FEASIBILITY OF CROSS-FLOW MICROFILTRATION FOR COMBINED SEWER OVERFLOWS

by

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ABSTRACT

FEASIBILITY OF CROSS-FLOW MIRCROFILTATION
FOR COMBINED SEWER OVERFLOWS

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Combined sewer overflows contribute high levels of suspended solids, pathogenic microorganisms, oxygen-demanding compounds and other pollutants into the receiving stream [US EPA, 2001]. The level of pollution coupled with regulatory pressure is challenging communities to find feasible treatment alternatives. Microfiltration may be a preferred treatment alternative. The feasibility of cross-flow microfiltration for the treatment of a dilute primary sewage effluent simulating combined sewer overflow wastewater was investigated. Ceramic membranes of various pores sizes (0.05 - 5.0 μm) were tested at the bench and field scale to understand the impact of operating conditions on the permeate water quality and flux rate. A 0.2 μm membrane operated with a 1.8 m/s cross flow velocity, a transmembrane pressure less than 2.1 bar and a backpulse frequency of 60 seconds were selected as the preferred operating conditions. The 0.2 μm membrane consistently met water quality objectives for fecal coliforms, *E Coli*, e*nterococci*, BOD_5 and SS. The steady state flux rates are impacted by the feed suspended solids concentration and temperature, and an understanding of these parameters is critical to commercial scale design.

DESCRIPTORS

Bacteria

BOD

Combined Sewer Overflow

Cross Flow Velocity

Microfiltration

NH_3-N

Primary Sewage Effluent

Transmembrane Pressure

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1.0 INTRODUCTION

Combined sewer systems are designed to transport domestic sewage, industrial wastewater, and storm water to a wastewater treatment plant through a single pipe [US EPA, 2001]. During rainfall or snowmelt, the volume of water exceeds the capacity of the sewer system and the sewer system discharges excess water to nearby streams, rivers, lakes, or other surface waters [US EPA, 2001]. The excess discharged wastewater is known as combined sewer overflow (CSO).

Combined sewer overflows, found in 772 communities within the United States, contribute high levels of suspended solids, pathogenic microorganisms, toxic pollutants, floatables, nutrients, oxygen-demanding compounds, oil and grease, and other pollutants into the receiving stream [US EPA, 1984, 2001]. The high levels of pollutants may pose risks to human health, to aquatic life and habitat, and to the use and enjoyment of the waterways [US EPA, 1984].

The level of pollution coupled with regulatory pressure is challenging communities to find feasible treatment alternatives for CSO discharges [US EPA, 1999b]. CSOs can contain sewage wastewater and increase the risk of possible infection for water users. Therefore, the reduction of pathogenic bacteria will most likely be required to meet bacterial water quality standards [US EPA, 1999b].

Some reduction of bacteria can be achieved through solids removal by sedimentation, flotation and filtration [US EPA, 1999a]. Disinfection processes can further remove bacteria, with chlorine disinfection being the most common process [US EPA, 1999a]. Chlorine disinfection may not be widely accepted for combined sewer overflows because of the residual

disinfectant toxicity for the receiving waters, the difficulty in regulating the addition of the disinfectant, the wide variety of bacterial compositions and concentrations, and the high suspended solids concentrations of the CSO wastewater [US EPA, 1999a]. Therefore, chlorine alternatives such as ozonation, ultraviolet radiation, peracetic acid and electron beam irradiation are now being considered for the treatment of CSOs [US EPA, 1999a].

With the recent growing awareness of membrane technology and the declining cost of membranes, membrane technology may be a superior option for CSO treatment. Some advantages of membrane filtration include improved water quality (free of bacteria, substantially reduced virus contents and no residual chemicals), reduced land requirements compared to storage basins and the potential for mobile treatment. [Gan 1999, Till et al., 1998].

2.0 LITERATURE REVIEW

2.1 Evidence of Combined Sewer Overflow Pollution

Combined sewer overflows (CSOs) contribute high levels of suspended solids, pathogenic microorganisms, toxic pollutants, floatables, nutrients, oxygen-demanding compounds, oil and grease, and other pollutants to the receiving stream [US EPA, 1994, 2001]. High levels of pollutants may pose risks to human health, to aquatic life and habitat, and to the use and enjoyment of the waterways [US EPA, 1994]. The primary human health risk associated with CSOs is exposure to bacteria and viruses [US EPA, 2001]. Recreational waters that are subjected to bacterial pollution increase the risk of possible infection for waters users.

The city of Pittsburgh, PA has a combined sewer system that discharges excess wastewater to nearby streams and rivers. The rivers surrounding the greater Pittsburgh region provide evidence for bacterial pollution following storm events. In a recent sampling survey during the summer of 2001, bacterial levels as high as 50,000 fecal coliforms CFU/100 mL, 39,000 *Escherichia Coli* (*E Coli*) CFU/100 mL, and 1,060 *Enterococci* CFU/100 mL were detected in the Allegheny river [USGS, 2001].

In addition, a local Pittsburgh stream, Saw Mill Run, has been monitored during dry weather and wet weather to understand the impacts of CSO discharges upon the stream. Water quality data from that study (Table 1) demonstrates an elevated level of pollution within Saw Mill Run during wet weather storm events [Gibson et al, 1998]. Upper Saw Mill Run demonstrated fecal coliforms levels greater than two orders of magnitude higher during wet weather than during dry weather.

Table 1: Saw Mill Run Dry and Wet Weather Fecal Coliforms Levels

Dry Weather/ Wet Weather	Upper Saw Mill Run Fecal Coliforms (CFU/100 mL)	Lower Saw Mill Run Fecal Coliforms (CFU/100 mL)
Dry Weather Geometric Mean	642	1,137
Wet Weather Geometric Mean	107,203	18,238
Source: Gibson et al, 1998		

In addition to bacteria, CSOs contribute solids, oxygen demanding materials and other pollutants to the receiving stream [US EPA, 2001]. A comparison between CSO wastewater and other pollutant sources (Table 2) demonstrates that a typical CSO discharge can be of significant strength. Pollutants such as solids and oxygen demanding material have the ability to adversely impact the aquatic habitat causing shell fish bed closures, decreased oxygen levels and fish kills [US EPA, 2001].

Table 2: Combined Sewer Overflow Water Quality Characteristics

Contaminant Source	BOD_5 (mg/L)	TSS (mg/L)	Total N (mg/L)	Total P (mg/L)	Fecal Coliforms (CFU/100 mL)
Untreated Domestic Wastewater	100 – 400	100 – 350	20 – 85	4 – 15	$10^7 – 10^9$
Treated Domestic Wastewater	<5 - 30	<5 - 30	15 - 25	<1 - 5	< 200
Urban Runoff	10 - 250	67 - 101	0.4 – 1.0	0.7 – 1.7	$10^3 – 10^7$
CSO	25 - 100	150 - 400	3 - 24	1 - 10	$10^5 - 10^7$
Source: US EPA, 2001					

2.2 Applicable Combined Sewer Overflow Regulations

Prior to the implementation of combined sewer overflow treatment by membrane filtration, the technology needs to be demonstrated to remove pollutants to a satisfactory level. Many states, including Pennsylvania, have not taken action towards developing water quality standards for wet weather events for CSO communities. The present Environmental Protection Agency (EPA) regulations and guidance allow the states some flexibility in selecting water quality standards based on site-specific conditions. Therefore, with no enforceable standards within the state of Pennsylvania, the selection of CSO treatment goals is not an easy task.

Despite no specific water quality standards for CSOs in Pennsylvania, there are many applicable bacterial and treatment standards. Applicable bacterial water quality standards include: Pennsylvania Department of Environmental Protection (PADEP) surface water quality standards, EPA suggested surface water quality criteria, Pennsylvania Department of Health

standards and the Ohio River Valley Sanitation Commission standards. In addition to bacterial water quality standards, CSO treatment may also be required to meet PADEP secondary treatment standards.

2.2.1 Pennsylvania Bacterial Surface Water Quality Standards

The PADEP regulates surface water quality under PA Code Title 25, Subpart C, Article II, Chapter 93.7a. The regulations require that the monthly geometric mean of fecal coliforms during the warm weather months of May through September should be less than 200 CFU/100 mL and no more than 10% of the samples can be greater than 400 CFU/100 mL. For the remainder of the year, the maximum fecal coliforms level should be less than a monthly geometric mean of 2,000 CFU/100 mL.

2.2.2 Environmental Protection Agency Suggested Bacterial Water Quality Criteria

The United States Environmental Protection Agency (EPA) is expected to require all states to adopt new bacterial standards based on the 1986-EPA's Ambient Water Quality Criteria for bacteria that go beyond fecal coliforms [Slack et al., 2000]. The suggested criteria for freshwater is a monthly geometric mean of 126 CFU/100 mL for *E. Coli* and 33 CFU/100 mL for *Enterococci*, with a monthly maximum dependent on the water body use (Table 3) [US EPA, 1986].

Table 3: US EPA Suggested Freshwater Water Quality Criteria for Bacteria

Indicator Organism	Geometric Mean (CFU/100 mL)	Single Sample Maximum for Full Body Contact based upon water body usage (CFU/100 mL)			
		Designated Beach Area	Moderate Recreation	Lightly Used	Infrequently Used
Enterococci	33	62	78	107	151
E Coli	126	235	298	410	576
Source: US EPA, 1986					

2.2.3 Pennsylvania Department of Health Bacterial Standards

The Pennsylvania Department of Health regulates water quality for swimming and bathing waters under Title 28, Chapter 18 of the Pennsylvania Code. The public uses the receiving waters from combined sewer overflows for recreational activity during the summer months. Therefore, Pennsylvania Department of Health standards deserve consideration. Title 28, Chapter 18, Part 28 regulations for beach contamination is stated as follows:

(a) Use of a bathing beach found to be contaminated shall be discontinued until written approval is obtained from the Department. The approval will be given when the Department finds that the waters of the bathing beach are no longer contaminated.

(b) The water in the bathing beaches will be considered contaminated for bathing purposes when one of the following conditions exists:

(1) The Department determines that a substance is being discharged or may be discharged into the water and is or may be hazardous to the health of persons using the bathing beach.

(2) The fecal coliforms density of a sample collected at a bathing beach exceeds 1,000 per 100 milliliters.

(3) The fecal coliforms density in at least five consecutive samples of the water taken over not more than a 30-day period exceeds a geometric mean of 200 per 100 milliliters.

2.2.4 Ohio River Valley Water Sanitation Commission Bacteria Standards

The Ohio River Valley Sanitation Commission (ORSANCO) sets pollution control standards for industrial and municipal wastewater dischargers to the Ohio River. The standards designate specific uses of the river and establish guidelines to ensure that the river is capable of supporting those uses. The ORSANCO bacterial standards as stated within the document *Ohio River Valley Water Sanitation Commission - POLLUTION CONTROL STANDARDS for discharges to the Ohio River, 2000 Revision* under human health protection are as follows:

BACTERIA:

a. Maximum allowable level of fecal coliforms bacteria for use as a source of public water supply -- for the Months of November through April, content shall not exceed 2,000/100 mL as a monthly geometric mean based on not less than five samples per month.

b. Maximum allowable level of fecal coliforms bacteria for contact recreation -- for the months of May through October, content shall not exceed 200/100 mL as a monthly geometric mean based on not less that five samples per month; nor exceed 400/100 mL in more that 10 percent of all samples taken during the month

c. Maximum allowable level of *E Coli* bacteria for contact recreation -- for the months of May through October, measure of *E Coli* bacteria may be substituted for fecal coliforms. Content shall not exceed 130/100 mL as a monthly geometric mean, based on not less than five samples per month, nor exceed 240/100 mL in any sample.

2.2.5 Pennsylvania Secondary Treatment Standards

PA Code Title 25 92.2c(a) regulates sewage treatment in Pennsylvania; however, the regulations do not include CSO discharges. CSO communities are required to implement a long-term control plan and the nine minimum controls to minimize or eliminate the CSO discharge. Therefore, there are no specific concentration based treatment requirements. However, discharges from a sanitary sewer overflow (SSO) are prohibited and require secondary treatment. Therefore, secondary treatment standards are applicable to this project as membrane filtration may be applicable to both CSOs and SSOs.

Under 92.2c(a) of the Pennsylvania Code, secondary treatment of sewage accomplishes compliance with federal regulations under the code of federal regulations (CFR) 40 Part 133 with a provision for effective disinfection. The disinfection requirements from May 1 through

September 30 are an effluent geometric mean not greater than 200 fecal coliforms per 100 mL and a no more than 10% greater than a maximum of 1,000 fecal coliforms per 100 mL. 40 CFR Part 133.102 provides criteria for secondary treatment in terms of the five day biochemical oxygen demand (BOD_5), suspended solids (SS) and pH. The BOD_5 criteria are a 30-day average less than 30 mg/L, a 7-day average less than 45 mg/L and a 30-day percent removal greater than 85%. The SS criteria are a 30-day average less than 30 mg/L, a 7-day average less than 45 mg/L and a 30-day percent removal greater than 85%. The pH criteria is an effluent within the limits of 6.0 to 9.0, unless inorganic chemicals are not added to the waste steam as part of the treatment process and industrial sources do not cause the pH of the effluent to be less than 6.0 or greater than 9.0. The membrane process does not use inorganic chemicals in the treatment process; therefore, the pH requirements are not considered to be applicable.

In addition, 40 CFR 133.103 provides special consideration for dilute sewage from a combined or separate sewer system. The regulations acknowledge that less concentrated wastewater causes difficulty for compliance with the percent removal requirements. Therefore, for dilute wastewaters that consistently meet the concentration requirements, lower percent removal requirements may be allowed as determined by the state.

2.2.6 Selection of Water Quality Treatment Objectives

The lack of concentration based CSO standards provides for a debate as to what is an adequate level of treatment for CSOs. A summary of applicable standards is shown in Table 4. The selection of the most stringent standards from Table 4 as the treatment objectives will be the most conservative and will ensure protection of the receiving waters. Therefore, the treatment objectives shown in Table 5 will be used in the decision making process for this study.

Table 4: Summary of Applicable Standards

Parameter	PA Surface Water Quality[1]	US EPA Suggested Surface Water Quality[2]	PA Department of Health[3]	ORSANCO[4]	PA Secondary Treatment[5]
Fecal Coliforms	200 CFU/100 mL		200 CFU/100 mL	200 CFU/100 mL	
E Coli		126 CFU/100 mL		130 CFU/100 mL	
Enterococci		33 CFU/100 mL			
BOD_5					30 mg/L
SS					30 mg/L

[1] PA Code Title 25 Chapter 93.7 [2] US EPA, 1986 [3] PA Code Title 18 Chapter 18 Part 28 [4] ORSANCO Pollution Control Standards, 2000 Revision [5] PA Code Title 25 Chapter 92.2

Table 5: Water Quality Treatment Objectives

Parameter	Concentration
Fecal Coliforms [1]	200 CFU/100 mL
E Coli [2]	126 CFU/100 mL
Enterococci [2]	33 CFU/ 100 mL
BOD_5 [3]	30 mg/L
SS [3]	30 mg/L

[1] PA Code Title 25 Chapter 93.7, [2] US EPA, 1986 [3] PA Code Title 25 Chapter 92.2

2.3 Membrane Overview

As a result of increasingly stringent discharge standards, the use of membrane technology in the wastewater industry is growing rapidly. As advances are being made, it may be feasible to replace or combine membrane processes with conventional treatment approaches.

Membrane filtration separates particles from a wastewater (Figure 1). The wastewater, referred to as the feed, is driven through a membrane by an applied driving force. The water that passes through a membrane is referred to as the permeate. The driving force for separation can be pressure, concentration, electrical potential or a thermal force. The most common driving force and the one used in this study is an applied pressure.

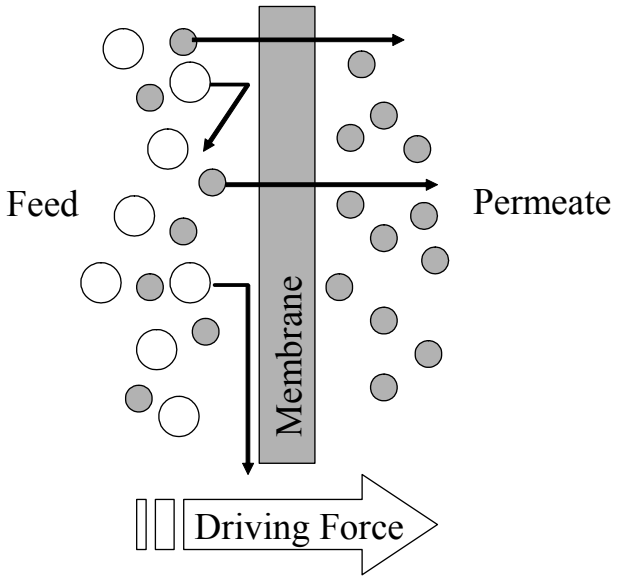


Figure 1: Basic Membrane Separation

The various membrane processes are categorized by the size of the particles that are able to pass through the membrane. The basic classifications of membrane processes are microfiltration, ultrafiltration, nanofiltration and reverse osmosis. Table 6 demonstrates the size

difference, the typical operating pressures and the types of particles that are rejected for each membrane classification. The selection of microfiltration membranes for CSO treatment is the most appropriate due to their ability to reject bacteria at lower operating pressures.

Table 6: Membrane Classifications

Membrane Classification	Size Range	Operating Pressure	Rejected Particles
Microfiltration	0.01 – 1 μm	0.5 – 2 bar	Bacteria, Silts, Cysts, Spores
Ultrafiltration	1 nm – 100 nm	1 – 5 bar	Proteins, Viruses, Endotoxins, Pyrogens
Nanofiltration	200 – 1,000 MWCO(1)	3 – 15 bar	Sugars, Pesticides
Reverse Osmosis	< 200 MWCO(1)	10 – 60 bar	Salts

Source: Cardew and Le, 1998 (1) MWCO- Molecular Weight Cut Off

Four mechanisms for particle rejection are shown in Figure 2. The mechanism of surface sieving rejects particles by the size of the membrane pores. The mechanism of surface collection rejects particles by the membrane surface charge. The mechanism of surface cake collection allows for particles to be rejected by the particles that accumulate on the membrane surface. The mechanism of internal pore adsorption allows for particles to adhere to the inside of the membrane pores. The particles that accumulate on the membrane surface and within the membrane are known as the fouling layer.

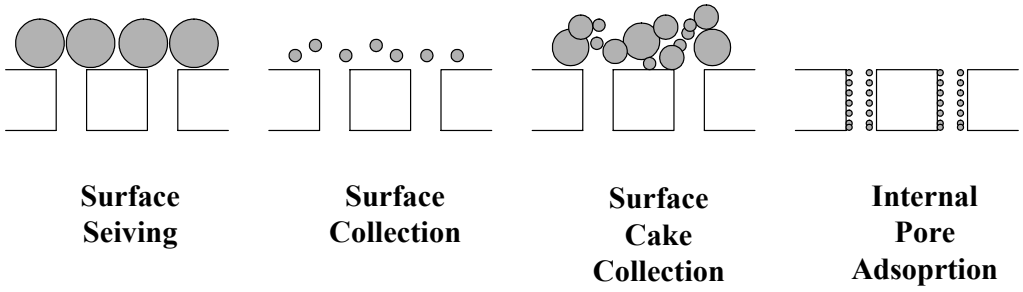


Figure 2: Filtration Mechanisms

Membrane processes can be further classified by the membrane material and the system configuration. The ceramic membranes used in this study are a special class of microporous membranes that have increased durability and can withstand variations in temperature, pressure and pH. A microporous membrane is similar in structure and function to a traditional filter. It has a rigid, highly porous structure with randomly distributed, interconnected voids.

