new membrane. If a close match between the two profiles is achieved, it is said that the membrane is clean enough be begin another run.
Each of the cleanings was able to restore flux close to its original values. Available filtrate flow profiles are plotted in Figure 4 below.

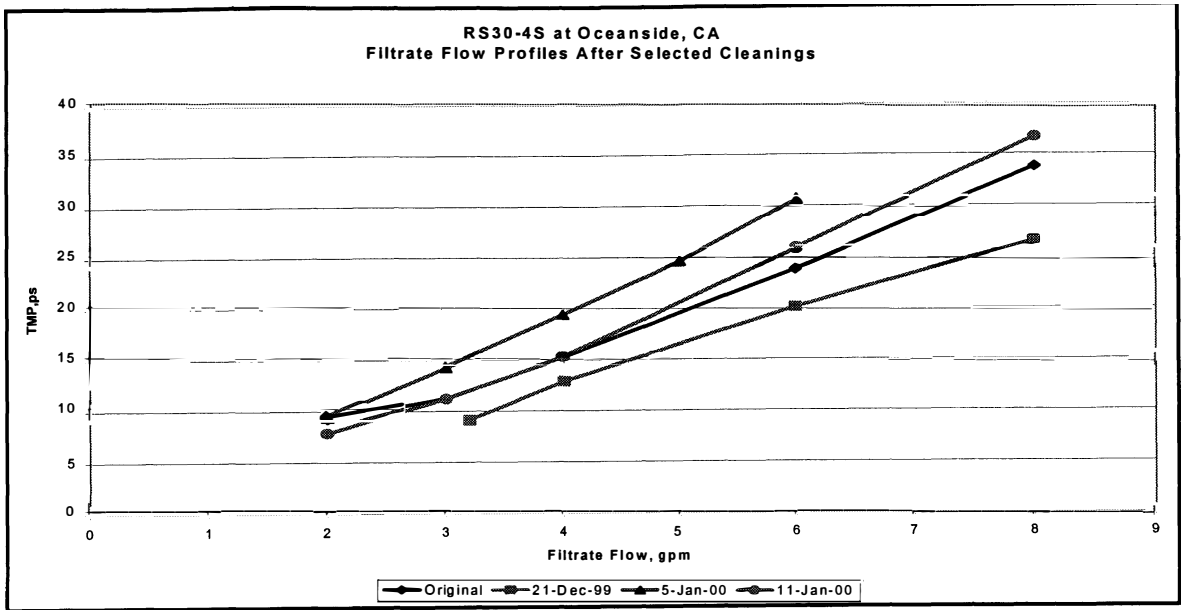


Figure 4. RS30-4S Cleaning Results at Oceanside, CA.

Out of 49 days that this unit was available, 9 days were spent off line due to the membrane fouling. Figure 5 shows unit availability versus time in operation each day.

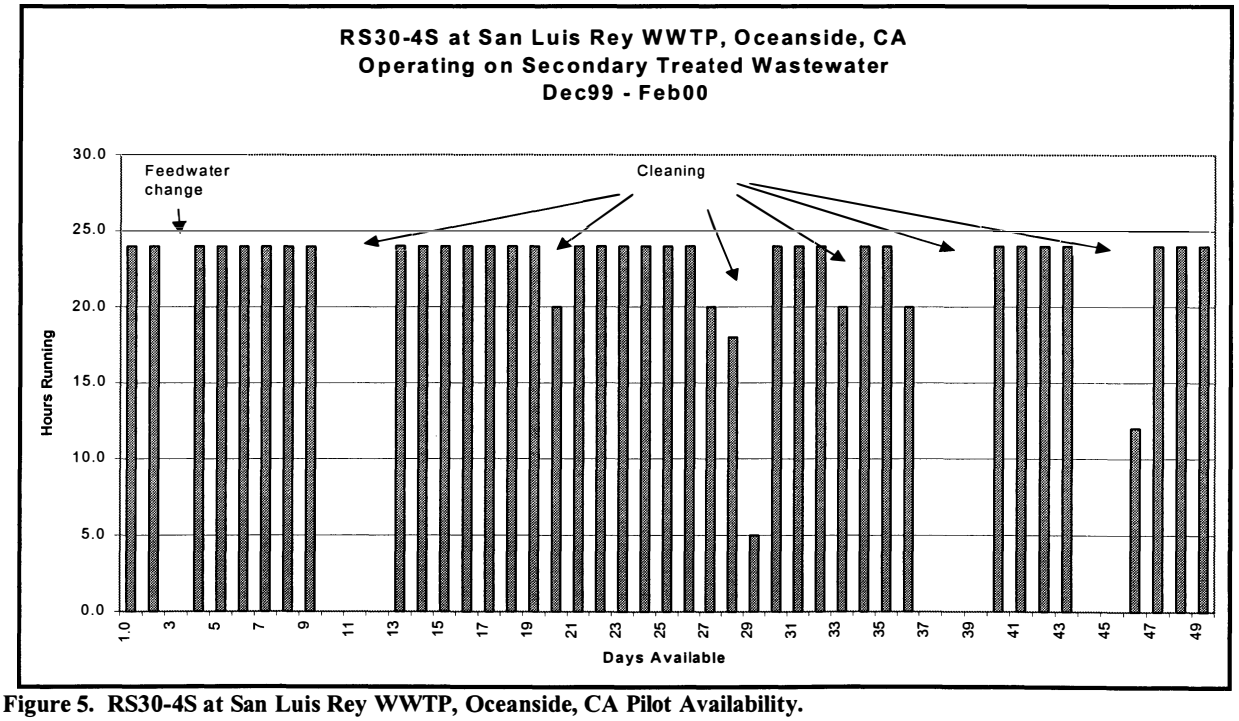


Figure 5. RS30-4S at San Luis Rey WWTP, Oceanside, CA Pilot Availability.

Table 3. RS30-4S Field Results.