Membrane processes are available in a variety of configurations. Four basic types of membrane configurations are dead-end, spiral wound, cross-flow, and hollow fiber. The different configurations have been developed to facilitate higher permeate flux rates, process flexibility, and ease of maintenance and operation. The configuration used in these experiments is cross flow. During cross flow filtration the wastewater flows parallel to the membrane surface scraping particles away from the surface and reducing the impact of the fouling layer (Figure 3). The main advantage of the cross-flow configuration is the ability to treat wastewaters with elevated suspended solids concentrations. For cross flow filtration, the bulk wastewater is known as the feed, the treated water is known as the permeate, and the untreated water is known as the retentate.

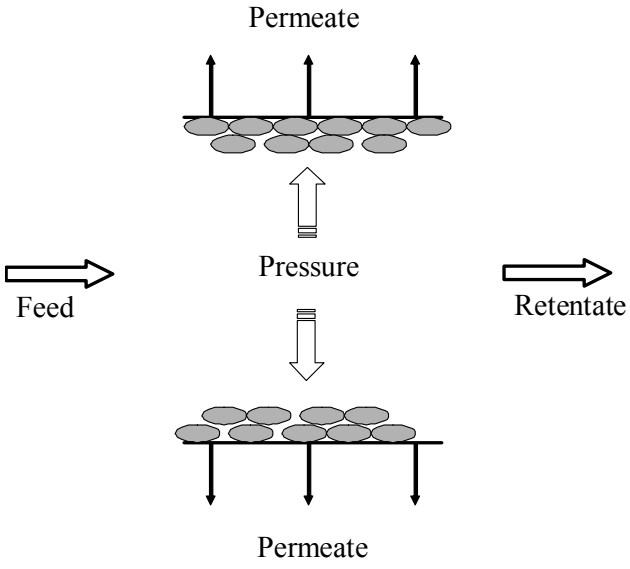


Figure 3: Cross Flow Configuration

2.4 Process Parameters

The key process parameters for cross flow microfiltration include membrane pore size, permeate flux rate, cross flow velocity, transmembrane pressure, membrane fouling and cleaning, operating temperature, and power consumption by the system.

2.4.1 Membrane Pore Size

The membrane pore size is the barrier for pollutant rejection. A smaller pore size will provide for better permeate quality, but it will also reduce the permeate flow rate for the same driving force. An investigation using cross-flow ceramic membranes with a mean pore size between 0.22 – 1.3 μm for the treatment of a primary sewage effluent demonstrated an initial large variation in the permeate flow rate with the difference diminishing significantly with filtration time [Gan, 1999]. The similar flow rates were attributed to the larger pore sizes being more likely to have more severe in-pore fouling [Gan, 1999]. Furthermore, cross flow microfiltration for beer clarification demonstrated a greater permeate flux rate for a 0.5 μm membrane than for a 1.3 μm membrane [Gan et al, 1997]. Again, the reason for the larger pore size providing for lower permeate flow rate was attributed to in-pore fouling [Gan et al, 1997]. These results suggest that the particles that accumulate on the membrane surface and within the membrane may be more critical in determining the permeate flow rate than the membrane pore size.

2.4.2 Permeate Flux Rate

The permeate flux rate determines the required membrane surface area for a design flow rate. The flux is defined as the permeate flow rate per unit surface area of the membrane and is calculated as follows:

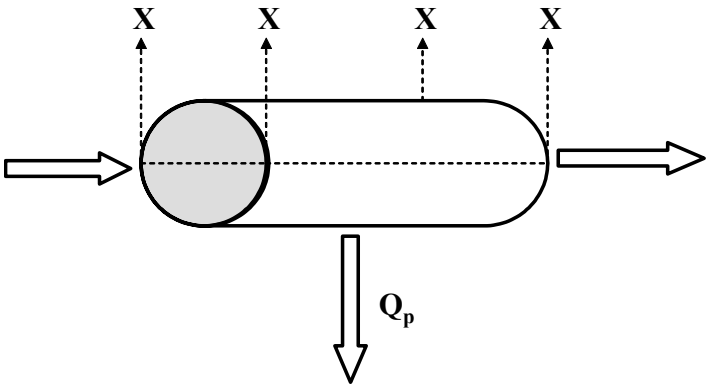
$$J = \frac{Q_p}{A_S} \tag{1}$$

where;

J = flux (L/hr-m^2)

Q_p = permeate flow rate (L/hr) (See Figure 4 Part (i))

A_s = membrane surface area available for filtration (m^2) For the membranes used in this study, the available surface is the inside surface area of the tube or channel (See Figure 4 Part (ii))



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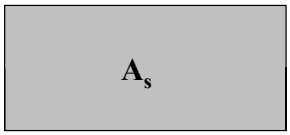


Section X

(ii)

Figure 4: Defining Flux Parameters

During cross flow microfiltration the permeate flux rate is initially very high followed by a rapid decrease and then a gradual decrease towards a constant flux rate (Figure 5). The constant flux rate is referred to as the steady state flux rate and is the flux rate most often used for process design.

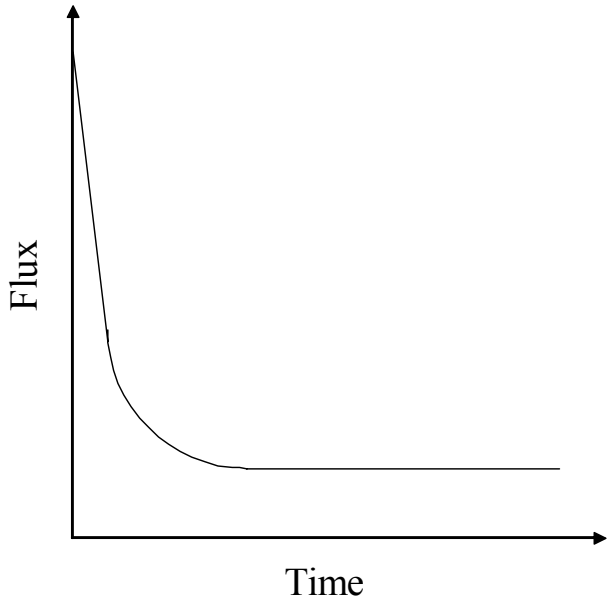


Figure 5: Steady State Flux

2.4.3 Cross Flow Velocity

The cross flow velocity is the rate at which the feed water flows through the channels of the membrane and is calculated as follows:

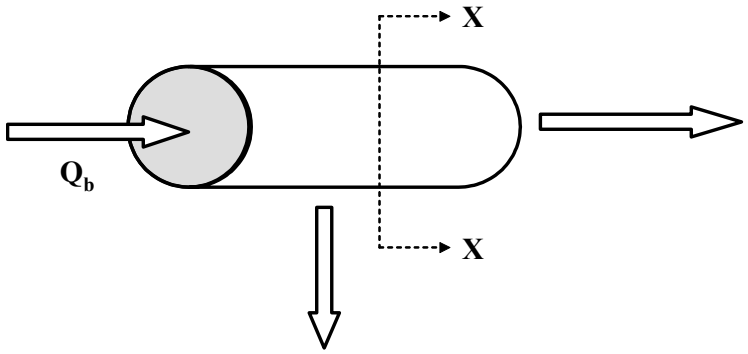
$$V = \frac{Q_b}{A_c} \tag{2}$$

where;

V = cross flow velocity (m/s)

Q_b = bulk flow rate of the raw water within the tube (m^3/s) (See Figure 6 Part (i))

A_c = cross sectional area of the channel (m^2) (See Figure 6 Part(ii))



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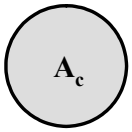

Section X

(ii)

Figure 6: Defining Cross Flow Velocity Parameters

The cross flow velocity is a critical design parameter for cross flow microfiltration systems. The selection of a preferred velocity depends on the trade off between an improved flux rate and an increase in pumping costs. An increase in cross flow velocity should increase the flux rate because more particles are being swept away from the membrane surface decreasing the thickness of the fouling layer (Figure 7).

Previous studies demonstrated a 15% flux improvement with an increase in cross-flow velocity from 2 to 6 m/s during microfiltration of a primary sewage effluent [Gan, Allen 1999]. Similarly, cross-flow microfiltration of a primary and secondary effluent at velocities from 0.9 to 5.7 m/s demonstrated an improved flux rate [Judd et al, 2000].

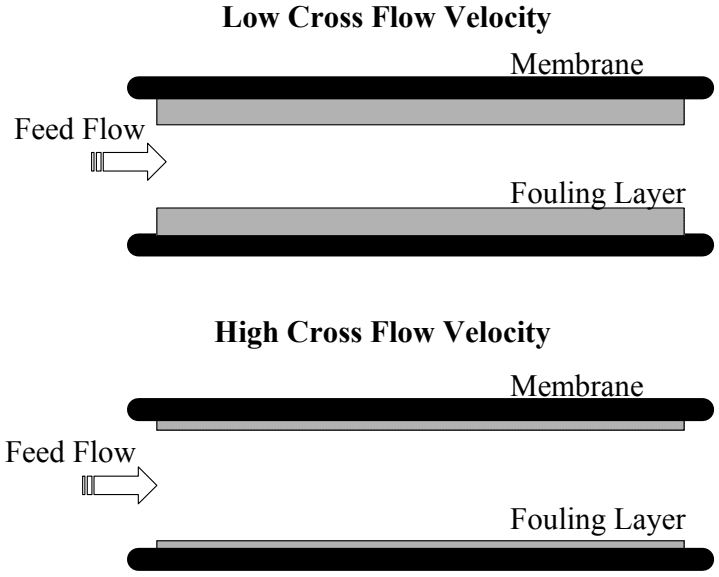

Figure 7: Impact of Cross Flow Velocity on the Fouling Layer

2.4.4 Transmembrane Pressure

For this study, the transmembrane pressure is the driving force for filtration. The transmembrane pressure is the difference in pressure from the feed side of the membrane to the permeate side of a membrane and is calculated as follows:

$$\Delta P = \frac{P_i + P_o}{P_p} \tag{3}$$

where;

ΔP = transmembrane pressure (bar)

P_i = inlet pressure to the membrane module (bar) (See Figure 8)

P_o= outlet pressure to the membrane module (bar) (See Figure 8)

P_p = permeate pressure (bar) (See Figure 8)

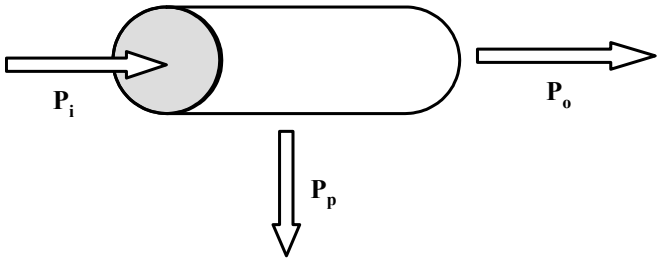

Figure 8: Defining Transmembrane Pressure Parameters

The transmembrane pressure is a critical design parameter for cross flow microfiltration systems. An increase in transmembrane pressure is expected to increase the flux rate. The selection of a preferred pressure depends on the trade off between an improved flux rate and an

increase in pumping costs. A discussion of the impact of transmembrane pressure on the flux rate is included in Section 2.4.6.

2.4.5 Membrane Fouling

The accumulation of particles on the membrane surface, near the membrane surface and within the membrane pores is referred to as membrane fouling. This is a broad term used to describe the various mechanisms of flux decline, which is the key factor governing the use of membrane filtration in environmental engineering practice.

The fouling layer is typically comprised of a concentration polarization layer and/or a gel layer. The concentration polarization layer refers to the solids that accumulate on or near the membrane surface. At very low transmembrane pressures, the impact of the concentration polarization layer is not as significant because the particles have the capability to be swept away by the feed water. As the applied transmembrane pressure increases, the particles are compressed on the membrane surface and the effect of the concentration polarization layer increases (Figure 9).

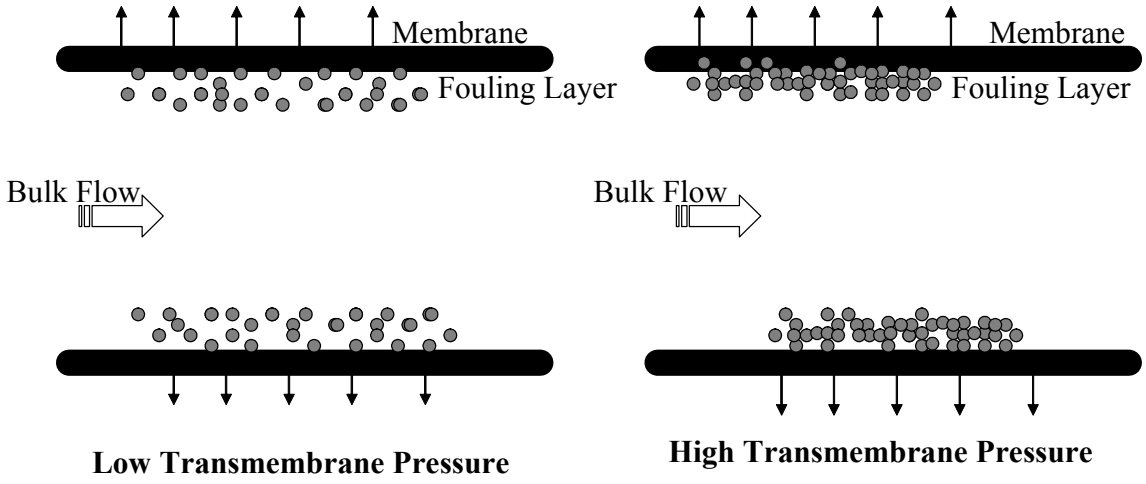

Figure 9: Impact of Transmembrane Pressure on the Fouling Layer

At high transmembrane pressures, the particles become so concentrated at the membrane surface that a gel layer will form. The gel layer acts like a hydraulic barrier controlling the permeate flux rate (limiting flux); thus, making the membrane pore size less important.

An investigation into the cross flow microfiltration of primary sewage effluent was performed at various transmembrane pressures [Gan, Allen 1999]. The data demonstrated a 41% steady state flux increase for an increase in transmembrane pressure from 0.5 to 2.5 bar [Gan, Allen 1999]. However, the increase from 0.5 to 1 bar was 25%, while further increases from 2.0 to 2.5 bar offered less than 1% increase in permeate flux. This lack of an increase in permeate flux demonstrates the concept of limiting flux at elevated transmembrane pressures. The elevated pressures compact the particles on the membrane surface creating a denser fouling layer making filtration more and more difficult as the transmembrane pressure is increased (Figure 9).

2.4.6 Membrane Cleaning (Backpulsing and Chemical Cleaning)

Low permeate flux rates are attributed to the build up of particles on the membrane surface and within the membrane [Shondi, 2001]. In attempt to maintain a high flux rate, the backpulse technique has been incorporated into the membrane process. Backpulsing is the redirection of water flow from the permeate side of the membrane to the feed side of the membrane. The water flow is reversed by supplying a greater pressure on the permeate side of the membrane. The flow of solution is redirected and breaks up the fouling layer carrying particles away from the membrane surface (Figure 10).

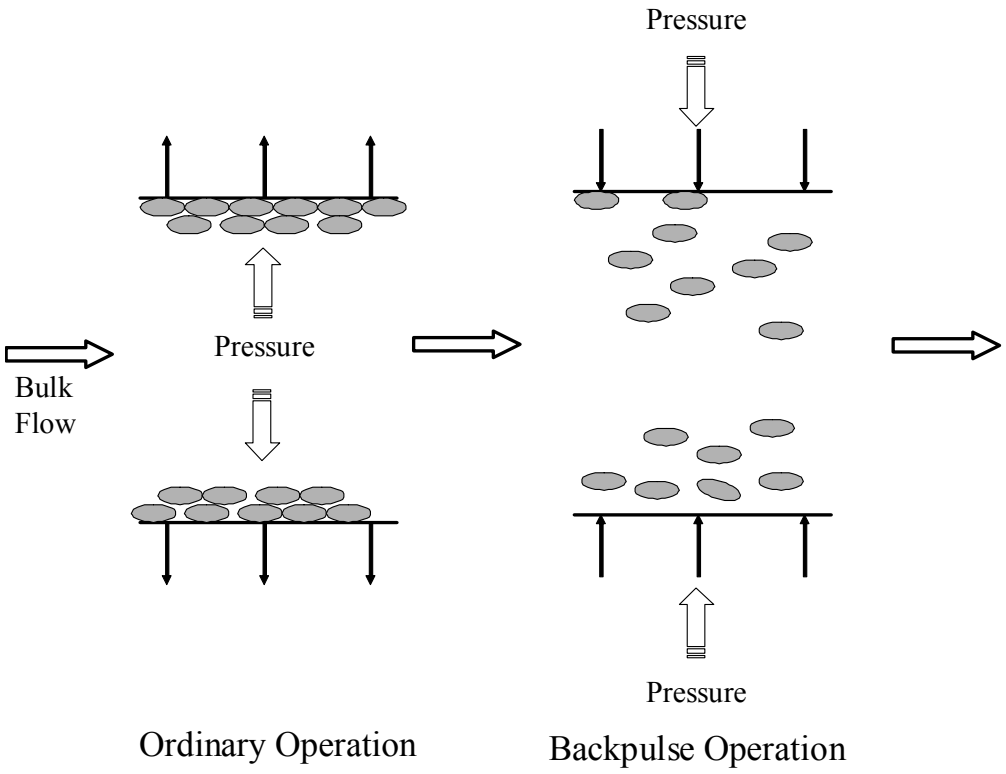

Figure 10: Filtration During Ordinary and Backpulse Operation

The backpulse technique is different from conventional backwashing. Backpulsing is done more frequently and for shorter durations. A typical backpulse operation is performed once a minute for less than a second. Recent research on a ceramic cross flow microfiltration system studying the impact of backpulsing on a primary sewage effluent demonstrated that backpulsing results in a higher flux rate [Gan, 1999].

In addition to the physical cleaning of the backpulse, a chemical cleaning can be performed to break apart the fouling layer. Common chemical cleaning solutions include sodium hypochlorite and nitric acid. The solutions and procedures used in this study are presented in Sections 3.1.5 and 3.2.5. The effectiveness of those solutions and procedures are discussed in Section 4.2.10. The measurement of cleaning effectiveness is based on the initial permeability

using clean water, such as city water or deionized water. The permeability of the membrane is a means of expressing the permeate flux rate independent of the applied transmembrane pressure. The permeability is calculated as follows:

$$P = \frac{J}{\Delta P} \tag{4}$$

where;

P = permeability (L/hr-m^2-bar)

J = flux (L/hr-m^2)

ΔP = transmembrane pressure (bar)

2.4.7 Temperature

As the temperature of a fluid increases, the viscosity of the fluid decreases. Therefore, an increase in temperature will create higher permeate flux rates. In order to compare flux rates obtained at different temperatures, the standard viscosity correction factor, shown below, was used [Lorch, 1987].

$$J_{20} = J_T \times 1.03^{(20-T)} \tag{5}$$

where;

J_{20} = Permeate Flux at 20°C (L/hr-m^2)
J_T = Permeate Flux at Actual Temperature (L/hr-m^2)
T = Actual Temperature (°C)

2.4.8 Power

The selection of a preferred cross flow velocity and transmembrane pressure will be based on the tradeoff between improved flux rates and increased power costs. Therefore, an understanding of power consumption becomes important. The power consumption can be calculated based on measurements of voltage and amperage as follows:

$$P = V \times A \tag{6}$$

where;

P = Power Requirement (W)
V = Voltage (Volts)
A = Amperage (Amps)

2.5 Darcy's Law Model

Several theoretical models for membrane filtration are offered in the literature. Each model varies depending on the assumptions made and the chosen mechanism of particle rejection. The Darcy's Law model is discussed below.

The Darcy's Law Model describes both the membrane and the fouling layer as porous media. It states that the flux is proportional to the pressure drop across the membrane and inversely proportional to the resistance [Al-Malack et al., 1997].

$$J = \frac{\Delta P}{\eta \times R_t} \tag{7}$$

where, J is the flux (m/s), ΔP is the transmembrane pressure (N/m^2), η is the viscosity of the feed water ($N/s\text{-}m^2$), and R_t is the total resistance to flow (1/m).

The total resistance to flow (R_t) of the membrane includes the resistance of the membrane (R_m) and the resistance of the fouling layer (R_f).

$$R_T = R_m + R_f \tag{8}$$

The intrinsic resistance of the membrane (R_m) is a specific physical property of the membrane that remains constant over time. The resistance of the fouling layer (R_f) is negligible for a clean membrane and will increase with time as particles accumulate inside the membrane and on the membrane surface. The resistance of the membrane can be calculated as:

$$R_m = \frac{\Delta P}{\eta \times J_o} \tag{9}$$

where, Jo represents the initial flux of clean water through a clean membrane (See Figure 5 at time zero).

Knowing the membrane resistance (R_m), the resistance of the fouling layer, which causes a decrease in flux during wastewater filtration can then be calculated as:

$$R_f = \frac{\Delta P}{\eta \times J} - R_m \tag{10}$$

2.6 Water Quality Parameters

The ability of membranes to reject pollutants is an extremely important advantage of membrane filtration as an alternative for combined sewer overflow treatment. The regulatory discussion presented in Section 2.2 suggests that fecal coliforms, *E Coli*, e*nterococci*, 5-day biochemical oxygen demand (BOD_5) and suspended solids (SS) are the most relevant water quality parameters that should be evaluated for any CSO treatment approach.

2.6.1 Bacteria Parameters

Several studies investigated the ability of microfiltration membranes to reject bacteria from sewage effluents for membranes of various pore sizes (Table 7). These studies demonstrate that membranes with a mean pore size of 1.3 μm or less are capable of reducing bacterial concentrations to a satisfactory level. All membranes with pore sizes below 0.45 μm satisfied applicable standards, but only one membrane with a pore size greater than 0.45 μm (1.3 μm) was capable of meeting those standards.

Polymeric microfiltration membranes with pore sizes between 0.45 and 1.2 μm were investigated for the removal of fecal coliforms bacteria from both primary and secondary sewage effluents [Till et al, 1998]. An initial breakthrough of fecal coliforms was observed for both membranes. At steady state, the 0.45 μm and 1.2 μm membranes produced a permeate water quality of 910 fecal coliforms CFU/100 mL and 11,000 fecal coliforms CFU/100 mL, respectively. Similarly, low-cost tubular polypropylene membranes with a mean pore size of 0.67 μm or less accomplished 4-5 log rejection of *E Coli* from a primary sewage effluent [Judd

et al, 2000]. However, breakthrough of bacteria at the beginning of operation was also observed for these membranes [Judd et al, 2000].

Table 7: Bacteria Rejection of Sewage Effluents

Paper	Membrane Material	Pore Size (μm)	Configuration	Feed	Bacteria Type	Feed Concentration (col/100 mL)	Permeate Concentration (col/100 mL)	Log Rejection
Vera	Composite	0.14	Cross Flow	SE	Fecal Coliform	-	0	-
Judd 2000	Polypropylene	0.2	Cross Flow	PE	E Coli	$1.1 – 3.6 \times 10^7$	-	4.7
Judd 2000	Polypropylene	0.2	Cross Flow	SE	E Coli	$0.4– 32.3 \times 10^6$	-	4.2
Sethi 2002	Polypropylene	0.2	Hollow Fiber	PE	Fecal Coliform	1.1×10^6	11	5.6
Gan 1999	Ceramic	0.22	Cross Flow	PE	Fecal Coliform	-	0.00	-
Gan 1999	Ceramic	0.35	Cross Flow	PE	Fecal Coliform	-	0.00	-
Till 1997	Polymeric	0.45	Cross Flow	PE	Fecal Coliform	2.7×10^7	910	4.8
Till 1997	Polymeric	0.45	Cross Flow	SE	Fecal Coliform	2.2×10^6	440	4.1
Judd 2000	Polypropylene	0.45	Cross Flow	PE	E Coli	$1.1 – 3.6 \times 10^7$	-	4.8
Judd 2000	Polypropylene	0.45	Cross Flow	SE	E Coli	$0.4– 32.3 \times 10^6$	-	3.9
Judd 2000	Polypropylene	0.67	Cross Flow	PE	E Coli	$1.1 – 3.6 \times 10^7$	-	4.5
Judd 2000	Polypropylene	0.67	Cross Flow	SE	E Coli	$0.4– 32.3 \times 10^6$	-	4.7
Judd 2000	Polypropylene	1.2	Cross Flow	PE	E Coli	$1.1– 3.6 \times 10^7$	-	3
Judd 2000	Polypropylene	1.2	Cross Flow	SE	E Coli	$0.4– 32.3 \times 10^6$	-	1.9
Till 1997	Polymeric	1.2	Cross Flow	PE	Fecal Coliform	1.0×10^7	11,000	3.3
Till 1997	Polymeric	1.2	Cross Flow	SE	Fecal Coliform	3.8×10^6	390,000	1.3
Gan 1999	Ceramic	1.3	Cross Flow	PE	Fecal Coliform	-	<0.01	-

2.6.2 Biochemical Oxygen Demand

In addition to bacteria removal, membrane filtration may be applicable to meet secondary treatment standards for the 5-day biochemical oxygen demand (BOD_5). Similar to the bacterial studies, several studies investigated the BOD_5 and the chemical oxygen demand (COD) rejection as a function of pore size (Table 8). These data suggest that only the 0.1 μm membrane would meet the 30 mg/L BOD_5 standard. However, many studies used COD measurements instead of BOD_5. Assuming the COD is 1.5 times the BOD_5, many other membranes may also meet the applicable standard.

Table 8: Oxygen Demanding Materials Rejection of Sewage Effluents

Paper	Membrane Material	Pore Size (μm)	Configuration	Feed	Parameter	Feed Concentration (mg/L)	Permeate Concentration (mg/L)	% Removal
Ahn 1999	Polyvinylchloride	0.1	Hollow Fiber	Septic Tank Effluent	BOD	59	4.2	92
Ahn 1999	Polyvinylchloride	0.1	Hollow Fiber	Septic Tank Effluent	COD	122	8.8	93
Sethi 2002	Polypropylene	0.2	Hollow Fiber	PE	BOD_5	124.3	64.8	48
Till 1997	Polymeric	0.45	Cross Flow	PE	COD	194	54.6	72
Till 1997	Polymeric	0.45	Cross Flow	SE	COD	134.3	47	65
Till 1997	Polymeric	1.2	Cross Flow	PE	COD	242.3	83.8	65
Till 1997	Polymeric	1.2	Cross Flow	SE	COD	148.9	54.5	63

2.6.3 Suspended Solids

In addition to the bacterial and oxygen demand concerns, regulatory agencies may also enforce suspended solids standards. Several studies measured the suspended solids in the permeate for membranes of various pore sizes (Table 9). The literature suggests that microfiltration membranes with a pore size below 1.2 μm produced a permeate with less than 2.1 mg/L SS, which is well below the 30 mg/L requirement.

Table 9: Suspended Solids Rejection of Sewage Effluents

Paper	Membrane Material	Pore Size (μm)	Configuration	Feed	Parameter	Feed Concentration (mg/L)	Permeate Concentration (mg/L)	% Removal
Ahn 1999	Polyvinylchloride	0.1	Hollow Fiber	Septic Tank Effluent	SS	91	0.2	99
Sethi 2002	Polypropylene	0.2	Hollow Fiber	PE	SS	38.6	1.5	97.7
Till 1997	Polymeric	0.45	Cross Flow	PE	SS	110	1.8	99
Till 1997	Polymeric	0.45	Cross Flow	SE	SS	62	1.5	98
Till 1997	Polymeric	1.2	Cross Flow	PE	SS	98.8	2.1	98
Till 1997	Polymeric	1.2	Cross Flow	SE	SS	65.7	1.5	98

3.0 MATERIALS AND METHODS

This experimental investigation was conducted to evaluate the microfiltration process for permeate water quality and flux rate at both a bench and pilot scale. The bench scale testing was conducted at the University of Pittsburgh. Pilot scale testing was conducted at the Allegheny County Sanitary Authority (ALCOSAN).

Testing at both locations used the same process design and the same membrane material. Each system was comprised of a feed reservoir, a pump, a membrane module housing a single membrane and a backpulse device (Figure 11).

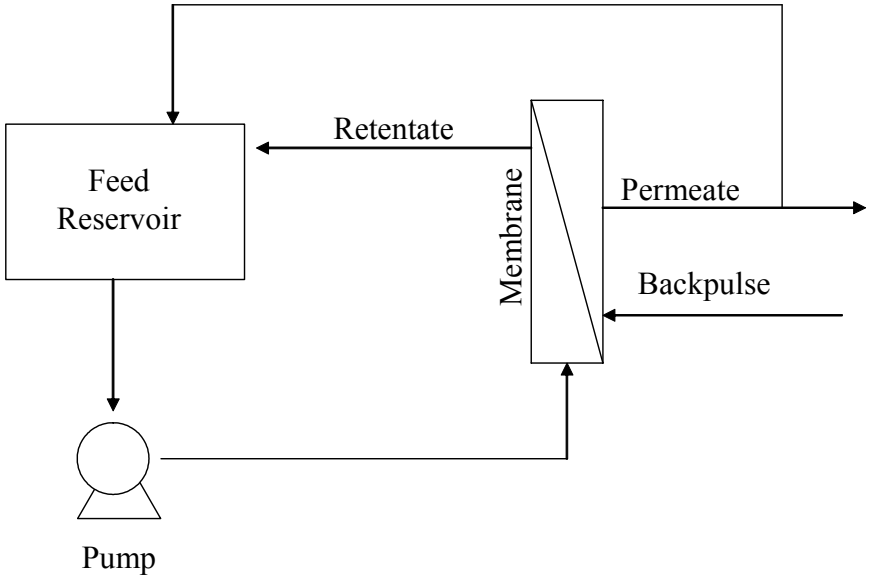

Figure 11: Basic Experimental Equipment Process Flow Diagram

3.1 Bench Scale System

3.1.1 CSO Simulated Wastewater

Primary Sewage Effluent (PSE) from the Allegheny County Sanitary Authority (ALCOSAN), Pittsburgh, PA, was used to simulate the wastewater produced during a CSO event. The PSE was collected just after storm events and was transported to the laboratory immediately before the filtration experiments. The PSE suspended solids were allowed to settle prior to transfer into the feed reservoir.

3.1.2 Membrane System

Laboratory testing was performed using a bench-scale cross-flow filtration unit, Membralox® Model 1T1-70. The apparatus (Figure 12) consists of a ¾ HP centrifugal pump, a 15-L feed tank, an in-line flow meter, a module housing one membrane, a temperature gauge, an automatic backpulse device, eight process control ball valves, and three pressure gauges to monitor the inlet, outlet and permeate pressure. The filtration system can achieve a cross flow velocity of 1.6 m/s to 8.2 m/s and an inlet pressure to the membrane housing of 0 bar to 3.8 bar. The backpulse device uses 5.5 to 8.3 bar of oil-free, dried, filtered nitrogen gas. The device sends pressurized nitrogen gas to a piston on the permeate side of the membrane where a small amount of clean permeate water is stored in a reservoir. The piston compression creates higher pressure on the permeate side of the membrane, thereby redirecting the flow from the permeate side of the membrane to the feed side of the membrane. The frequency and duration of the backpulse can be controlled independently. Flow measurements were taken using a graduate cylinder and a timing device.

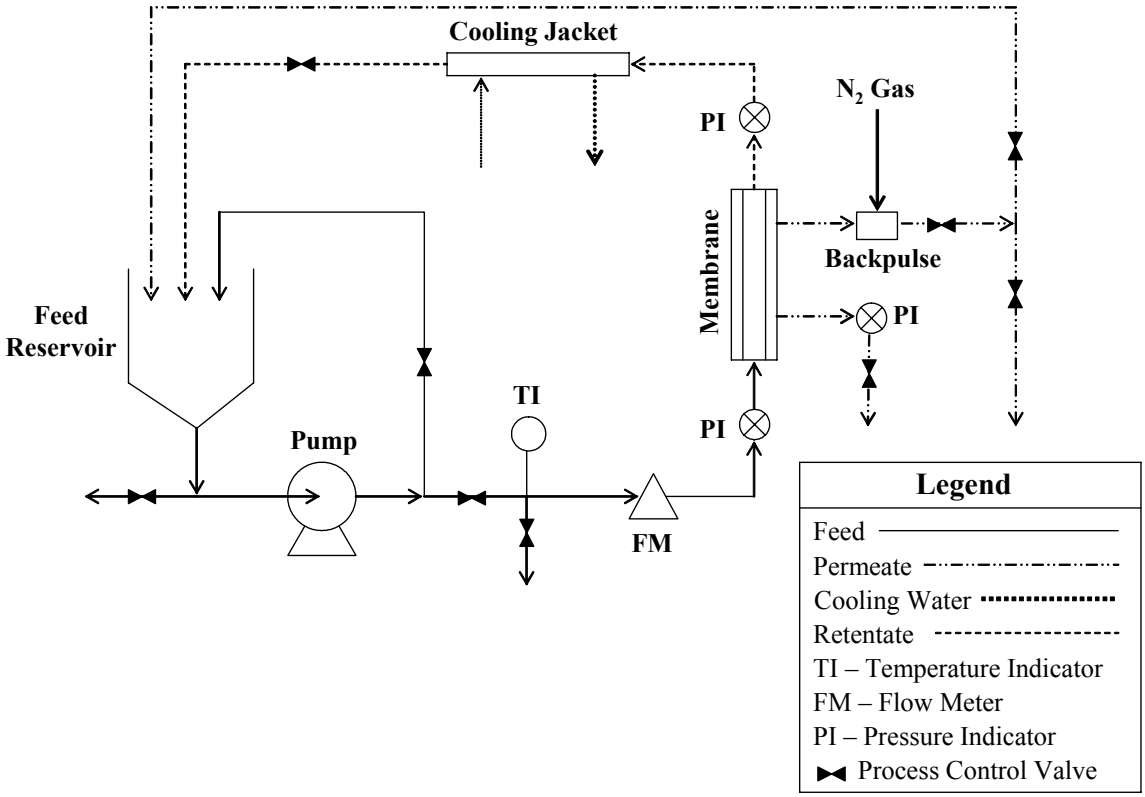

Figure 12: Bench Scale Process Flow Diagram

3.1.3 Membranes

Four Membralox® T1-70 alpha alumina membranes with mean pore size of 0.2, 0.8, 2.0 and 5.0 μm were evaluated in the bench study. These microfiltration membranes were selected to maximize the flux rate while accomplishing a satisfactory level of bacteria removal. Each tubular membrane is 250 mm in length, 7 mm in diameter and has 55 cm^2 of available surface area. The membranes are capable of withstanding a pressure limit of 7.9 bar, a temperature limit of 225 ^oC and a pH range of 0-14.

3.1.4 Water Quality Analysis

The membrane influent and permeate were analyzed for fecal Coliforms, *E Coli*, *Enterococci* and chemical oxygen demand (COD) at various times during filtration tests according to the Standard Methods for the Examination of Water and Wastewater (APHA, 1995).

3.1.5 Membrane Cleaning and Maintenance

The membranes were chemically cleaned and the system was disinfected between filtration experiments. The chemical cleaning solution is city water with 1,500 mg/l sodium hypochlorite raised to a pH greater than 11 by the addition of sodium hydroxide. The cleaning solution was processed through the system for two hours with the permeate valves closed at a temperature greater than 45^{o}C. The system and feed tank were then drained and clean water permeability tests were conducted. The results from the clean water permeability tests were compared to the clean water permeability rates using a 0.2 μm filtered deionized water. The clean water permeability test verified that the solids buildup has been removed using this procedure.

The system needs to be disinfected between test experiments due to bacterial contamination on the shell side of the membrane caused by the passage of bacteria through larger pore size membranes. The system was disinfected by recirculating a 1,000 mg/L sodium hypochlorite solution at a pH above 11 for 30 minutes without a membrane in the membrane housing module and with the permeate valve open.

When membranes were not in use they were individually stored in a 1,500 mg/L sodium hypochlorite solution with a pH greater than 11. Storage in this solution aided the cleaning process and prevented biological growth on the membrane surface and within the membrane.

3.2 Pilot Scale System

3.2.1 CSO Simulated Wastewater

Primary Sewage Effluent (PSE) from Allegheny County Sanitary Authority (ALCOSAN), Pittsburgh, PA, was used to simulate the wastewater produced during a CSO event. The PSE was piped to the system via the ALCOSAN primary effluent sampling pumps.

3.2.2 Membrane System

Pilot testing was performed using a commercial cross-flow filtration unit, USFilter Silverback® Model 150. This commercial system is typically used to treat industrial alkaline cleaners using a 0.05 μm membrane. The difference in the purpose and scope of this project required several modifications to the commercial unit. Modifications included instrumentation and a variable frequency pump drive.

The apparatus (Figure 13) consists of a 3-HP suction pump, a settling tank, a process tank, a small permeate reservoir, an in-line flow meter with electronic output, a module housing one commercial membrane, an automatic backpulse device, eight process control ball valves, two solenoid valves for the backpulse air and the feed wastewater, two floats to monitor the tank water levels, three pressure gauges to monitor the inlet, outlet and permeate pressures, and three electronic pressure transducers to monitor the inlet, outlet and permeate pressures. The filtration

system can achieve a cross flow velocity of 0.5 m/s to 5 m/s and an inlet pressure to the membrane housing to 3.5 bar. The backpulse device uses 4.1 bar of compressed air supplied from an external air compressor. The device sends pressurized air to the solenoid valve on the permeate side of the membrane where a small amount of clean permeate water is stored in a reservoir. The solenoid valve opens to create a greater pressure on the permeate side of the membrane, thereby redirecting the flow from the permeate side of the membrane to the feed side of the membrane. The frequency and duration of the backpulse can be controlled independently. Permeate flow measurements were taken electronically and using a graduate cylinder and a timing device. The temperature in the process tank was measured using a handheld thermometer. City water running through a commercial garden hose placed in the process tank was used to maintain a relatively constant temperature. The digital multimeter with an attached amp probe was used to measure voltage and amperage.

In addition, the unit was instrumented to continuously monitor the pressures and flow rates. The feed flow rate, permeate flow rate, inlet pressure, outlet pressure and permeate pressure were equipped with electronic sensors. The sensors send a 4-20 mA signal to a National Instruments Field Point I/O module. The I/O module converts an analog signal into digital form and the National Instruments LabView software was used to record the transmembrane pressure, cross flow velocity and the flux rate.