				Pressures, PSI						Turbidity				
Date	Hours	Days in Operation	Temp F	Screen	Top	Bottom	Filt	TMP	GPM Filtr	Feed	Filtr.	Flux, gfd	Sp. Flux	Cl in BW
12/6/99	7201.4	0.06	64	11	9	11	0.2	9.8	3.5	0.127	0.089	31.21	3.18	4
12/7/99	7217.5	0.73	55	16	14	15	1.9	12.6	3			26.75	2.12	
12/13/99	7242.2	1.76	58	14.1	12.1	14	0.5	12.55	3.5	4.942	0.263	31.21	2.49	3
12/14/99	7267.1	2.80	72	19.5	18.3	19.7	0	19	3	3.029	0.268	26.75	1.41	3
12/15/99	7289.3	3.72	72	30.5	29.5	30.7	0	30.1	3	3.092	0.279	26.75	0.89	0.45
12/16/99	7308.5	4.52	70	35.5	36	34.8	0	35.4	3	2.999	0.354	26.75	0.76	0.3
12/17/99	7334.4	5.60	72	42.5	42.1	43.7	0	42.9	3	3.13	0.816	26.75	0.62	1.2
12/18/99	7358.7	6.61	69	49.8	50	51	0	50.5	2.4	3.921	1.019	21.40	0.42	1.2
12/21/99	Cleaning													
12/22/99	7359.7	6.65	71	13.5	11.8	13.5	0	12.65	4.3	8.085	0.734	38.34	3.03	1.2
12/23/99	7380.5	7.52	71	17.2	16.2	17.7	0	16.95	3	3.669	0.185	26.75	1.58	0.1
12/23/99	7384.9	7.70	73	19.2	18.6	19.4	0	19	3	3.88	0.173	26.75	1.41	1
12/24/99	7407.4	8.64	74	18.9	17.9	19.3	0	18.6	3	4.99	0.157	26.75	1.44	2
12/26/99	7448	10.33	73	26	24.8	27.2	0	26	2.9	5.636	0.159	25.86	0.99	1
12/27/99	7468.3	11.18	74	41	40.5	41.9	0	41.2	3	5.672	0.157	26.75	0.65	2.5
12/28/99	7488.2	12.01	70	46	45	45.9	0	45.45	3	6.25	0.177	26.75	0.59	2
12/29/99	7509.9	12.91	70	50	50.2	51	0	50.6	1.8	5.484	0.179	16.05	0.32	2
12/29/99	Cleaning													
12/29/99	7511.1	12.96	71	13.7	12.6	14.2	0	13.4	3	1.798	0.254	26.75	2.00	2
12/30/99	7532.1	13.84	70	14.6	12.9	14.5	0	13.7	3	1.035	0.153	26.75	1.95	1.5
01/02/00	7600.5	16.69	70	22.2	21	22.3	0	21.65	3	0.983	0.285	26.75	1.24	2
01/03/00	7616.2	17.34	68	33.1	27.8	29	0	28.4	3	1.723	0.866	26.75	0.94	1.5
01/04/00	7636.3	18.18	69	48	36.5	37.6	0	37.05	3	3.434	1.635	26.75	0.72	2
01/05/00	7657.2	19.05	67	50.8	37.1	38.2	0	37.65	0.7	1.631	0.554	6.24	0.17	2
01/05/00	Cleaning													
01/05/00	7657.9	19.08	63	16	9.7	11.2	0	10.45	3	9.832	0.673	26.75	2.56	2
01/06/00	7678.2	19.93	69	29.2	12.8	14.2	0	13.5	3	1.174	0.458	26.75	1.98	1.3
01/06/00			0.75 liters caustic added to 20 gallons of water in the filtrate tank, and then backwashed.											
01/06/00	7678.7	19.95	69	30.1	14.7	16	0	15.35	3	1.131	0.435	26.75	1.74	
01/06/00			4 lbs. Citric acid added to 30 gallons of water in the filtrate tank, and then backwashed.											
01/06/00	7678.9	19.95	69	31.3	15	16.2	0	15.6	3	1.131	0.443	26.75	1.71	
01/06/00			Pre filter was cleaned											
01/06/00	7679.5	19.98	69	17.7	16.3	17.9	0	17.1	3	1.135	0.418	26.75	1.56	2
01/07/00			Found the unit shut down due to "low feed pressure"											
01/07/00	7682	20.08	66	18	16.7	18.1	0	17.4	3	3.613	0.505	26.75	1.54	2
01/07/00			1 liter of caustic added to 30 gallons water and normal chlorine levels during backwas											
01/07/00	7682.3	20.10	66	16.5	15	17	0	16	3	3.559	0.64	26.75	1.67	
01/07/00	7682.5	20.10	66	16	14.3	16.2	0	15.25	3	3.484	1.3	26.75	1.75	
01/07/00	7683.2	20.13	66	18.1	16.4	18.1	0	17.25	3	3.676	0.937	26.75	1.55	
01/07/00			4 pounds citric acid added to 30 gallons water and no chlorine during backwash.											
01/07/00	7683.3	20.14	66	17.8	16.2	17.7	0	16.95	3	3.698	0.52	26.75	1.58	
01/07/00	7683.5	20.15	66	18.9	17.2	18.9	0	18.05	3	3.762	0.426	26.75	1.48	2
01/09/00	7727.4	21.98	69	44.2	44	45.5	0	44.75	3	4.068	0.872	26.75	0.60	0.5
01/10/00	7747.9	22.83	68	50.8	51	51.8	0	51.4	1.5	2.072	0.523	13.37	0.26	
01/11/00	Cleaning													
01/11/00	7748.2	22.84	61	13	11.1	12.7	1	10.9	3			26.75	2.45	
01/12/00	7770.3	23.76	69	28.5	27.4	28.9	0	28.15	3	2.017	0.31	26.75	0.95	1.5
01/13/00	7790	24.58	71	45.7	45.7	46.7	0	46.2	3	2.278	0.382	26.75	0.58	
01/14/00	7810.1	25.42	71	49.8	50	50.9	0	50.45	2.5	2.805	0.328	22.29	0.44	2.5
01/14/00	Cleaning													
01/19/00	7831.5	26.31	67	20	19	20.6	1	18.8	3	33.57	0.264	26.75	1.42	
01/21/00	7874.8	28.12	68	41.2	41.2	42	0.5	41.1	3	52.64	0.246	26.75	0.65	0.3
01/24/00	Cleaning													
01/24/00	7879.1	28.30	73	13.8	12.1	14	3	10.05	3	2.268	0.335	26.75	2.66	0.5
01/25/00	7899.5	29.15	68	15.8	14.8	16.2	1.5	14	3	1.084	0.565	26.75	1.91	2
01/26/00	7918.9	29.95	69	20.8	20	21.2	0	20.6	3	2.207	1.051	26.75	1.30	1.5
1/27/00	7935	30.63	60	35.2	34.9	36	0	35.45	3	1.434	0.903	26.75	0.75	1.5

HYDRAcap Operation

HYDRAcap was ran on the same feed as RS30-4S, with 80% recovery, and chlorine dosing in every other backwash to achieve 3 to 5 ppm free chlorine in the effluent. After getting some initial data it was decided to use continuous ferric chloride dosing into the feed. As a result, TMP was immediately stable and run times of up to 30 days without cleaning were observed. Operating parameters for HYDRAcap are listed in Table 4.

Table 4. HYDRAcapOperating Conditions.

	Waste Water
Element Type	HYDRAcap
Element Size	8" diameter 40" long
Number of Elements	1
Target Operating Flux	43 gfd
Total Filtrate Recovery	80%
Backwash Flux	180 gfd
Backwash Pressure	25 - 35 psi
Backwash Frequency	20 min
Total Backwash Duration	95 sec
Forward Flush Duration	9 sec
Backwash Top Duration	12 sec
Backwash Bottom Duration	12 sec
Backwash Top/Bottom Duration	0 sec
Soak	99 sec
Rinse	12 sec
Backwash Effluent Free Chlorine	1.0 to 3.5 ppm
NaOCl dosing rate	200 ppm
Prefilter Micron Rating	80
NaOCl Concentration in Sump	12.5 %
Chlorination Frequency	Every 2 cycles
$FeCl_3$ Dosing into Feed	7 ppm (after 32 days in operation)

HYDRAcap Pilot Unit Layout/Operation

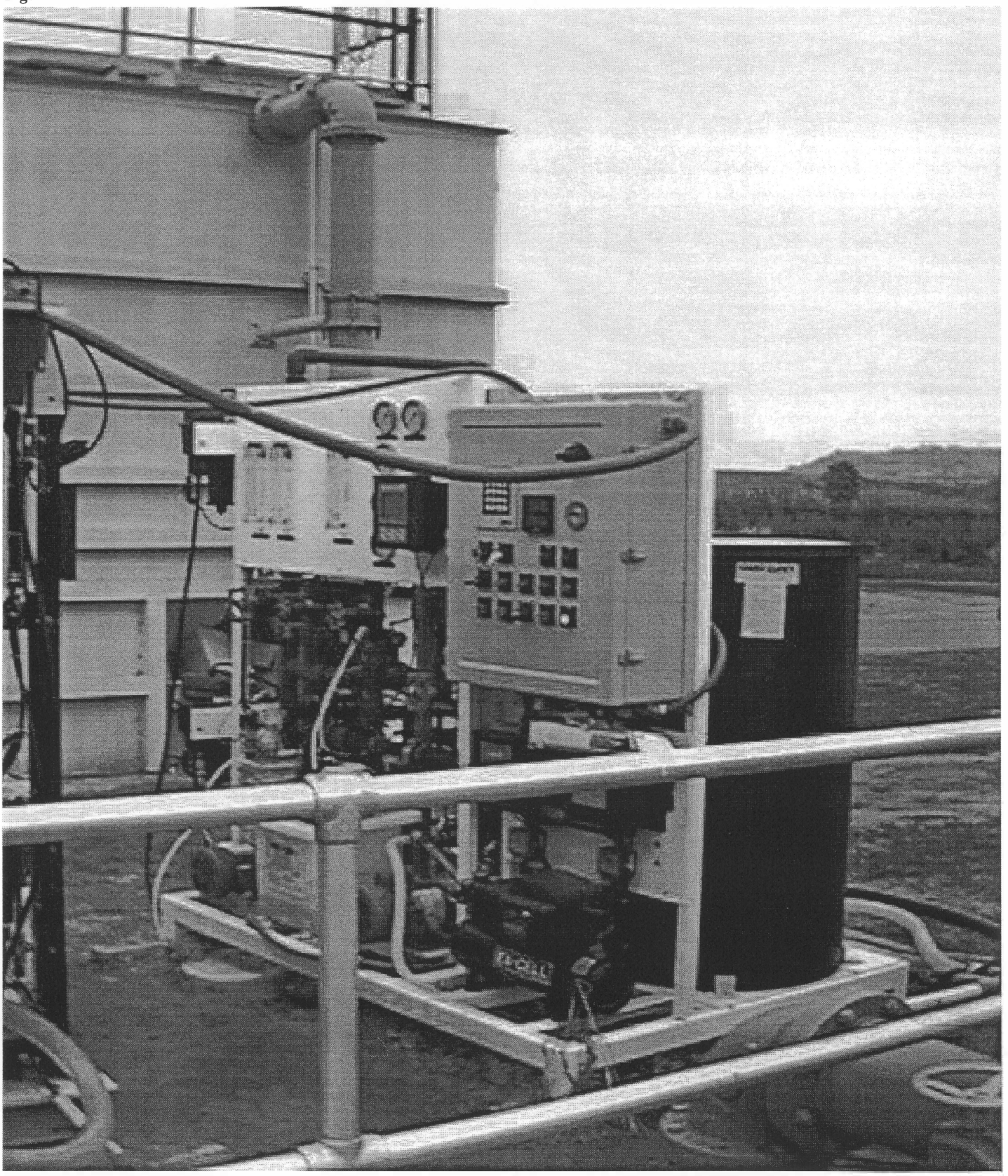
The secondary wastewater is pumped to a 100 gallon holding tank via a submersible pump. A float valve on the holding tank performs incoming wastewater flow control. Residence time in the holding tank is on the order of 15 minutes. The secondary wastewater in the holding tank feeds the HYDRAcap™ pilot system. The HYDRAcap UF pilot consists of a single 8" x 40" HYDRAcap™ membrane with ~10,000 0.08mm i.d. fibers. Flow through the capillaries is inside out; that is, feed water enters the center of the capillary tubes and filters through the wall and is collected outside the fibers. The capillary material is PolyEther Sulfone (PES). A 150um prefilter protects the fibers from irreversibly plugging. The unit consists of one UF modules mounted vertically; also included are: one feed and one backwash pump, actuated valves, a control panel with PLC to control backwash frequency and duration, filtrate holding tank, chlorine metering pump and week storage tank. Flow and pressure are monitored with flow meters and pressure gauges. A photograph of the UF pilot is in Figure 6.