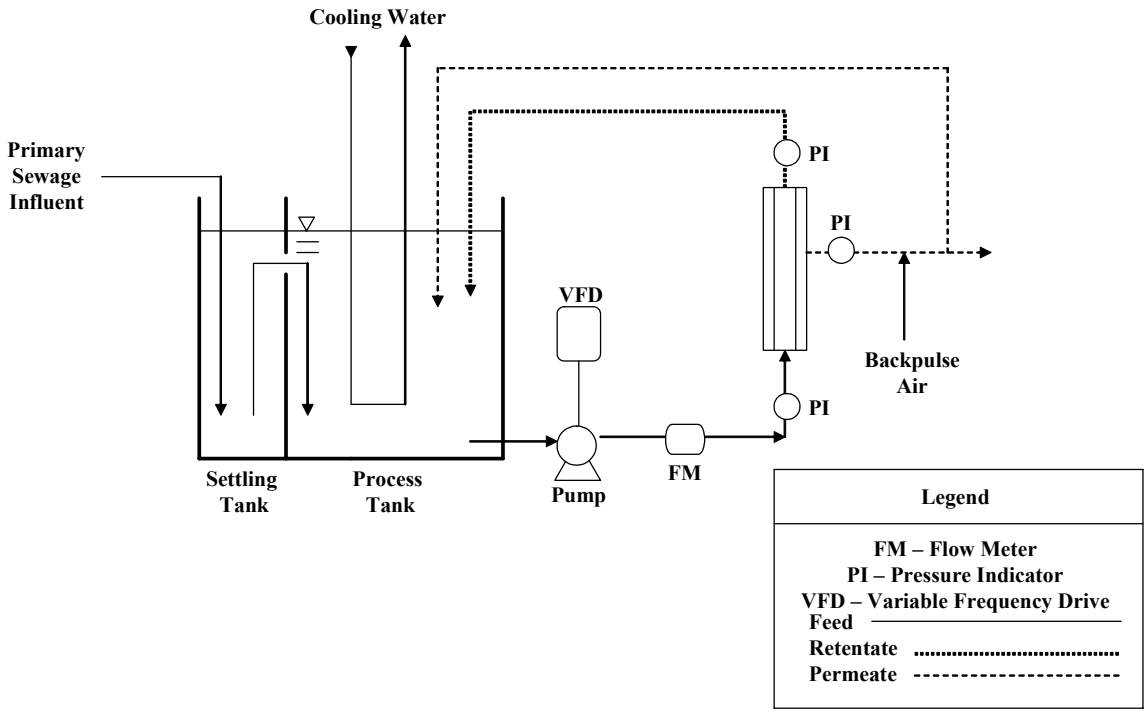

Figure 13: Field Scale Process Flow Diagram

3.2.3 Membranes

Five Membralox® alpha alumina membranes, Model 1P19-60, with mean pore size of 0.05, 0.2, 0.5, 0.8 and 1.4 μm were evaluated in the pilot study. Each tubular membrane is 1020 mm in length and consists of 19 channels that are 6 mm in diameter. Total surface area of the membrane module is 0.36 m^2. The membranes are capable of withstanding a pressure limit of 7.9 bar, a temperature limit of 220 ^oC and a pH range of 0-14.

3.2.4 Water Quality Analysis

All water quality analysis was conducted by the ALCOSAN laboratory. The samples were immediately transported to the ALCOSAN laboratory to ensure minimum holing time. The samples were analyzed for fecal coliforms (Standard Method 9222D), *E Coli* (EPA Method 9223B), *Enterococci* (EPA Method 9223B), biochemical oxygen demand (Standard Method 5210B), chemical oxygen demand (EPA Method 410.4), suspended solids (Standard Method 2540D) and ammonia nitrogen (EPA Method 350.2).

The *E Coli* and *Enterococci* analysis used a defined substrate methodology. Samples to be tested are mixed with specific media and substrates and are incubated at specific temperatures. If the indicator organisms are present, they will cleave the chromofluorogenic substrate with a specific enzyme, producing a chromogen/flurogen that will produce a distinct color/fluorescence. Quantification is performed using a standard MPN algorithm. For more details, see Yakub et al., 2002.

3.2.5 Membrane Cleaning and Maintenance

The membranes were chemically cleaned and the system was disinfected between filtration experiments. The standard chemical cleaning solution is city water containing 1,500 mg/l sodium hypochlorite at pH above 11. The cleaning solution was processed through the system with the permeate valves closed at a temperature above 45^{o}C. The cleaning solution was approximately 10^{o}C at the beginning of the cleaning process. Cleaning was unsuccessful when attempted for 2 hours at the lower temperature. Therefore, cleaning was performed overnight so that the appropriate 45^{o}C cleaning temperature could be attained.

The sodium hypochlorite solution was effective in cleaning the membrane most of the time. However, as the number of times the membrane was cleaned increased and as the concentration of suspended solids in the feed increased, a more aggressive cleaning solution was eventually required. The more aggressive cleaning solution was a 1% nitric acid solution. The nitric acid cleaning was recirculated overnight to reach a temperature of 45^{o}C. Acid cleaning was always done after the alkaline cleaning was completed.

Upon completion of the cleaning process, the system was drained and rinsed and the clean water permeability tests were performed. The results from the clean water permeability tests were compared to the clean water permeability rates using the city water. The clean water permeability test verified that the solids buildup has been removed using the cleaning procedure described above.

The system needed to be disinfected between experiments due to bacterial contamination on the shell side of the membrane caused by the passage of bacteria through larger pore size membranes. The system was disinfected by recirculating a 1,000 mg/L sodium hypochlorite solution at a pH above 11 for 30 minutes without a membrane in the membrane housing module and with the permeate valve open.

When membranes were not in use they were stored in a 1,500 mg/L sodium hypochlorite solution with a pH above 11. Storage in this solution aided the cleaning process and prevented biological growth on the membrane surface and within the membrane.

4.0 RESULTS AND DISCUSSION

This section contains results from both the bench and pilot scale systems. Both systems received primary sewage effluent; the bench scale system operated from April 2002 to October 2002 and the pilot scale system was operated from January 2003 to May 2003. Primary Sewage Effluent (PSE) from the Allegheny County Sanitary Authority (ALCOSAN), Pittsburgh, PA, was used to simulate the wastewater produced during a CSO event. A comparison between the ALCOSAN PSE water quality and typical CSO wastewater quality demonstrates that the primary effluent simulates both the strength and the bacterial levels of CSO wastewater (Table 10). The primary effluent did contain less suspended solids than typical combined sewer overflow wastewater. However, the beginning of a CSO event will contain high solids and bacterial loadings, but the concentration will decrease as the storm event continues [US EPA, 1999b].

Table 10: Average ALCOSAN Primary Effluent Quality Compared to Typical CSO Quality

	Parameter				
	BOD_5	TSS	Total N	NH_3-N	Fecal Coliforms
Wastewater	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(CFU/100 mL)
ALCOSAN PSE [(1)]	68	70	-	9	5,692,000
CSO [(2)]	25 - 100	150 - 400	3 - 24	-	10^5 - 10^7
[(1)] Average Results from Pilot Scale Experimental Data [(2)] US EPA, 2001					

4.1 Bench Scale System

The purpose of the bench scale investigation was to assist in the planning and design of pilot scale experimental protocols. The bench scale experiments evaluated the membrane pore sizes capable of meeting bacterial surface water quality standards, the effect of backpulse on the flux rate, and the impact of the pore size on the permeate flux rate for extended operation.

4.1.1 Impact of Pore Size on Permeate Water Quality

Initial experiments were performed for one to two hours for each membrane (0.2, 0.8, 2.0 and 5.0 μm) to determine the achievable permeate water quality. A specific emphasis was placed on meeting bacterial water quality standards for selecting the membranes to be investigated at the pilot scale. The results from these initial experiments are presented in Table 11. In general, the permeate water quality improved as the mean pore size of the membrane decreased (Figure 14). The membranes with a pore size greater than 0.2 μm produced a variable bacterial permeate water quality, while the 0.2 μm membrane consistently produced permeate with no detectable bacteria. The membranes with a mean pore size of 0.2 and 0.8 μm were capable of meeting water quality standards for bacteria and it was decided to focus the remainder of the bench scale study on these membranes.

Table 11: Primary Effluent and Permeate Water Quality-Initial Bench Research

Primary Effluent

	COD (mg/L)	Fecal Coliforms (CFU/100 ml)	*E Coli* [(1)] (CFU/100 ml)	*Enterococci* [(1)] (CFU/100 ml)
	61-108	1,660,000 - 2,165,797	1,215,000	133,000

Permeate

Pore Size (μm)	COD (mg/L)	Fecal Coliforms (CFU/100 ml)	*E Coli* [(1)] (CFU/100 ml)	*Enterococci* [(1)] (CFU/100 ml)
5.0	48 – 80	750,000 - 1,240,000	905,000	108,000
2.0	45 – 52	4,100 - 46,500	115,000	1,950
0.8	32 – 42	16 – 450	30	ND
0.2	24 – 31	ND	ND	ND

[(1)] *E Coli* and *Enterococci* data consist of a single sample set

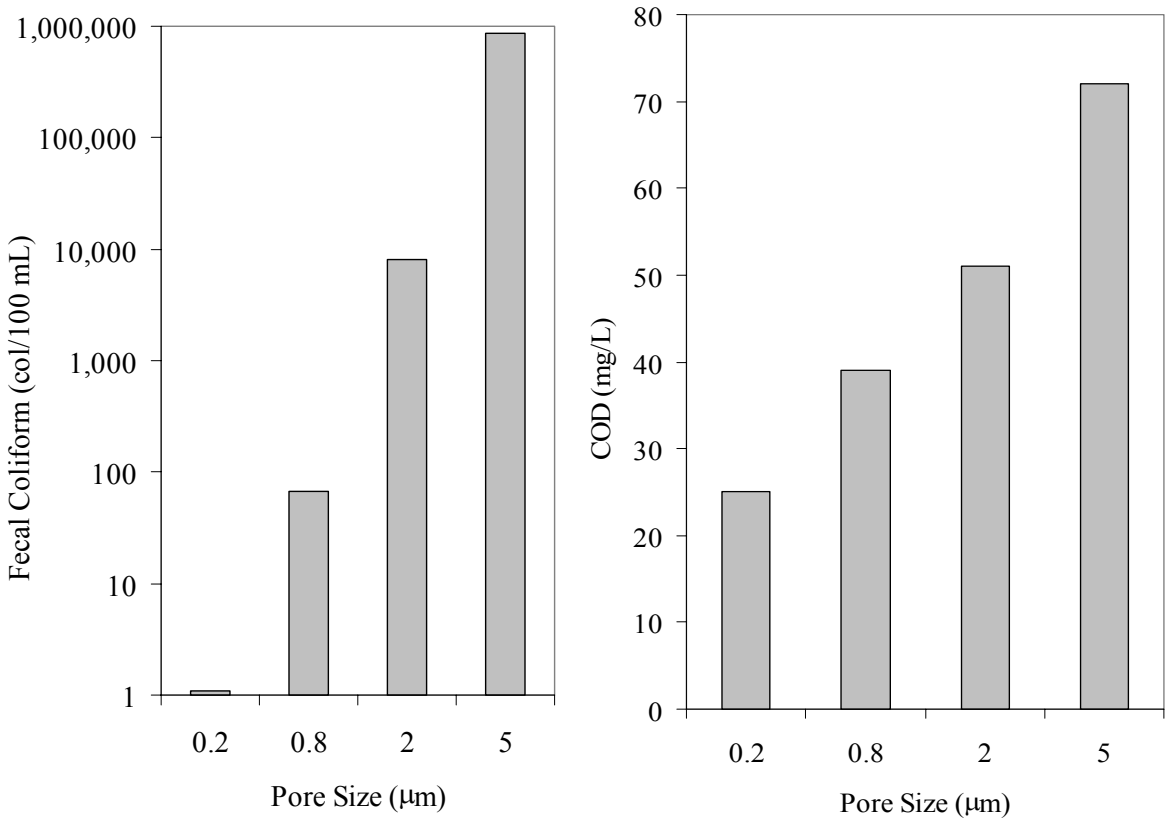

Figure 14: Impact of Pore Size on Average Permeate Water Quality-Initial Bench Research

4.1.2 Impact of the Backpulse

The use of a backpulse reduces membrane fouling and maintains a greater flux rate during filtration of a primary sewage effluent [Gan, 1999]. Initial short-term testing was performed to confirm the benefit of the backpulse on permeate flux rates (Figure 15). The 0.8 μm membrane was operated with a backpulse frequency of 30 seconds for one hour. The flux rate approached steady state at a flux of 170 L/hr-m^2. The backpulse was then switched off and a 63% decrease in the flux was observed within 15 minutes. The backpulse was then turned on and the membrane was operated for another 45 minutes. The backpulse could not completely restore

the permeate flux to a rate of 170 L/hr-m^2, but it is clear that it is effective in maintaining higher permeate flux and should be operated continuously.

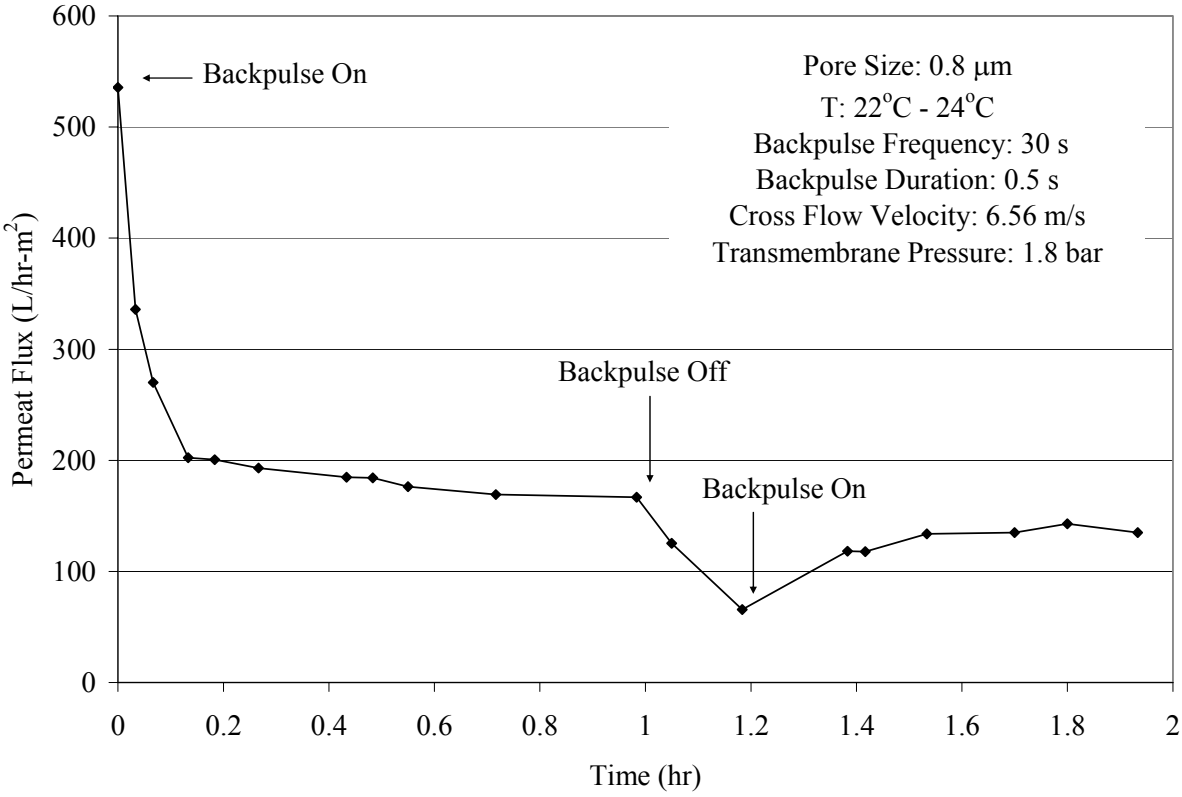

Figure 15: Demonstration of Backpulse Benefit

Despite the benefit in the permeate flux rate, the backpulse has an adverse effect on the permeate water quality (Table 12). Short-term (up to two hours) experiments were conducted with and without backpulsing for the 2.0, 0.8 and 0.2 μm membranes. The membranes were operated under identical conditions with a transmembrane pressure of 1.2 bar, a cross flow velocity of 6.56 m/s and within a temperature range of 21-25°C. The frequency of the backpulse was controlled at 94 sec with a 0.5 sec duration. The use of the backpulse facilitated a greater passage of bacteria for the 2.0 and 0.8 μm membranes, while the 0.2 μm membrane consistently

produced a permeate with no detectable fecal coliforms bacteria. Clearly, the faster and more extensive build up of the fouling layer in the absence of the backpulse helps in filtering bacteria from the primary effluent. These findings are supported by recent studies on the cross-flow microfiltration of primary sewage effluent, which demonstrated that the use of a backpulse resulted in a higher solids concentration in the permeate [Gan, 1999]. Despite the increase in bacterial passage, the ability of the backpulse to improve the permeate flux rate was considered to be a greater advantage that should be utilized to reduce costs.

Table 12: Impact of Backpulse on Permeate Water Quality

Pore Size (μm)	Backpulse (on/off)	Fecal Coliforms CFU/100 mL
2.0	on	6,212
	off	4,100
0.8	on	116
	off	16
0.2	on	ND
	off	ND

4.1.3 Impact of the Backpulse Frequency

The backpulse represents an additional cost to membrane operation and decreases effective filtration time. Therefore, the ability of an increased backpulse frequency to facilitate higher flux rates was investigated. The 0.2 and 0.8 μm membranes were operated for 24 hours with a backpulse frequency of 60 and 94 seconds for a backpulse duration of 0.5 seconds. The experiments were performed under identical operating conditions with a cross flow velocity of 6.56 m/s, a transmembrane pressure of 1.2 bar, a backpulse duration of 0.5 seconds and within a temperature range of 22-26 ^{o}C. The flux rates after 24 hours of filtration are shown in Table 13.

The increase in backpulse frequency has a beneficial impact on the permeate flux. An 18.3 percent improvement in the flux rate was observed for the 0.2 μm membrane and a 13.1 percent improvement in the flux rate was observed for the 0.8 μm membrane. The observation of a greater flux rate for the 0.2 μm membrane than the 0.8 μm membrane is discussed in Section 4.1.4.

Table 13: Impact of Backpulse Frequency on Flux

	24-Hour Steady State Flux (L/hr-m2)	
Backpulse	Pore Size (μm)	
Frequency (s)	0.2	0.8
60	273	229
94	223	199

The 0.8 μm membrane was then further investigated with a backpulse frequency of 30 seconds and 120 seconds. The experiments were performed under identical operating conditions with a cross flow velocity of 6.56 m/s, a transmembrane pressure of 1.2 bar, a backpulse duration of 0.5 seconds and within a temperature range of 22-26 ^{o}C. The steady state flux rates after 24 hours of operation are shown in Figure 16. The 24-hour steady state flux rates demonstrate unexpected variation in the permeate flux rate with changes in the backpulse frequency. It is not clear why a greater flux rate was observed for a 120-second backpulse frequency than for a 90-second backpulse frequency. As expected, the flux increased with an increase in the backpulse frequency increase from 90 seconds to 60 seconds. However, no further increase in the flux rate was observed when the backpulse frequency was increased to 30 seconds. Based on these results, the 60 second frequency was selected as the preferred backpulse frequency for this membrane system.