Steps involved in HYDRAcap unit operation are similar to those of RS30-4S. With HYDRAcap, however, there is also a possibility of crossflow.

Crossflow: This mode is the similar to a standard reverse osmosis system in that a concentrate stream allows continuous removal of rejected matter. The unit was programmed to switch to crossflow mode of operation when the readout of feed turbidity meter reached 10 NTU.

The normal operation of this unit consisted of direct dead-end feed processing with backwashing every 20 min. Every other backwash was chlorinated and followed by soak and rinse sequence.

Figure 6.



HYDRAcap Cleaning Procedure

Cleaning is necessary when the Trans Membrane Pressure (TMP) rises to ~20psi. The unit has been cleaned by recirculating the following solutions through the feed side of the membranes with the filtrate valves closed for 45 minutes (10gpm), followed by the filtrate valves partially OPEN for 45 minutes (5gpm Xflow and 5gpm filtrate flow). The solutions are then backwashed to drain at the end of each cycle, followed by three backwashes with city.

Solution 1- 2% Citric Acid pH ~2.2 Solution 2- 0.5% NaOH+200ppm NaOClpH~12.5

The unit was cleaned using the above procedure seven times during the time period of interest. Every cleaning restored filtrate flow profile back to its original shape.

HYDRAcap Integrity Test

A visual bubble test/pressure hold was incorporated into the pilot unit to determine the integrity of the membrane. The theory behind the pressure hold test is that the feed side is drained and pressurized with air to 20 psias the filtrate side is left open to atmosphere. A broken fiber will allow a rapid escape of the pressurized air. This air can be seen if a clear piece of pipe or rotameter is included in the filtrate line leaving the module. HYDRAcap was tested for integrity after each cleaning. Failure was detected right after time period described here, at which point the element was replaced with a brand new one and operation resumed.

HYDRAcap Results

Tables 5 and 6 below contain analytical data obtained from San Luis Rey WWTP Lab on feed and filtrate streams.

Table 5. Analytical Results for Secondary Wastewater (from San Luis Rey WWTP Lab)

Analyte	Units	Result	MDL	MethodSM 5210B
Carbonaceous BOD – 5 day	mg/L	nd<2	0.4	
Chemical Oxygen Demand	mg/L	36		SM 18th 5220 D
Fe by ICP	mg/L	1.45		EPA200.7
Ammonia in WW by titration	mg/L	1.96		SM 4500-NH3 B,C
pH		6.84		SM 4500-H+B
TSS	mg/L	5.2	0.5	SM 2540 D

Table 6. Analytical Results for HYDRAcap Product Water (from San Luis Rey WWTP Lab)

Analyte	Units	Result	MDL	MethodSM 5210B
Carbonaceous BOD – 5 day	mg/L	nd<2	0.4	
Chemical Oxygen Demand	mg/L	30		SM 18th 5220 D
Fe by ICP	mg/L	0.062		EPA200.7
Ammonia in WW by titration	mg/L	1.98		SM 4500-NH3 B,C
pH		7.15		SM 4500-H+B
TSS	mg/L	nd<0.5	0.5	SM 2540 D

Figure 7 below illustrates HYDRAcap's transmembrane pressure versus time in operation data.

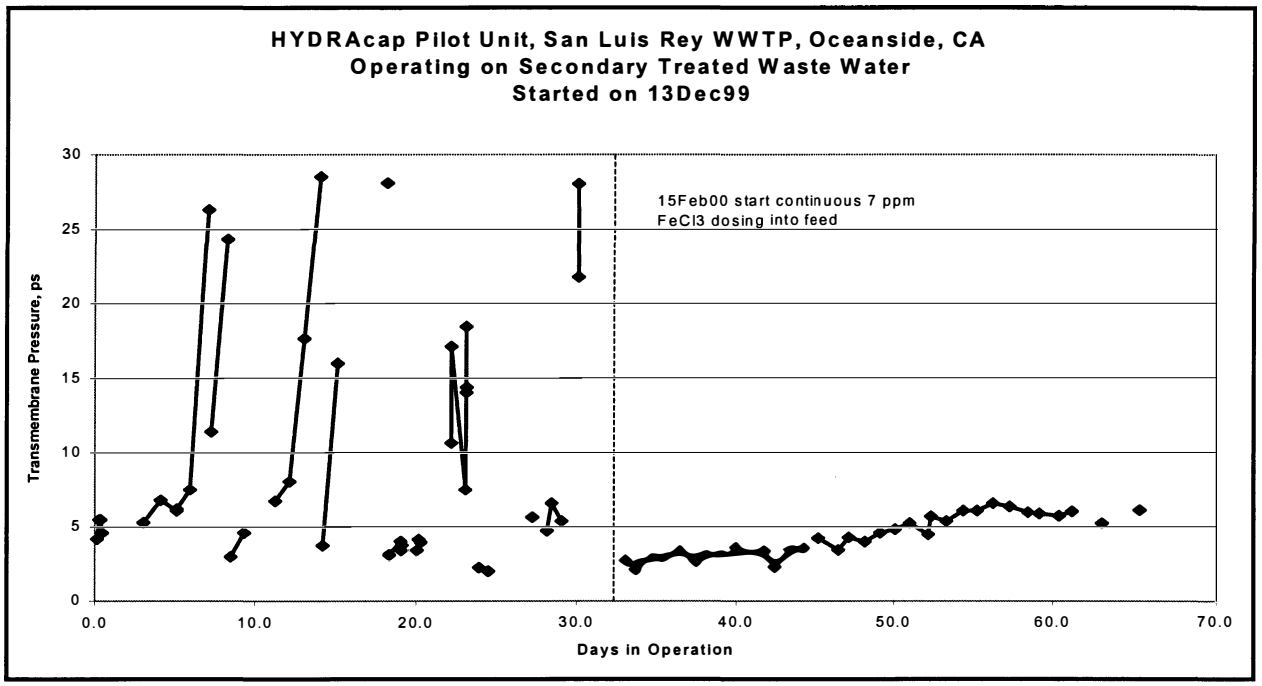


Figure 7. HYDRAcap at San Luis Rey WWTP, Oceanside, CA Operating Data

Feed and product turbidity data for HYDRAcap is plotted in Figure 8.

Normalized specific flux data for HYDRAcap is in Figure 9.

Figure 10 contains cleaning results for HYDRAcap. The results show that a combination of low pH/high pH solutions plus chlorine is sufficient to restore filtrate flow back to its original condition.

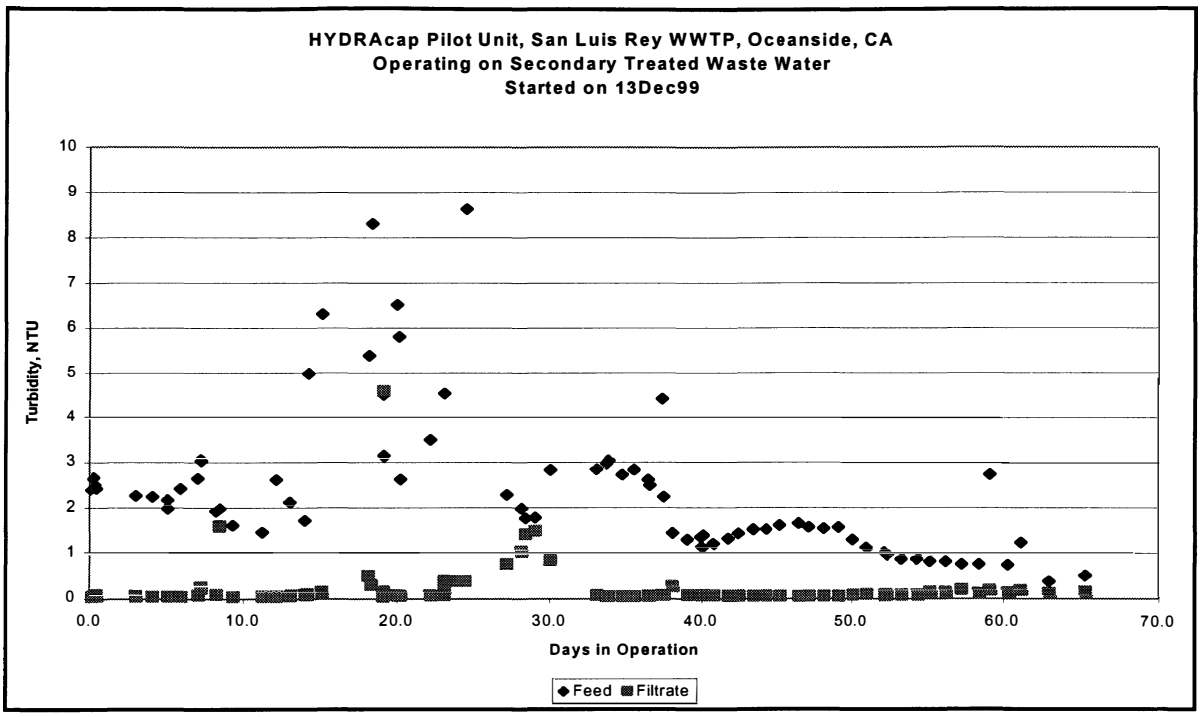


Figure 8. HYDRAcap at San Luis Rey WWTP, Oceanside, CA Product Quality Relative to Feed.

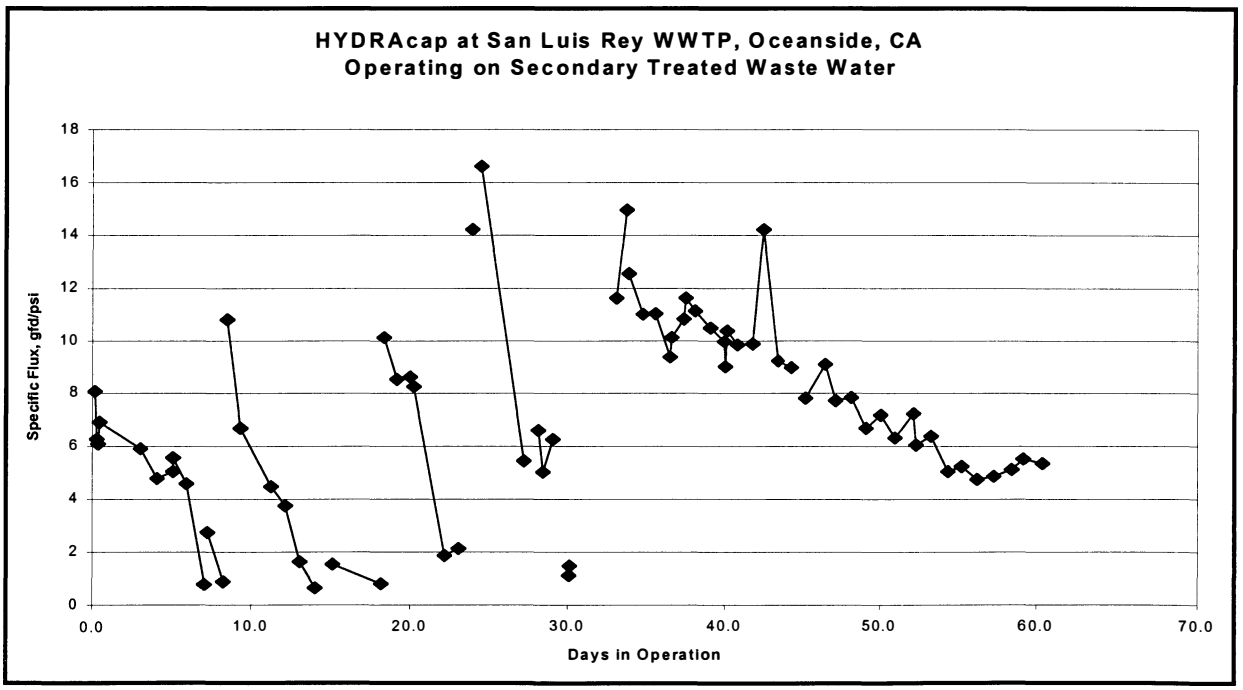


Figure 9. HYDRAcap Normalized Data.