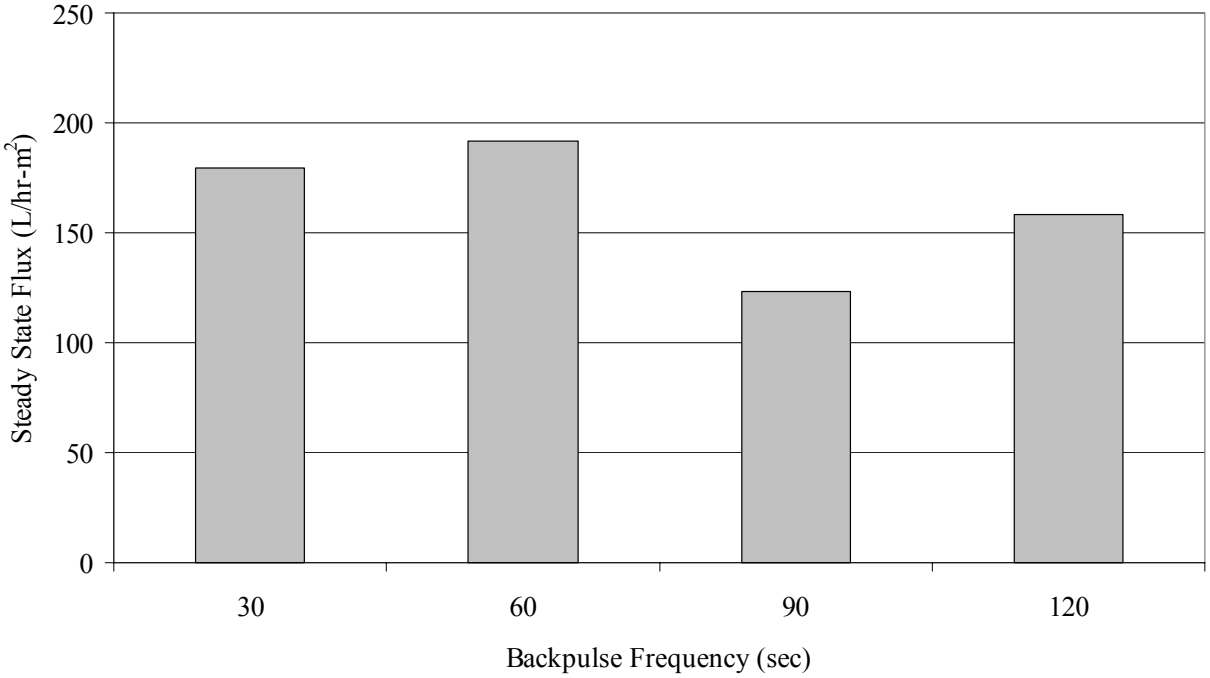

Figure 16: Impact of Backpulse Frequency on Flux – 0.8 μm

4.1.4 Long Term Performance

To better simulate an actual CSO event and to understand the long-term performance, 48-hour filtration experiments were conducted using both the 0.8 and 0.2 μm membranes. Experiments were preformed with a transmembrane pressure of 1.2 bar, a cross flow velocity of 6.56 m/s, a backpulse frequency of 94 s, a backpulse duration of 0.5 sec, and within a temperature range of 22-28^{o}C. The 0.8 μm membrane initially produced a permeate flux rate of 836 L/hr-m^2 compared to the initial permeate flux rate of 507 L/hr-m^2 for the 0.2 μm membrane. However, as can be seen in Figure 17, the 0.2 μm membrane produced a greater permeate flux rate than the 0.8 μm membrane in the later stages of the experiment. The final flux rates were

202 L/hr-m^2 and 181 L/hr-m^2 for the 0.2 μm and 0.8 μm membranes, respectively. Similar observations were also made in the case of beer clarification where a cross flow 0.5 μm ceramic membrane operated with a backpulse produced a greater permeate flux rate than a 1.3 μm membrane [Gan, et al, 1997]. The lower permeate flux rate for the larger pore size membrane is believed to be due to the difference in the fouling mechanism. The smaller pore size rejects many of the smaller particles that can enter the larger pores and create more severe internal fouling.

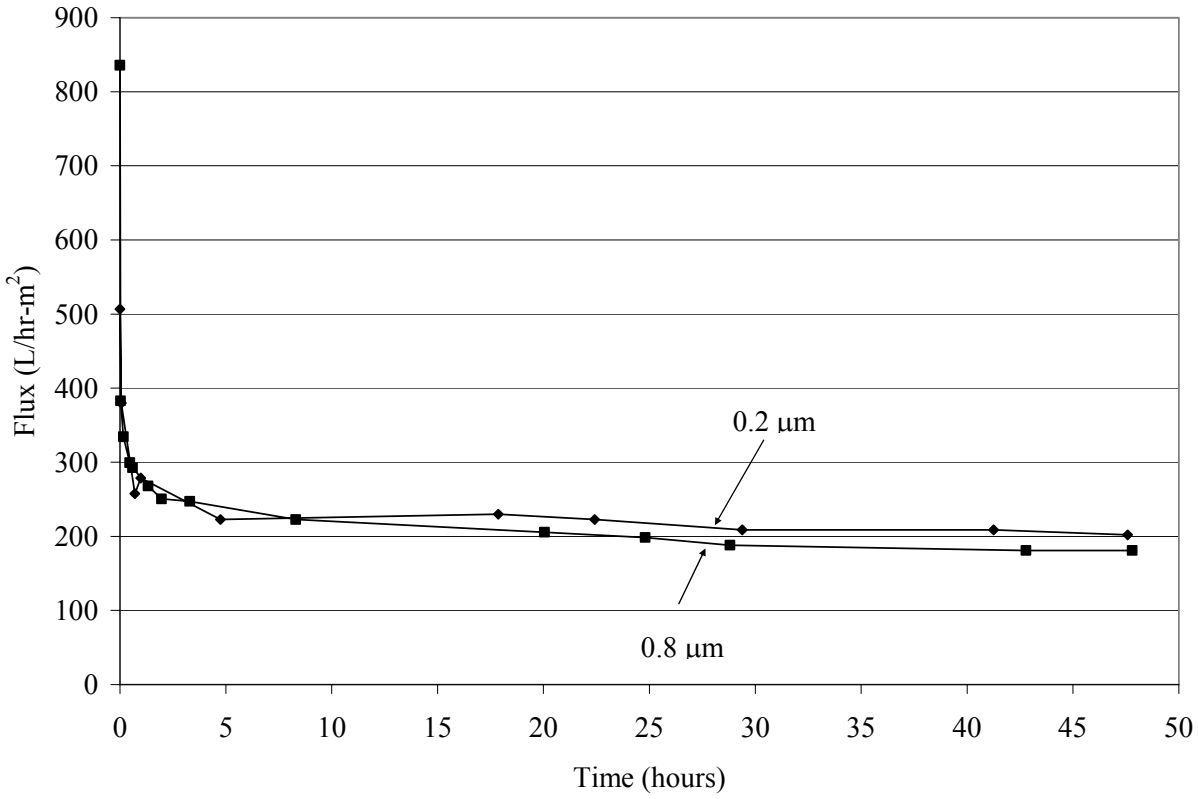

Figure 17: Long Term Performance

4.1.5 Impact of the Fouling Layer on Permeate Water Quality

The variation in fecal coliforms levels depicted in Table 11 can be attributed to the buildup of the fouling layer on the membrane surface during the filtration experiment. As can be seen in Figure 17, the flux decreases rapidly and then levels towards a steady state value. The decrease in the flux is attributed to the buildup of the fouling layer. Throughout testing, samples were taken during the period of rapid flux decline. Those results indicated that the formation of the fouling layer benefits the bacterial permeate quality for the 2.0 μm and 0.8 μm membranes, while the 0.2 μm membrane consistently produced a permeate water quality with no detectable fecal coliforms bacteria (Figure 18). These results are supported by previous research that demonstrated an initial breakthrough of fecal coliforms bacteria, with an increase in rejection as the membrane reaches steady-state operation [Till et al., 1998].

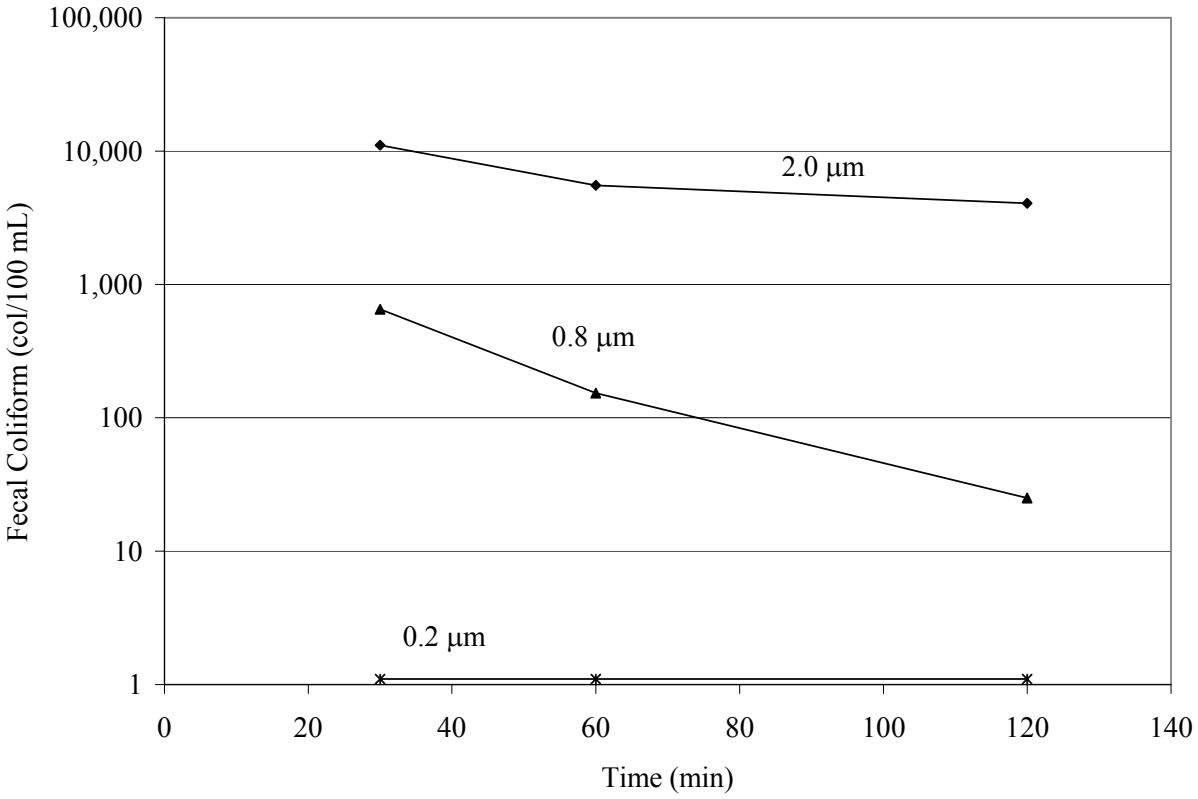

Figure 18: Improvement in Permeate Quality with Time

4.2 Pilot Scale System

The pilot scale experiments were conducted to determine the preferred membrane pore size, cross flow velocity, transmembrane pressure and operating mode. In addition, experiments were performed to determine the impact of suspended solids and temperature on the steady state flux rates.

4.2.1 Impact of Pore Size

The bench scale system demonstrated that membranes with a mean pore size less than 2.0 μm were capable of meeting applicable bacterial water quality standards. Therefore, five membranes with a mean pore size below 2.0 μm (0.05, 0.2, 0.5, 0.8 and 1.4 μm) were tested to select a preferred pore size for further evaluation based on the permeate water quality and steady state flux rates

The five membranes were operated with a transmembrane pressure of 0.7 bar, a cross flow velocity of 2.7 m/s, a backpulse frequency of 60 seconds and the permeate was discharged to the drain. Bench scale testing demonstrated that a steady state flux rate with primary effluent is reached after 6 hours (Figure 17). Thus, each pilot scale experiment in this phase of the study was performed in duplicate for a period of 6 hours. The feed and permeate water quality was sampled after 0.5 and 5.5 hours of operation. The membranes were chemically cleaned with alkaline sodium hypochlorite solution prior to each experiment to ensure accurate flux data.

All water quality results from these experiments are presented in Appendix A Table A.1 to A.5. These results are summarized in Table 14. The data indicate that all membranes are capable of meeting the applicable water quality standards for bacteria, BOD_5 and suspended solids. All membranes with a pore size less than 0.8 μm demonstrated no detectable bacteria in

the permeate. Surprisingly, the 1.4 μm membrane demonstrated no detectable bacteria in the permeate, while the 0.8 μm allowed for bacterial passage. Therefore, the 1.4 μm was cleaned and operated for another 24 hours. The permeate was analyzed for bacteria at 0.5 and 24 hours and no detectable bacteria were observed.

Table 14: Feed and Permeate Water Quality

Pore Size (μm)	Fecal Coliforms (CFU per 100 mL)	*E.Coli* (MPN per 100 mL)	*Enterococci* (MPN per 100 mL)	BOD (mg/L)	SS (mg/L)	COD (mg/L)	NH_3-N (mg/L)
Feed							
	6,334,176	402,618	155,545	74	84	157	8
Permeate							
0.05	< 2	< 1	< 1	18.3	0.6	58.6	5.60
0.2	< 6	< 1	< 1	9.7	0.8	71.5	4.50
0.5	< 2	< 1	< 1	14.3	0.3	34.8	5.00
0.8	8	8	< 4	16.7	0.4	61.8	5.30
1.4	< 2	< 1	< 1	18.3	0.4	52.0	6.70
Feed Sample Size - 20, Permeate Sample Size - 4							

In addition to monitoring the water quality, the flux rates were monitored throughout each experiment. The 6-hour steady state flux was selected as the main criteria for evaluation. The 6-hour steady state flux rate for each experiment and the corresponding suspended solids levels are shown in Figure 19. Slight variations in the flux rate can be attributed to the variation in the feed suspended solids concentration. The flux rates for each pore size were then averaged and plotted in Figure 20. The flux rates shown in Figure 19 and Figure 20 are corrected to 20^{o}C.

The results in Figure 17 demonstrate an improved flux rate with an increase in pore size from 0.05 to 0.2 μm. For all membranes greater than 0.05 μm, a similar steady state flux rate was observed. These results suggest that the 0.05 μm membrane represents a physical barrier that

contributes a significant role in controlling the flux rate and/or developing the fouling layer. For pore sizes greater than 0.05 μm, the common steady state flux rate may be attributed to a similarity of the fouling layer or to larger pore sizes being more likely to have more pronounced internal fouling. A discussion in Section 4.2.8 addresses the reasons for the similarity in the flux rates observed in Figure 20.

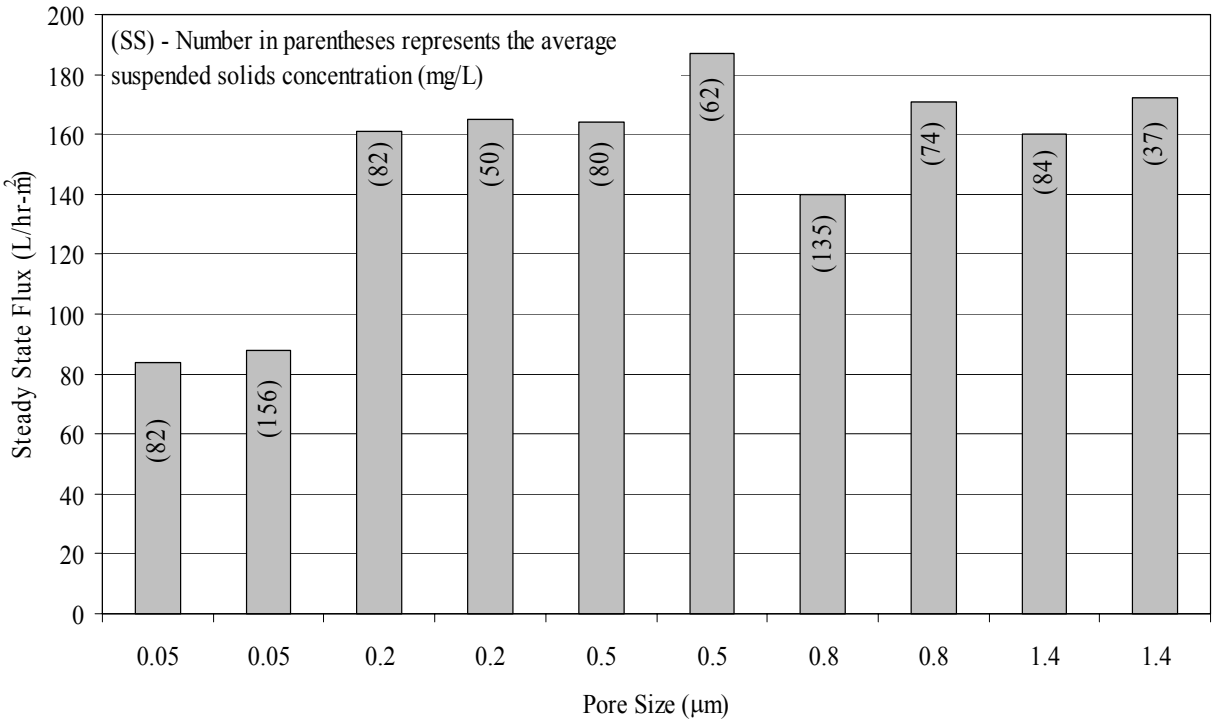

Figure 19: Steady State Flux Rates

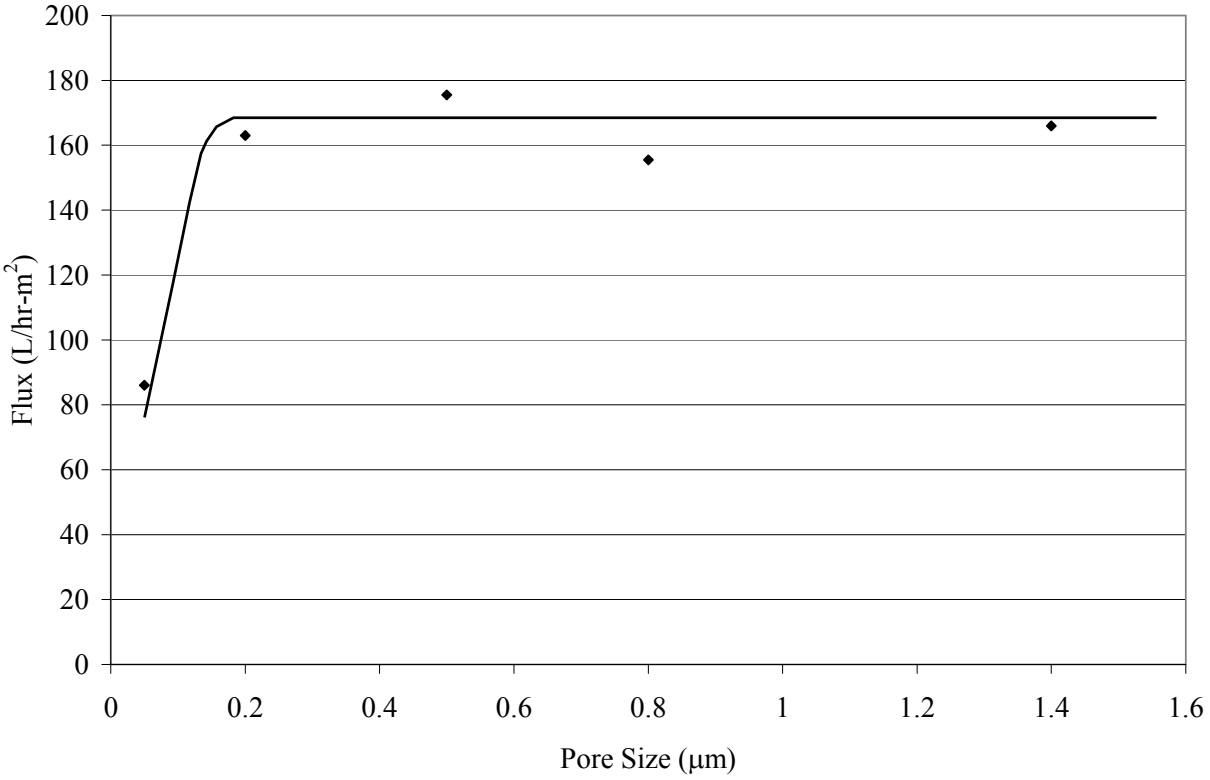

Figure 20: Pore Size versus Steady State Flux Rate

The 6-hour steady state flux rates indicate that by using a membrane with a pore size greater than 0.2 μm no benefit in flux will be achieved. In addition, an increase in pore size from 0.2 μm would increase the risk of bacteria passage through the membrane. Therefore, the 0.2 μm membrane was selected for further testing.

4.2.2 Impact of Cross Flow Velocity and Transmembrane Pressure

A 15 experiment testing matrix using the 0.2 μm membrane was utilized to evaluate the process for cross flow velocity and transmembrane pressure. The matrix consisted of three transmembrane pressure settings (0.7, 1.4 and 2.1 bar) operated at four or five cross flow velocity settings (0.5, 0.9, 1.8, 2.7 and 3.7 m/s). Each experiment was performed for 6 hours with a backpulse frequency of 60 seconds and the permeate was recycled to the process tank to maintain a constant feed concentration. The membrane was chemically cleaned with alkaline sodium hypochlorite solution prior to each experiment to ensure appropriate initial conditions. All flux rates and data presented in this section are based on the flux rate corrected to 20^{o}C. Feed and permeate water quality samples were taken after 0.5 and 5.5 hours of operation. All results are presented in Appendix A Tables A.6 to A.19. These water quality results, along with the results from other experiments will be discussed in Section 4.2.7.

The focus of these experiments was placed on the steady state flux rate. The 6-hour steady state flux rate as a function of the cross flow velocity is depicted in Figure 21 for each transmembrane pressure. These results clearly point to an improvement in flux with an increase in cross flow velocity until the cross flow velocity reaches 1.8 m/s. For an increase in cross flow velocity greater than 1.8 m/s, the improvement in flux rate is negligible. The increase in pumping costs for all velocities greater than 1.8 m/s will not be rewarded with a higher flux rate. Therefore, from a process engineering perspective, the preferred cross flow velocity is 1.8 m/s.

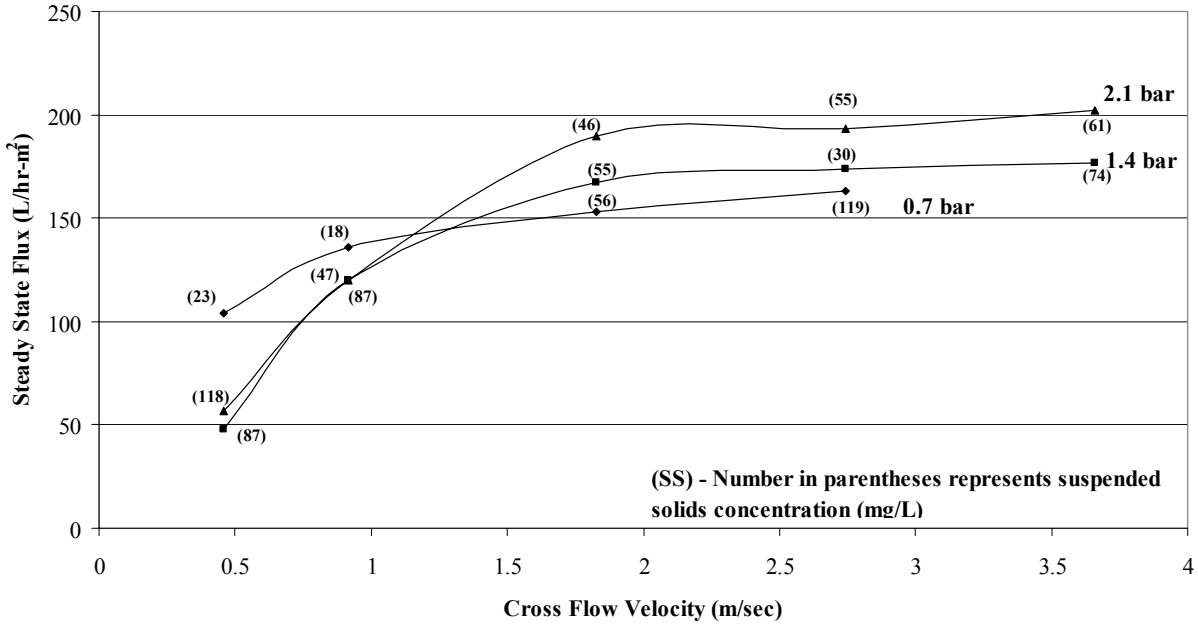

Figure 21: Impact of Cross Flow Velocity on Steady State Flux – 0.2 μm

The three curves on Figure 21 follow a similar trend. For cross flow velocities greater than 0.8 m/s, a higher flux rate is achieved at a higher transmembrane pressure. While, a similar flux rate is achieved for a cross flow velocity of 0.5 or 0.8 m/s regardless of the transmembrane pressure, except for a 0.7 bar transmembrane pressure. The experiments at 0.7 bar do not have the same trend because the suspended solids concentrations in the feed were one-half to one-sixth of the feed concentrations for other experiments. The data collected at 1.4 and 2.1 bar indicate that the scouring effect at low cross flow velocities (< 1.0 m/s) may not be sufficient enough to overcome the adhesion and compaction of the solids on the membrane surface. Thus, for low cross flow velocities (< 1.0 m/s) the particles that accumulate at the membrane surface may form a hydraulic barrier that controls the steady state flux rate.

The same data set can be used to evaluate the impact of transmembrane pressure on the steady state flux. Figure 22 shows the impact of transmembrane pressure on the steady state flux rate for each cross flow velocity. Experiments with suspended solids concentrations in the feed below 30 mg/L are ignored. These data demonstrate a marginal improvement in permeate flux for an increase in transmembrane pressure at low cross flow velocities (0.5 and 0.9 m/s). At higher cross flow velocities (1.8 and 2.7 m/s), the steady state flux rate increases as the transmembrane pressure increases.

The selection of a preferred transmembrane pressure is not as straightforward as the selection of a preferred cross flow velocity. For the preferred cross flow velocity of 1.8 m/s there is a continual increase in the steady state flux rate as the transmembrane pressure is increased (Figure 22). However, the improvement in the steady state flux rate with an increase in pressure is not substantial. Thus, the tradeoff between pumping costs and improved flux rates can not be easily determined. A continued discussion on the selection of a preferred transmembrane pressure is contained in Section 4.2.3.

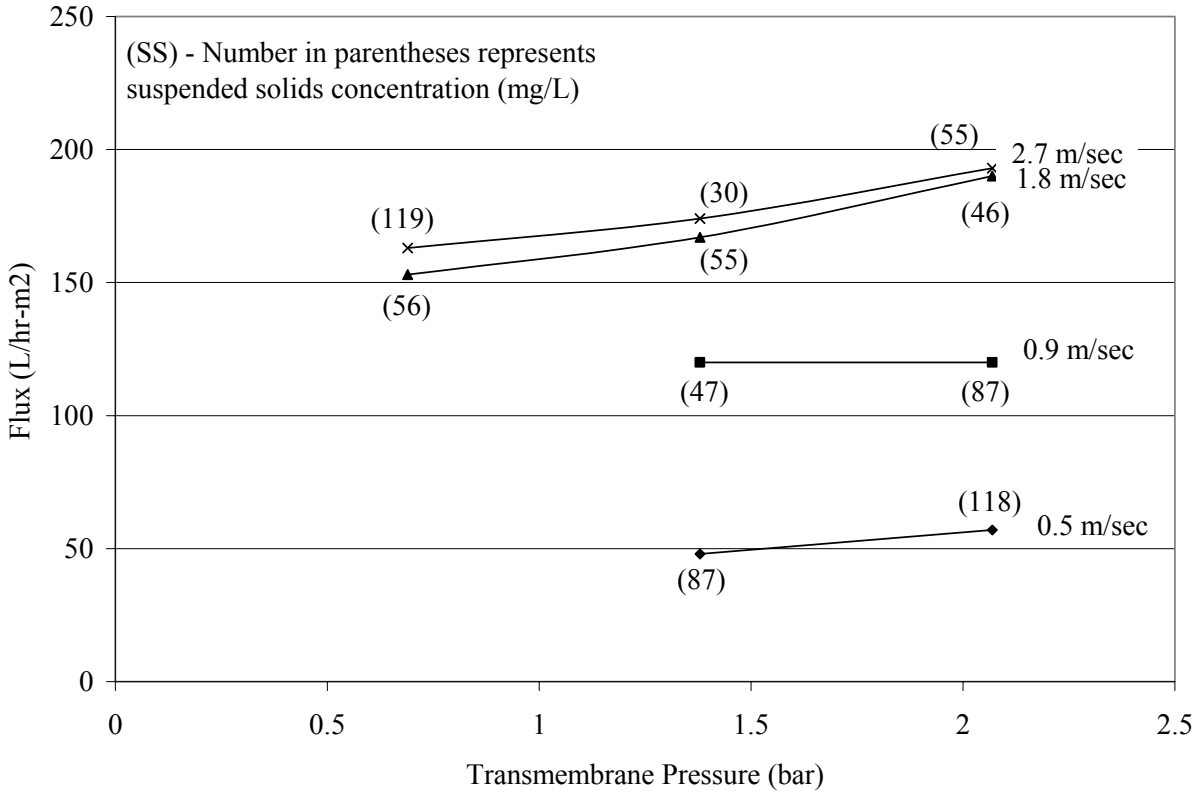

Figure 22: Impact of Transmembrane Pressure on Steady State Flux – 0.2 μm

4.2.3 Power Analysis

The power requirement was measured for each experiment in section 4.2.2. Isolating the pumping power created a safety hazard due to the exposure of bare wire in a wet environment. Therefore, measurements include the power to operate the pump and the variable frequency drive (VFD). The power requirement of the VFD is considered to be significant and the results in this section are system specific as a VFD is not necessary for the operation of a membrane system.

This system uses a 480-Volt 3-Phase power supply. The current for all power phases were measured for each experiment. The average current and voltage draw were then used to

calculate the power usage. These results, presented in Table 15, show that power usage increases with an increase in transmembrane pressure or cross flow velocity.

Table 15: System Specific Power Usage (Watts) for the Pump and VFD

	Cross Flow Velocity (m/s)				
Transmembrane Pressure	0.5	0.9	1.8	2.7	3.7
0.7 (bar)	230	336	502	686	-
1.4 (bar)	464	475	667	886	1049
2.1 (bar)	558	671	898	1186	1289

Next, the power usage (Table 15) was combined with the steady state permeate flow rates (Figure 20) to determine the estimated operating costs per 1,000 L of permeate based on an energy cost of $0.03/kilowatt-hr. Experiments with suspended solids concentrations in the feed less than 30 mg/L are not included within this analysis. These results are tabulated in Table 16 and graphically shown in Figure 23.

Table 16: System Specific Power Costs ($) for 1,000 L of Permeate

	Cross Flow Velocity (m/s)				
Transmembrane Pressure	0.5	0.9	1.8	2.7	3.7
0.7 (bar)	-	-	0.27	0.35	-
1.4 (bar)	0.80	0.33	0.33	0.42	0.50
2.1 (bar)	0.82	0.47	0.39	0.51	0.53

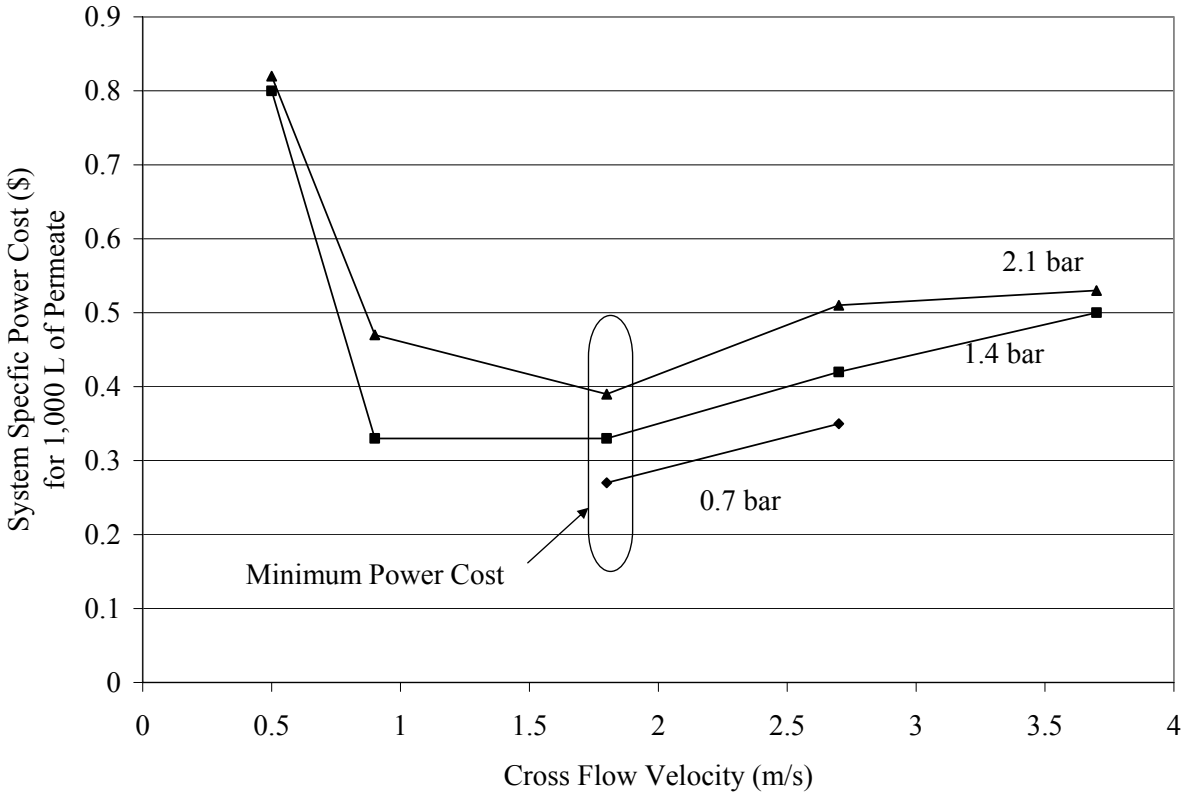

Figure 23: System Specific Power Costs ($) for 1,000 L of Permeate

As previously discussed in Section 4.2.2., the preferred cross flow velocity is 1.8 m/s. That result is supported by the system specific power costs. Figure 23 demonstrates a decrease in cost until the cross flow velocity reaches 1.8 m/s. For all velocities greater than 1.8 m/s the cost increases. Therefore, from a power cost perspective, the preferred cross flow velocity is 1.8 m/s.

The selection of an optimal transmembrane pressure is still unclear. Using the preferred 1.8 m/s cross flow velocity, an increase in transmembrane pressure from 0.7 to 2.1 bar causes a 44% increase in power costs. Based on power costs, the preferred transmembrane pressure would be 0.7 bar. However, there is more than power costs associated with membrane systems, such as

the high capital costs of the membranes. The consideration of the overall cost efficiency then becomes a tradeoff between operating costs and capital costs. A more detailed cost analysis would be needed to better understand the tradeoff between pumping cost and capital costs.

4.2.4 Impact of Suspended Solids

An increase in the feed suspended solids concentration is anticipated to encourage the development of the fouling and make filtration more difficult. In order to develop a system that can handle a variety of influent suspended solids concentrations, the relationship between the feed suspended solids and the steady state flux rate needs to be understood.

An experiment, using the 0.2 μm membrane, was conducted over a 5-day period and evaluated four suspended solids concentrations. The process tank was filled with the primary sewage effluent and the permeate was returned to the tank to ensure a constant feed concentration. The steady state flux rate was recorded after 24 hours of operation and both the feed and permeate water quality samples were collected. Then, the permeate was discharged to the drain and the water level in the tank was lowered. The permeate routinely has less than 1.0 mg/L of suspended solids. Therefore, the feed wastewater will now be more concentrated. When the water level reached the desired height, the permeate was returned to the feed tank and the steady state flux was measured after 24 hours of filtration and feed and permeate water quality samples were collected. The feed suspended solids were increased in the same manner in subsequent tests. The experiment was performed with a transmembrane pressure of 0.7 bar, a cross flow velocity of 1.9 m/s and a backpulse frequency of 60 seconds. The water quality results are available in Appendix A Table A.20. Water quality results from this experiment, along with the results from other experiments will be discussed in Section 4.2.7. The membrane was chemically cleaned with alkaline sodium hypochlorite solution prior to the experiment to ensure

appropriate initial conditions. These are the same operating conditions as an experiment performed in Section 4.2.2. The steady state flux rate from that experiment along with the results from this experiment is given in Figure 24. All flux rates and data presented within this section are corrected to 20°C.

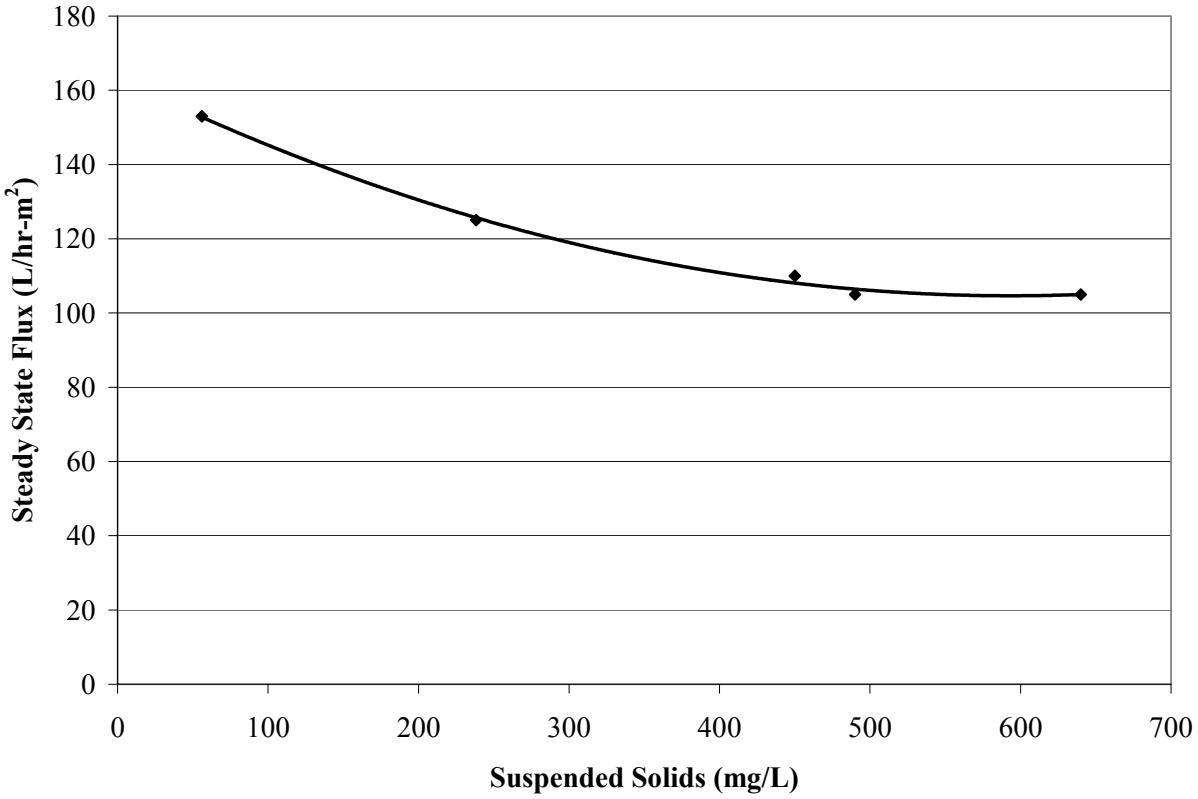

Figure 24: Field Unit – Impact of Suspended Solids on Steady State Flux – 0.2 μm

Figure 24 demonstrates that the steady state flux rate is affected by the concentration of suspended solids in the feed wastewater. The steady state flux decreased until the feed solids concentration reached between 400 to 500 mg/L. The steady state permeate flux appears to remain constant at approximately 105 L/hr-m^2 for all concentration greater than 500 mg/L.