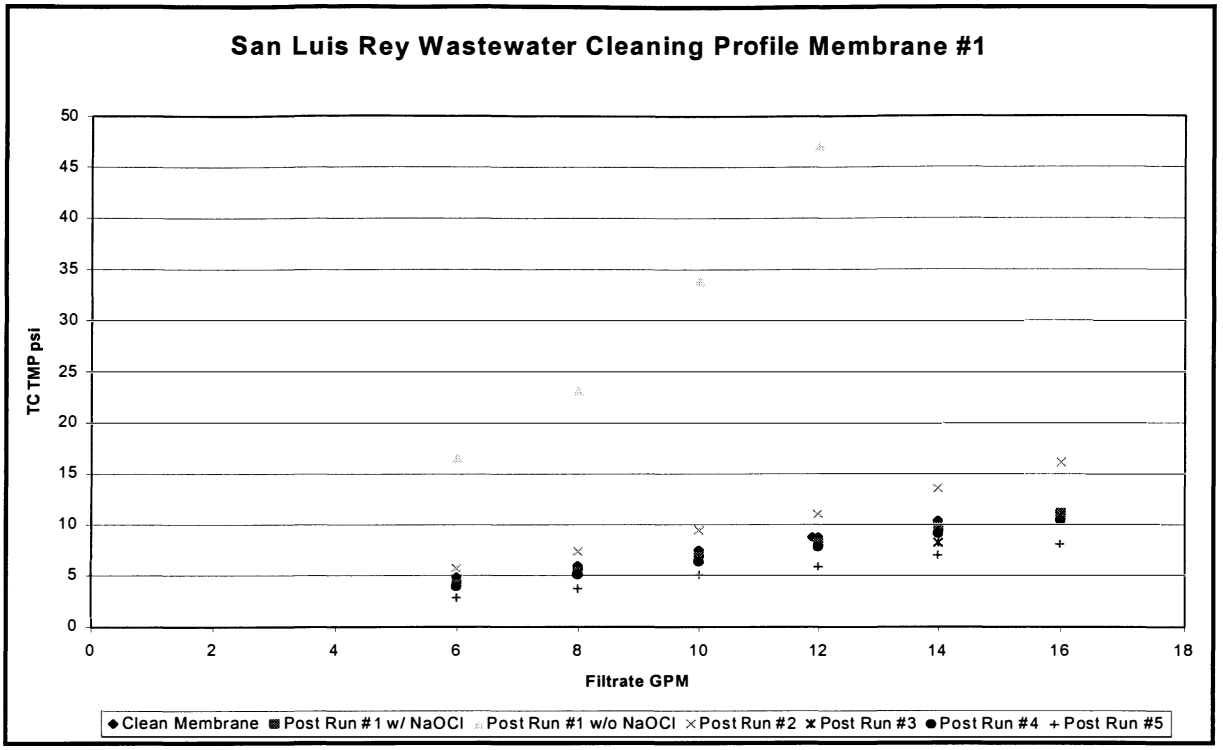


Figure 9. HYDRAcap Cleaning Results.

Due to longer cleaning times and downtime required to make process changes, less time was spent actually producing filtrate. Please refer to Figure 10 for the availability data.

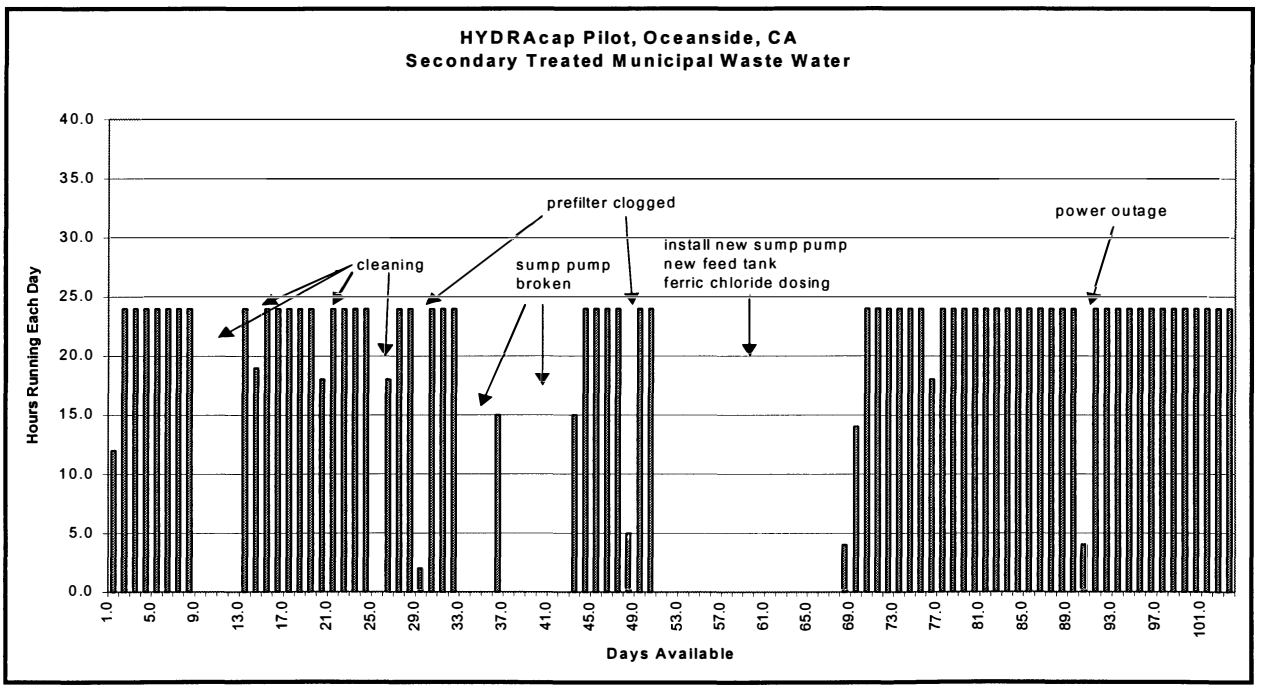


Figure 10. HYDRAcap at San Luis Rey WWTP, Oceanside, CA Availability Data

Field results for HYDRAcap pilot unit are found in Table 7.

Table 7.

Date	RunHr	Run D	Temp	Fin psi	Btm psi	Top psi	Filtr psi	TMP	Filtr gpm	Recirc gpm	Conc gpm	Fd NT	Filt NTU	BW Tot	Notes	Flux	TC GFD	SpFlx gfd/psi
12/9/99	1020.5	0.0	11	28.9	27.9	27.1	16.5	11	14	0	0				Clean Flux Profile	74.7	88.601	8.05462565
12/9/99	1020.5	0.0	11	29.5	28.5	27.2	18.6	9.25	11.9	0	0				Clean Flux Profile	63.5	75.311	8.14170269
12/9/99	1020.5	0.0	11	29.5	29.2	28.2	20.8	7.9	10	0	0				Clean Flux Profile	53.3	63.286	8.01092967
12/9/99	1020.5	0.0	11	30.2	29.7	27.9	22.6	6.2	8	0	0				Clean Flux Profile	42.7	50.629	8.16597993
12/9/99	1020.5	0.0	11	30.5	29.9	29.1	24.4	5.1	6	0	0				Clean Flux Profile	32	37.972	7.44545229
12/9/99	1020.5	0.0	11	30	29.1	28.3	24.1	4.6	6	0	0				Clean Flux Profile	32	37.972	8.25474058
12/9/99	1020.5	0.0	11	29.8	28.9	27.9	22.1	6.3	8	0	0				Clean Flux Profile	42.7	50.629	8.0363612
12/9/99	1020.5	0.0	11	29.1	28.2	27.2	20.4	7.3	10	0	0				Clean Flux Profile	53.3	63.286	8.66936225
12/9/99	1020.5	0.0	11	28.8	27.9	26.8	18.1	9.25	12	0	0				Clean Flux Profile	64	75.944	8.21012036
12/9/99	1020.5	0.0	11	27.9	27	25.8	16.2	10.2	14	0	0				Clean Flux Profile	74.7	88.601	8.686361
				Pressure decay		21	15	-4.5	psi/min									
						21	14.8	-4.3	psi/min									
								0										
12/10/99	1023.8	0.2	21.5	31.5	30.9	30.2	26.7	3.85	6	0	0	2.4	0.052			32	31.1	8.07800346
12/10/99	1027.0	0.3	21	31	31	30	25.5	5	6	0	0	2.644	0.063			32	31.397	6.27947253
12/10/99	1028.9	0.4	22	31.1	30.9	30	25.4	5.05	6	0	0	2.484	0.068			32	30.806	6.10021275
12/10/99	1031.3	0.5	22	30.9	30.8	30.5	26.2	4.45	6	0	0	2.4	0.06			32	30.806	6.92271335
12/13/99	1093.7	3.1	20.9	32.1	31.9	32.1	26.6	5.4	6.1	0	0	2.253	0.052			32.5	31.981	5.92248098
12/14/99	1119.3	4.1	22	32	31.9	31.6	25.1	6.65	6.2	0	0	2.224	0.05			33.1	31.833	4.7869088
12/15/99	1143.4	5.1	22	31.9	31.8	32	25.7	6.2	6.1	0	0	2.165	0.054	9494.5		32.5	31.32	5.05153371
12/15/99	1143.6	5.2	22	31.3	31.2	31.7	25	6.45	7	0	0	1.988	0.054	9520.4		37.3	35.94	5.57215816
12/16/99	1163.4	6.0	21	32	32	31.8	24.5	7.4	6.5	0	0	2.4	0.053	10821.7		34.7	34.014	4.59646075
12/17/99	1190.2	7.1	22	32.5	32.3	32.6	6	26.5	4	0	0	2.63	0.082	12543.6		21.3	20.537	0.7764606
cleaning								0								0	0	#DIV/0!
12/22/99	1195.0	7.3	22	14.7	15.4	15	4	11.2	6	0	0	3.309	0.228	13767.2		32	30.806	2.75054236
12/23/99	1218.4	8.3	21	24.2	24.3	24.4	0	24.4	4.1	0	0	1.915	0.095	15061.8		21.9	21.455	0.88110326
cleaning								0								0	0	#DIV/0!
12/23/99	1224.3	8.5	21	30.5	30.2	30.2	27.2	3	6.2	0	0	1.975	1.585	15510.6		33.1	32.444	10.8146471
12/24/99	1244.5	9.4	22	30.5	30.4	30.8	26	4.6	6	0	0	1.607	0.046	17050.5		32	30.806	6.6969727
12/26/99	1290.2	11.3	22	30.3	30.8	30.5	23.9	6.75	5.9	0	0	1.446	0.043	20039.3		31.5	30.293	4.48779849
12/27/99	1311.9	12.2	22	30.4	30.8	30.5	22.6	8.05	5.9	0	0	2.609	0.046	21521		31.5	30.293	3.76306085
12/28/99	1333.4	13.1	21	31.1	31	31.3	13.5	17.7	5.5	0	0	2.118	0.061	22934.8		29.3	28.781	1.63064678
12/29/99	1356.6	14.0	21	31.8	32.1	31.9	3.5	28.5	3.5	0	0	1.709	0.076	24371.7		18.7	18.315	0.64263608
cleaning								0								0	0	#DIV/0!
12/29/99	1360.9		21	33.2	29.2	32.3	27	3.75	6	20	0	4.985	0.09	24801.5		32	31.397	8.37263004
12/30/99	1382.9	15.1	21	34.9	30.3	33.7	16	16	4.7	20	0	6.302	0.144	26376.9		25.1	24.595	1.53716255
1/2/00	1456.2	18.2	20	37	21.4	28.8	2	23.1	3.4	18	0	5.375	0.493	31202.7		18.1	18.133	0.78499278
cleaning								0								0	0	#DIV/0!
1/4/00	1460.6	18.4	21	32.1	31.2	31.8	28.4	3.1	6	0	0	8.314	0.297	32112.7		32	31.397	10.1281815
1/5/00	1479.9	19.2	20	32.3	30.7	31.2	27.2	3.75	6	0	0	3.134	0.156	33546.2		32	32	8.53333333
1/6/00	1500.0	20.0	20	32.9	29.1	27.7	25	3.4	5.5	0	0	6.511	0.067	35101		29.3	29.333	8.62745098
1/7/00	1505.9	20.2	19	32.2	30.8	30.5	26.7	3.95	6	0	0	2.619	0.066	35500.1		32	32.614	8.25676058
1/9/00	1552.8	22.2	20	31.5	25.7	25.5	8.5	17.1	6	0	0	3.49	0.069	38521.1		32	32	1.87134503
1/10/00	1574.0	23.1	20	34	9	8.6	1.3	7.5	3	0	0	4.535	0.078	39548.8		16	16	2.13333333
								0								0	0	#DIV/0!
1/14/00	1594.0	23.9	20	36.5	13	16.5	12.5	2.25	6	11	0	13.98	0.386	40903.9		32	32	14.2222222
1/17/00	sump pump broke unit of line							0								0	0	#DIV/0!
1/21/00	sump pump replaced															0	0	
1/21/00	1607.9	24.5	18	38.5	18	18	16	2	6	0	0	8.639	0.382	42022.1		32	33.24	16.6200988
1/24/00	1673.9	27.2	22	37.8	22.3	21	16	5.65	6	0	0	2.263	0.747	46579.4		32	30.806	5.45240255
1/25/00	prefilter cleaned a lot of sand observed on prefilter															0	0	
1/25/00	Caustic changed to 1 in 36 BW																	
1/25/00	1696.1	28.2	21	30	27.5	29	23.5	4.75	6	0	0	1.982	1.028	48037.9		32	31.397	6.60997108
1/26/00	1702.9	28.5	18	16	9.8	11	3.8	6.6	6	0	0	1.762	1.409			32	33.24	5.03639357
1/27/00	1718.0	29.1	17	17	16.8	17	11.5	5.4	6	0	0	1.783	1.485	49524.5		32	33.878	6.27374187
Low FF flow due to pump																0	0	
1/28/00	1742.0	30.1	20	33.1	31.7	32.4	4	28.1	5.9	0	0	2.84	0.85	51070		31.5	31.467	1.1218063
	1743.0	30.1	20	33.2	31.9	33	10.7	21.8	6	0	0					32	32	1.47126437
	Install new feed tank, sump pump															0	0	
	FeCl3 dosing 5 ppm in the feed water															0	0	
	BW every 15 min															0	0	
	Chlorine (~100ppm) every 2bw, no chemical dosing																	
2/15/00	1814.5	33.1	21	31.8	31.1	30.7	28.2	2.7	6	0	0	2.85	0.079	55780.3		32	31.397	11.6286528
2/16/00	1829.7	33.7	21	32	31.2	31	29	2.1	6	0	0	2.976	0.051	57465.5		32	31.397	14.9511251
Changed FeCl3 injection point to after feed tank																		
2/16/00	1833.5	33.9	21	31.5	30	30	27.5	2.5	6	0	0	3.046	0.048	57879.1		32	31.397	12.5589451
2/17/00	1854.9	34.8	21	32.3	31	29.1	27.2	2.85	6	0	0	2.73	0.05			32	31.397	11.0166185
Changed BW to every 20 min																		
2/18/00	1873.8	35.6	20	31.9	30.6	31.8	28.3	2.9	6	0	0	2.841	0.054	62347		32	32	11.0344828