4.2.5 Impact of Temperature

As the temperature of a fluid increases, the viscosity of the fluid decreases. Therefore, an increase in temperature will lead to higher flux rates. In order to compare flux rates independent of temperature the standard viscosity correction factor was used (Equation 5). An experiment using the 0.2 μm membrane was performed to evaluate the impact of temperature on the steady state flux rate and to evaluate the accuracy of the standard viscosity correction factor.

The membrane was chemically cleaned with alkaline sodium hypochlorite solution prior to the experiment to ensure accurate flux data. The process feed tank was filled with primary sewage effluent and filtration was performed for 6 hours with a transmembrane pressure of 1.4 bar, a cross flow velocity of 1.9 m/s, a backpulse frequency of 60 seconds and the permeate was recycled to the feed tank to ensure a constant feed concentration. After 6 hours, the process feed tank was drained and refilled with fresh primary effluent at a temperature of 12^{o}C. The fresh primary effluent was then sampled. Water quality results are presented in Appendix A Table A.21. These water quality results, along with the results from other experiments will be discussed in Section 4.2.7.

The temperature in the feed tank was increased to 26^{o}C and the flux rate was monitored as the temperature increased. These results are shown in Figure 25. The data demonstrate that as the temperature increases, the steady sate flux rate increases. An increase in temperature from 12 to 26^{o}C increased the flux by nearly 30% from 82 to 116 L/hr-m^2, which demonstrates that the operating temperature is a critical parameter in system design and performance. At each temperature the predicted flux rates were calculated using the standard viscosity correction factor. The measured and predicted flux rates are show in Table 17. These results demonstrate

that the largest variation being only 4% at 23°C. A plot of measured versus predicted flux shown in Figure 26 further demonstrates the accuracy of the standard viscosity correction factor. The data demonstrate a coefficient of determination (R^2) of 0.9904.

Table 17: Measured and Predicted Flux Rates

Temperature (°C)	12	15	18	21	23	26
Measured Flux (L/hr-m^2)	82	90	97	101	105	116
Predicted Flux to 20°C	104	104	103	101	97	97

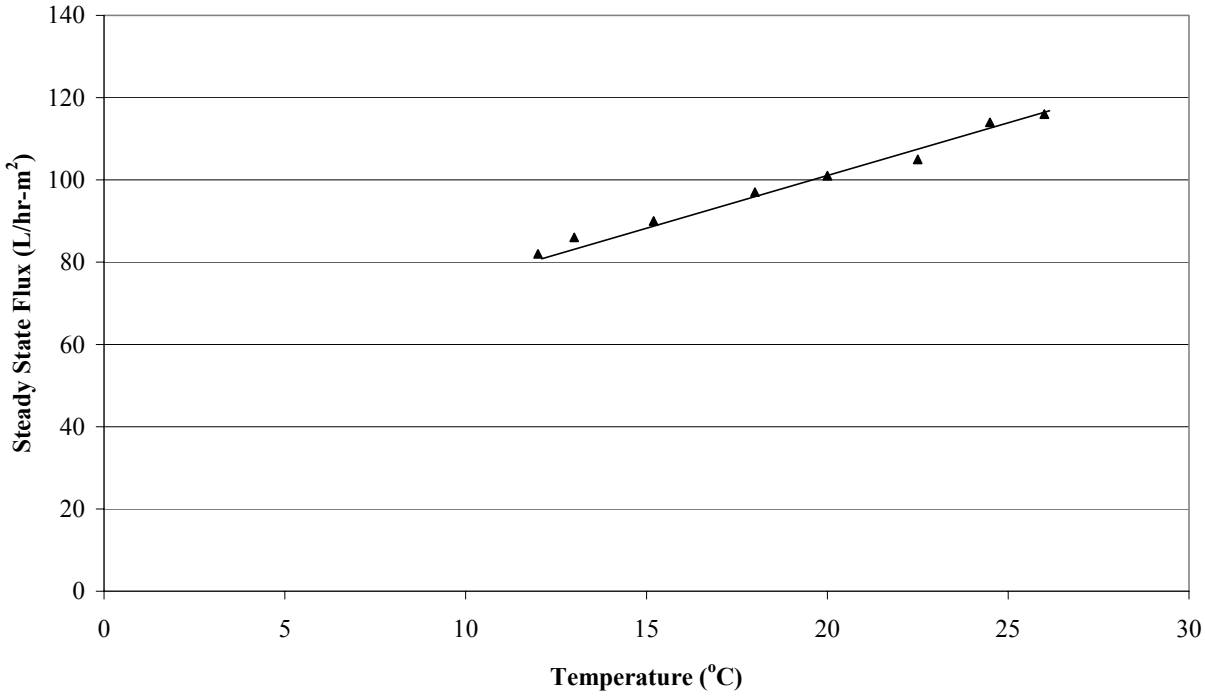

Figure 25: Field Unit – Impact of Temperature on Steady State Flux – 0.2 μm

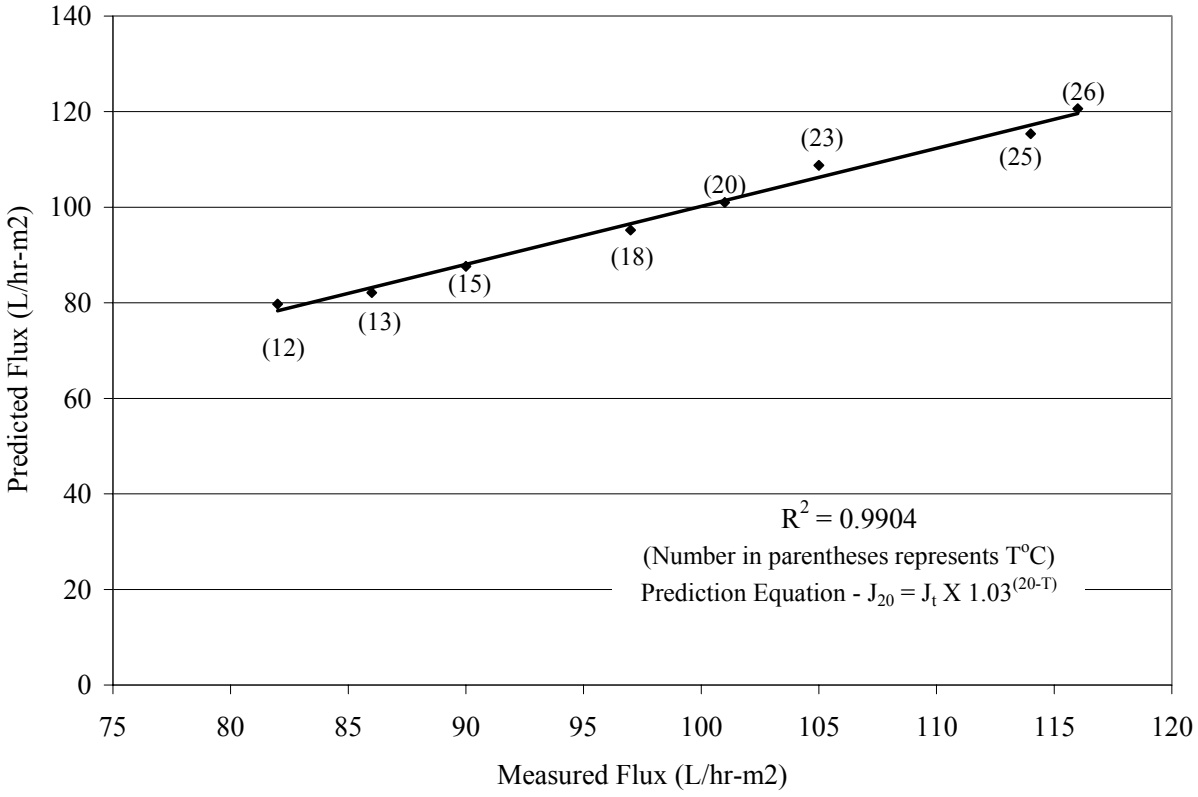

Figure 26: Field Unit – Accuracy of Flux Correction Equation

4.2.6 Impact of Operating Mode

Two common modes of operation for cross flow microfiltration systems are constant pressure operation and varying pressure operation. Constant pressure operation controls the transmembrane pressure and allows for the treatment of as much wastewater as possible. Under constant pressure operation, the relationship between flux versus time is similar to Figure 5, a rapid flux decline occurs until a steady state flux is reached.

Varying pressure operation attempts to keep the initial flux rate constant. Under varying pressure operation, the inlet and outlet pressure are held constant and the permeate pressure is

varied to maintain a constant flux rate. When the permeate pressure becomes atmospheric the mode of operation becomes constant pressure.

During constant pressure operation, it is believed that the initial rapid flow of water through the membrane forces particles into the membrane pores creating more severe internal fouling. By keeping the initial flux rate constant and varying the pressure, it is believed that fewer particles are pushed into the pores creating less severe fouling. Varying pressure operation is believed to minimize fouling by allowing for the formation of the fouling layer that prevents particles from being pushed into the membrane pores.

To simulate a CSO event and to evaluate the different modes of operation, a three day (72-hour) experiment was conducted for each operating mode using the 0.2 μm membrane. The constant pressure experiment was conducted with a 1.4 bar transmembrane pressure, a 1.8 m/s cross flow velocity and a backpulse frequency of 60 seconds. The varying pressure experiment was conducted with a feed pressure of 1.4 bar, a varying permeate pressure, a 1.8 m/s cross flow velocity and a backpulse frequency of 60 seconds. The membranes were chemically cleaned with alkaline sodium hypochlorite solution prior to each experiment to ensure accurate flux data. The varying pressure experiment attempted to maintain a flux rate of 150 to 160 L/hr-m^2. For each experiment, the permeate was discharged to the drain and fresh primary effluent was fed to the process tank. Water quality results are presented in Appendix A Tables A.22 to A.23. The water quality for the feed and permeate was monitored daily and these results, along with the results from other experiments will be discussed in Section 4.2.7.

The flux results from the constant pressure and varying pressure experiments (Figure 27) demonstrate that after 1-hour of operation both modes of operation produced similar flux rates. For the varying pressure experiment, the permeate pressure was atmospheric after two hours.

The mode of varying pressure did produce a higher flux rate after 24 hours, but not after 48 hours.

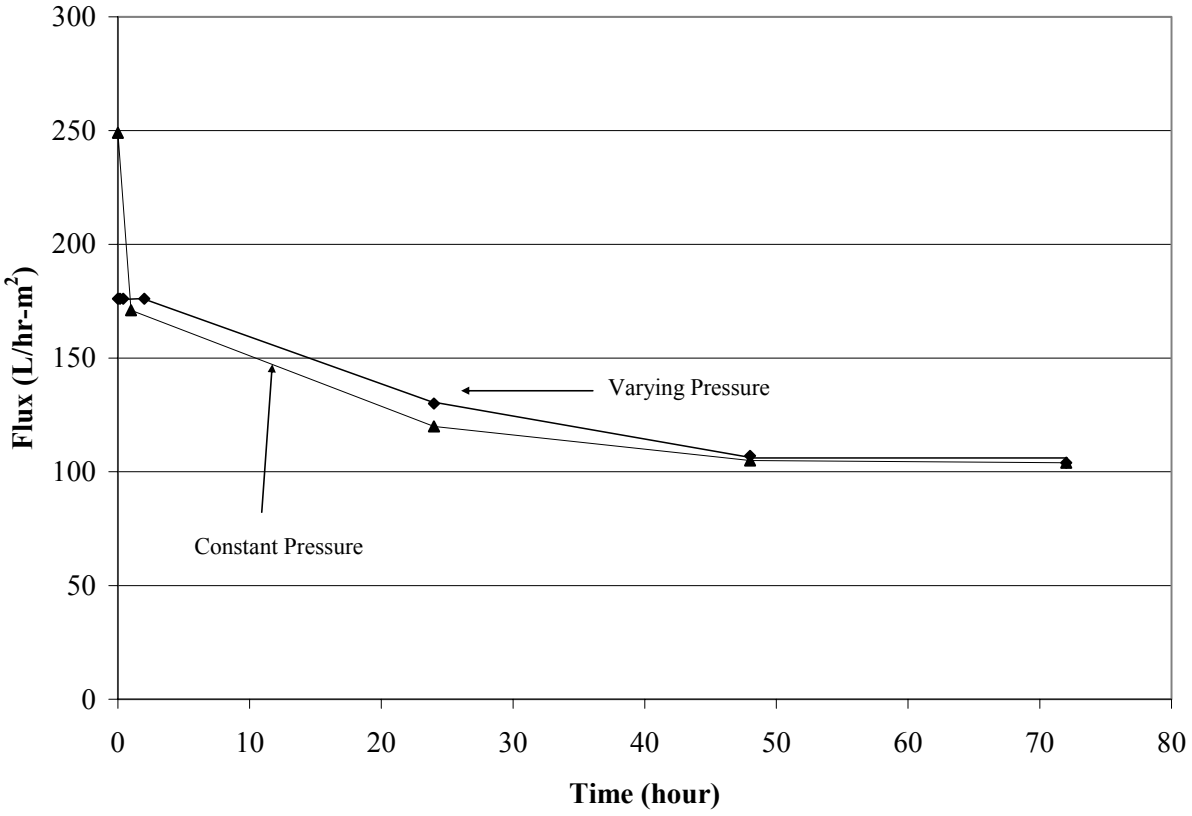

Figure 27: 72-Hour Mode of Operation Experiments – 0.2 μm

During the suspended solids experiments (Section 4.2.4), after the initial steady state flux rate was achieved, the permeate flow rate was slow enough that the flux rate is continually at steady state. Therefore, the relationship between suspended solids and the steady state flux rate can be determined for each operating mode. These results are shown in Figure 28. The varying pressure operation produced a greater flux rate until the suspended solids concentration reached approximately 300 mg/L. Beyond 300 mg/L, each mode of operation produced similar flux rates.

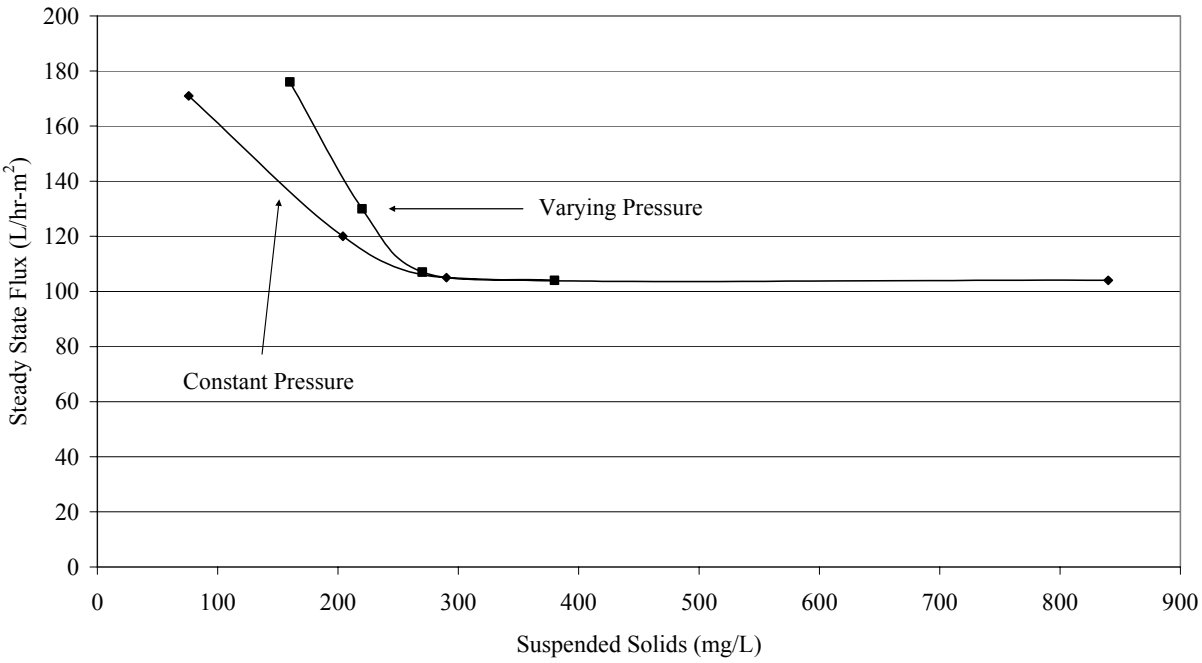

Figure 28: Impact of Suspended Solids for Mode of Operation Experiments – 0.2 μm

The results from these experiments indicate that the varying pressure operation will produce a greater flux rate for feed suspended solids concentrations less than 300 mg/L and it should be the preferred mode of operation.

4.2.7 Water Quality Analysis to Meet WQS

Initial experiments at various pore sizes (Section 4.2.1) suggested a preferred membrane pore size of 0.2 μm. Thus, the 0.2 μm membrane was further evaluated for achievable permeate water quality. A total of 50 feed and 50 permeate samples were analyzed for fecal coliforms, *E Coli*, *enterococci*, BOD_5, COD, SS and NH_3-N. The maximum , minimum and average concentration, along with standard deviations for both the feed and the permeate are shown in Table 18. In addition, Table 19 shows the feed and permeate concentrations when the feed concentration was at a maximum.

The data clearly demonstrate that the 0.2 μm membrane continually met the water quality objectives for bacteria, BOD_5 and SS. The permeate bacteria quality was excellent, with only two of the 150 bacteria samples having detectable bacteria. Those two results were well below the water quality objective. All SS concentrations were below the objective of 30 mg/L, with an average permeate concentration of 1.0 mg/L. The average BOD_5 (18 mg/L) was well below the objective (30 mg/L), with only 8 out of the 50 BOD_5 samples being greater than 30 mg/L. In addition, the technology demonstrates consistent results independent of the feed concentration. The 0.2 μm membrane was able to meet all water quality objectives at the maximum influent levels for each parameter (Table 19).

Secondary treatment standards for BOD5 and SS not only require a monthly average concentration, but also a monthly average percent removal of 85%. The average SS removal of 99% is well above 85% removal required, while the average BOD_5 removal was only 71%. To meet the 30 mg/L requirement and have an 85% reduction, the feed BOD_5 must be 200 mg/L. The average BOD_5 for these experiments was only 103 mg/L. Of the 50 feed BOD_5 samples

analyzed, only 7 BOD_5 feed concentrations were greater than 200 mg/L. For those 7 feed concentrations, the average percent removal was 97%. Thus, the technology can meet the percent removal requirement when the feed BOD_5 is at normal levels. The regulations acknowledge that less concentrated wastewater causes difficulty for compliance with the percent removal requirements. Therefore, for dilute wastewaters that consistently meet the concentration requirements, lower percent removal requirements may be allowed as determined by the state.