Cost Evaluation

Based on current operating parameters for both units, annual operating cost of producing 1MG of filtrate was calculated. Assumed chemical costs are the following:
Chlorine for BW and Cleaning - $0.25/lb (100% soln.)
25% Caustic - $0.06/lb
40 % Ferric Chloride - $0.15/lb
Citric Acid Powder - $1.25/lb

Unit operating parameters that are relevant to the cost calculations are in Table 8.

Table 8. Operating Parameters.

	RS30-4S	HYDRAcap without $FeCL_3$	HYDRAcap with $FeCL_3$
Cleanings per Year	65.4	84.2	9.1
Cleaning Duration	1.5 hr	4 hr	4 hr
Volume Low pH	60 gal	25 -30 gal	25 – 30 gal
Volume High pH	100 gal	25 -30 gal	25 -30 gal
BW/day	130.7	68.3	68.3
Volume Used per BW	1.7 gal	14 gal	14 gal

All the dollar amounts calculated are per 1 MG of product per year. The results are listed in Table 9. RS30-4S proved to be more expensive to operate than HYDRAcap, mostly because of larger volumes of solutions required for cleaning and more frequent backwashing. HYDRAcap's operating cost improved significantly when ferric chloride injection started. This can be attributed to longer run times in between the cleanings.

Table 9. Cost Comparison.

Cost Item	RS30-4S	HYDRAcap without FeCl3 Dosing	HYDRAcap with FeCl3 Dosing
Chlorine in BW	$32.50	$28	$29.50
% Total Cost	5.3	12.0	26.0
Chlorine for Cleaning	$2.70	$0.52	$0.05
% Total Cost	3.3	0.2	0.0
Citric Acid	$538.50	$168.40	$18.50
% Total Cost	88.0	72.2	16.3
NaOH	$23.70	$9.20	$10.20
% Total Cost	3.7	4.0	9.0
FeCl3	na	na	$26.90
% Total Cost	na	na	23.7
Energy	$17.10	$27.20	$28.50
% Total Cost	2.7	11.6	25.0
Total Cost	$614.50	$233.30	$133.60

Conclusion

HYDRAcap with continuous ferric chloride dosing into the feed proved to be a more suitable product for treating secondary wastewater. With RS30-4S, stable unit operation or adequate turbidity removal could not be achieved; therefore it was decided to discontinue operation on secondary wastewater.