Table 18: Water Quality Analysis - 0.2 μm Membrane

	Fecal Coliforms	*E Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	CFU/100 mL	CFU/100 mL	CFU/100 mL	mg/L	mg/L	mg/L	mg/L
Feed							
Max	35.0×10^6	17.3×10^6	1.5×10^6	326	840	682	18
Average	7.9×10^6	2.9×10^6	0.2×10^6	103	141	216	9
Min	0.1×10^6	0.4×10^6	0.01×10^6	32	18	77	4
Standard Deviation	9.5×10^6	3.8×10^6	0.3×10^6	76	164	145	3
Sample Size	50	50	50	50	50	50	50
Permeate							
Max	17 [(1)]	1 [(1)]	< 1	40	5.9	118	10
Average	< 2	< 1	< 1	18	1.0	76	7
Min	< 1	< 1	< 1	< 2	0.1	19	3
Standard Deviation	2.29	0.00	0.00	9.74	1.12	22.16	1.70
Sample Size	50	50	50	50	50	50	50
Water Quality Objectives							
Monthly Average	200 [(3)]	126 [(2)]	33 [(2)]	30 [(4)]	30 [(4)]	-	-

[(1)] Max sample was the only detectable sample, 2[3)] US EPA 1986, [(3)] PA Code Title 25 Chapter 93.7, [(4)] PA Code Title 25 Chapter 92.2

Table 19: Permeate Quality for Maximum Feed Concentration - 0.2 μm Membrane

	Fecal Coliforms	*E Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	CFU/100 mL	CFU/100 mL	CFU/100 mL	mg/L	mg/L	mg/L	mg/L
Feed							
	35,000,000	17,330,000	1,530,000	376.2	840.0	682	17.78
Permeate							
	< 1	< 1	< 1	9.6	1.5	62	5.60
Water Quality Objectives							
Monthly Average	200 [(2)]	126 [(1)]	33 [(1)]	30 [(3)]	30 [(3)]	-	-
[(1)] US EPA 1986, [(2)] PA Code Title 25 Chapter 93.7, [(3)] PA Code Title 25 Chapter 92.2							

4.2.8 Impact of Filtration Time and Fouling Layer on Permeate Water Quality

The bench scale experiments demonstrated that the fouling layer has a beneficial effect on the permeate water quality during the period of rapid flux decline (Section 4.1.5). The data show that as the filtration time increases, the concentration of fecal coliforms in the permeate decreases. The decreased bacteria levels are attributed to the buildup of the fouling layer creating improved filtration. To greater support this observation, pilot scale samples were collected at strategic times.

The improved filtration during bench scale testing was observed for fecal coliforms bacteria. The same phenomena can not be observed during pilot testing because the permeate bacteria concentration was almost always non-detectable. In addition, the permeate SS concentrations were almost always less than 1.0 mg/L. Therefore, an improvement in filtration with time can only be analyzed by BOD_5, COD and NH_3-N.

An analysis of the BOD_5 and COD with time was performed for the 3-day mode of operations experiments using the 0.2 μm membrane (Section 4.2.6). Over the three days, the feed concentration was increased and samples were collected every 24 hours. The results are presented in Figures 29 to 32. Figure 29 and Figure 30 demonstrate that the permeate BOD_5 concentration decreases with time, while the feed BOD_5 concentration increases. Figure 31 and 32 demonstrate that the permeate COD concentration remains constant, while the feed COD concentration increases.

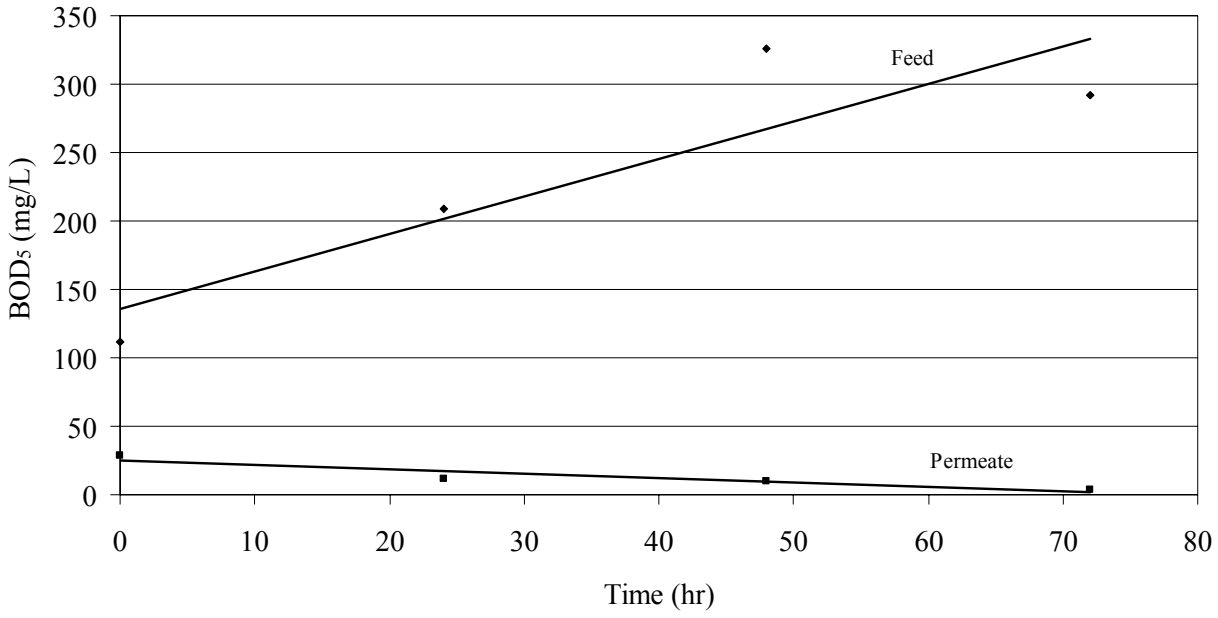

Figure 29: BOD Concentration with Time for Constant Pressure Operation – 0.2 μm

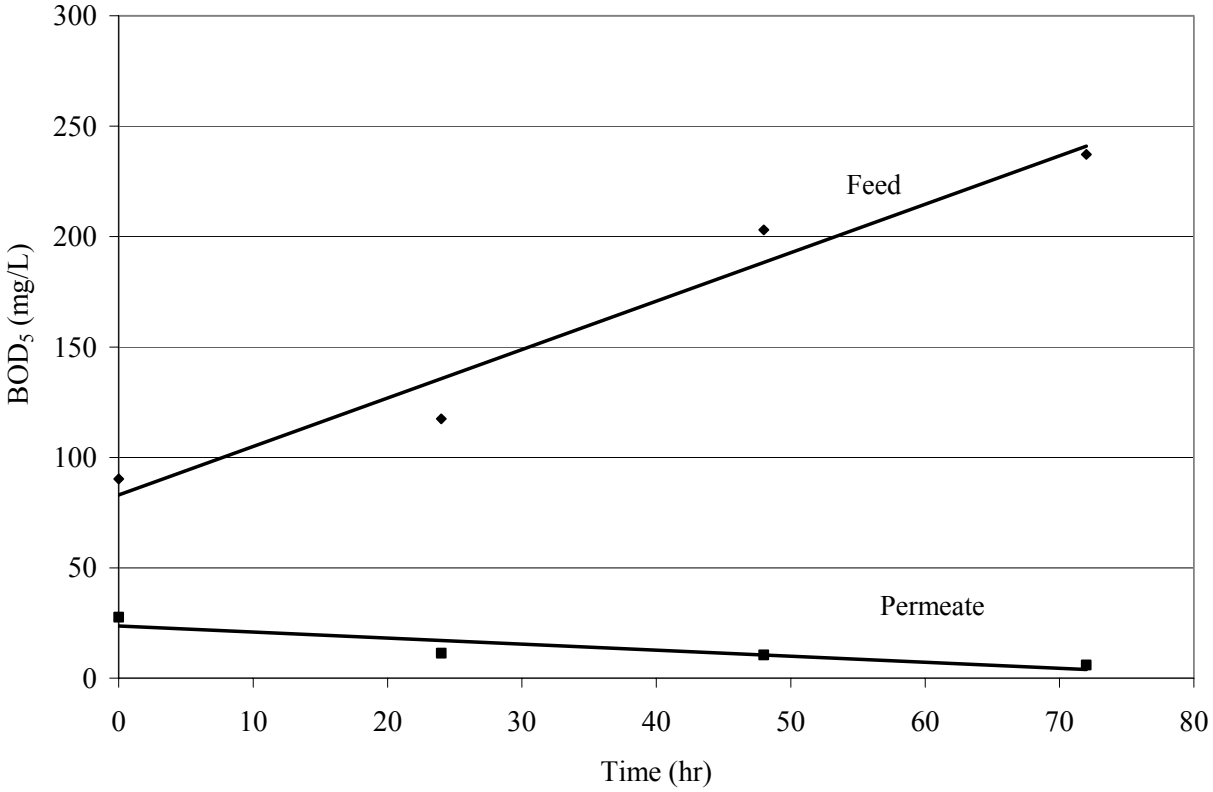

Figure 30: BOD Concentration with Time for Varying Pressure Operation – 0.2 μm

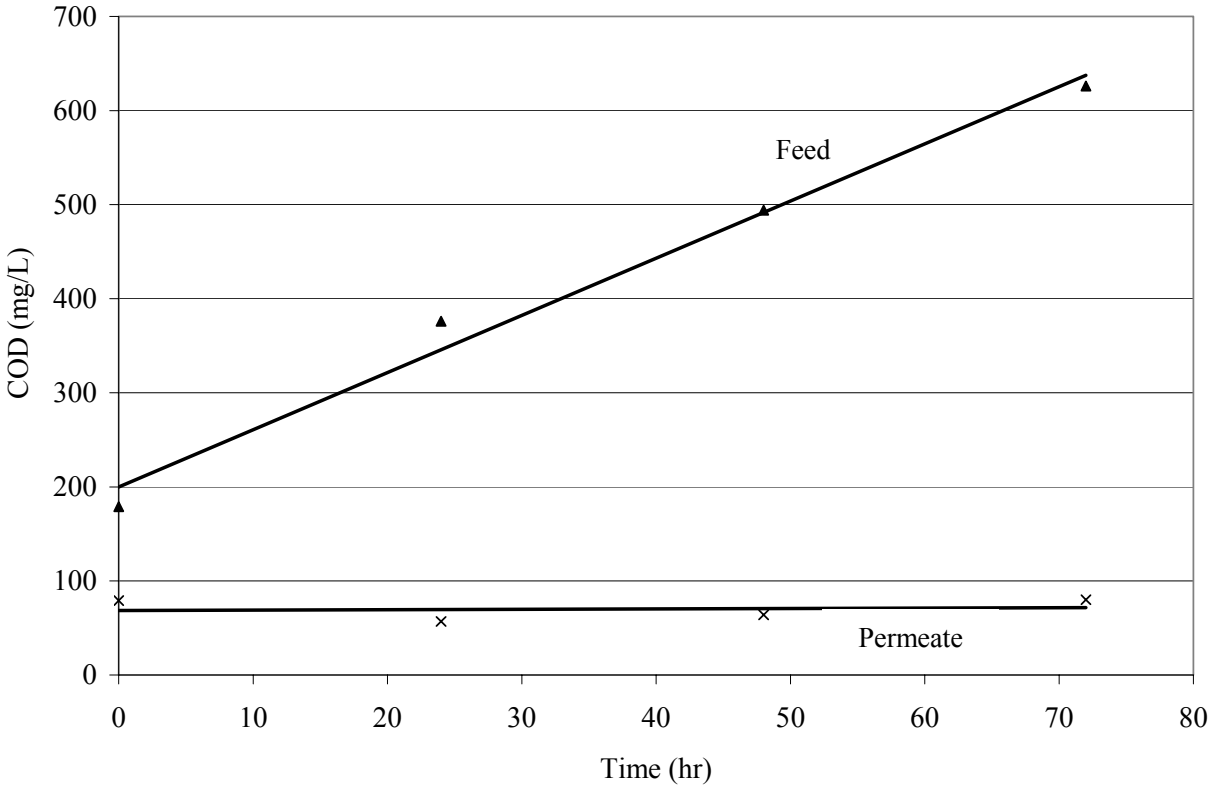

Figure 31: COD Concentration with Time for Constant Pressure Operation – 0.2 μm

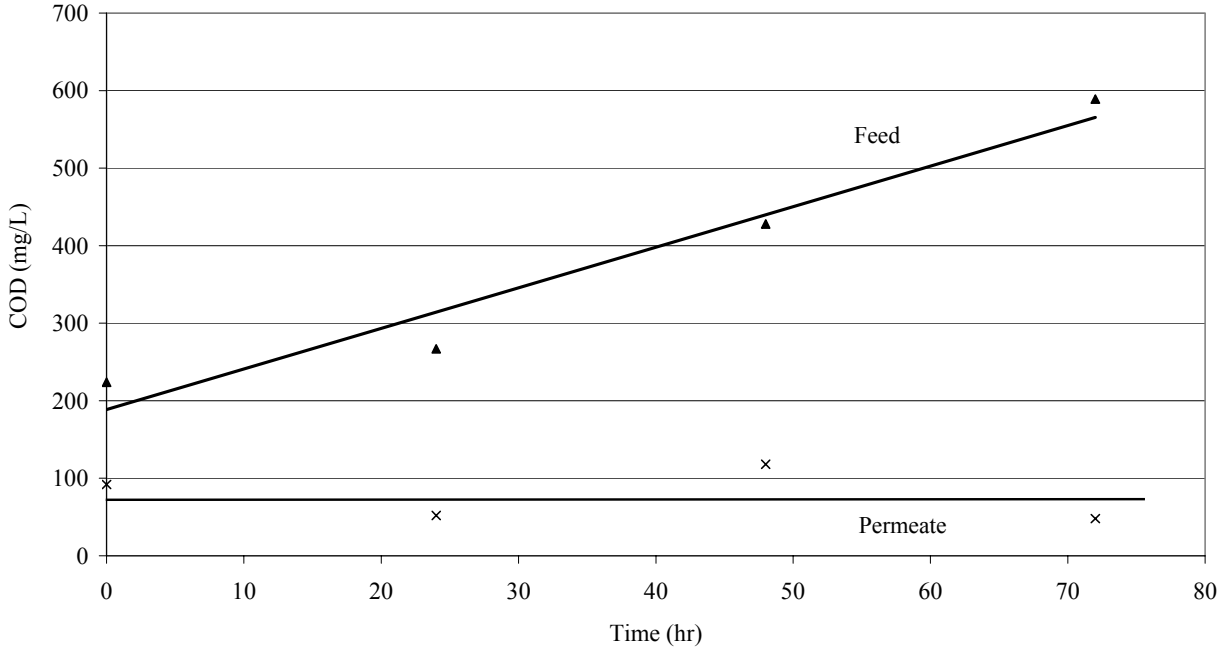

Figure 32: COD Concentration with Time for Varying Pressure Operation – 0.2 μm

The improvement in permeate BOD_5, but not the COD is surprising. The improvement in the permeate BOD_5 may be attributed to a more severe fouling layer that not only decreases the flux rate, but also improves physical filtration. However, if the improved water quality is attributed to an improved physical filtration, the same result would be expected for both BOD_5 and COD as improved filtration would be expected to enhance removal of particulate BOD_5 and COD. An alternative explanation would be the presence of an active biofilm on the membrane surface causing for the improvement in the permeate BOD_5.

Another unexpected result during pilot scale testing was the removal of ammonia. This was not expected as ammonia (NH_3-N) is soluble and should pass through the membrane. An ammonia reduction would only be expected if ammonia reducing organisms were present and

active on the membrane surface. However, on several occasions (24 of 50), using the 0.2 μm membrane, the permeate ammonia concentration was as least 1.0 mg/L less than the feed concentration. To understand the conditions that encourage the ammonia removal, a table comparing the ammonia reduction and the feed water characteristics was developed (Table 20). The data demonstrate that a greater ammonia reduction occurs when the feed wastewater has a high ammonia concentration and a low BOD_5, COD and SS concentration. These conditions favor the growth of ammonia reducing organisms. Therefore, future works to better understand the possible growth and activity of these organisms may be worthwhile.

Table 20: Feed Water Characteristics for NH_3-N Reduction – 0.2 μm Membrane

NH_3-N Reduction	Average NH_3-N Reduction	Feed NH_3-N	Feed COD	Feed BOD	Feed SS	Occurrences
(mg/L)	%	(mg/L)	(mg/L)	(mg/L)	(mg/L)	No.
< 1	5	6	223	107	150	26
1 to 3	19	9	266	134	190	10
3 to 5	35	13	206	99	137	6
5 to 10	45	13	129	48	38	5
7 to 10	69	18	128	41	49	1

4.2.9 Darcy's Law

Darcy's law, as discussed in Section 2.5, relates the flux to the applied transmembrane pressure, the viscosity of the wastewater, and the resistance to filtration caused by the membrane and the fouling layer. The governing equation of Darcy's Law allows for the determination of the membrane resistance (equation 9), the fouling layer resistance (equation 10), and the total resistance (equation 8). A comparison between the various resistances may be beneficial in trying to understand the mechanism of membrane fouling.

The initial experiment for each new membrane was to determine the intrinsic membrane resistance. For each new membrane, the initial permeate flow rate was measured using clean city water and the membrane resistance was calculated determined. The membrane resistance is assumed to be a physical property of the membrane that remains constant over time.

Experiments performed at various pore sizes (Section 4.2.1) utilized the same experimental conditions. Only the feed suspended solids concentration varied. Thus, the properties of the fouling layer would be expected to be relatively similar. The total resistance and the fouling layer resistance at steady state were determined for each pore size. These results and the previously determined membrane resistance are given in Table 21. The data indicate that the fouling layer is responsible for greater than 85% of the resistance and that the fouling layer is the main obstacle preventing greater permeate flux rates. The total and fouling layer resistance is much greater for the 0.05 μm than for the other membranes. This result suggests that the 0.05 μm membrane may encourage the development of a more severe fouling layer. For all membrane pore sizes greater than 0.05 μm, the total resistance varies by only 11%, while the pore size of the largest membrane (1.4 μm) is 7 times greater than the pore size of the smallest membrane (0.2 μm). A possible explanation for the similar resistances is that internal pore fouling increases

as the pore size increases. This reason is supported by previous studies that explained similar flux rates over time for various pore sizes were attributed to the larger pore sizes being more likely to have more severe in-pore fouling [Gan, 1999].

Table 21: Resistance to Flow for Each Pore Size

Pore Size	Intrinsic Membrane Resistance $R_m \times 10^{10}$	Fouling Layer Resistance at Steady State $R_f \times 10^{10}$	Total Resistance at Steady State $R_t \times 10^{10}$	Percent of Resistance attributed to Fouling
(μm)	(1/m)	(1/m)	(1/m)	(%)
0.05	40.0	239	279	86
0.2	18.0	130	148	88
0.5	8.0	140	148	95
0.8	4.8	143	148	97
1.4	3.3	144	147	98

Any change in the fouling layer would be expected to change the resistance to filtration. As discussed previously, the fouling layer thickness and density is anticipated to change with changes in cross flow velocity or transmembrane pressure (Figure 7 and 9). A greater cross flow velocity is anticipated to decrease the thickness of the fouling layer, while a greater transmembrane pressure is anticipated to create a more compacted and dense fouling layer.

Understanding changes in resistance with changes in cross flow velocity and transmembrane pressure may provide guidance on determining the fouling mechanism. The mechanism may be internal fouling and/or surface fouling. As the transmembrane pressure increases, it is possible that particles are forced deeper into the pores creating more severe in-pore fouling. Thus, a comparison at various transmembrane pressures is difficult. However, changes in cross flow velocity are not expected to influence in-pore fouling. Any increase or decrease in resistance caused by changes in cross-flow velocity may be attributed to variations in the surface fouling layer. The total resistance and fouling layer resistance were calculated based

on the steady state flux rate at fourteen different transmembrane pressure and cross flow velocity conditions using the 0.2 μm membrane. The total resistance results are shown in Figure 33 and the fouling layer resistance results are shown in Figure 34.

These results show that the total and the fouling layer resistance decrease until the cross flow velocity approaches 1.8 m/s. For cross flow velocities greater than 1.8 m/s, the resistances remain similar. These results suggest that the surface fouling layer influences the resistance to filtration. However, they do not demonstrate that the surface fouling layer controls the resistance to filtration. The controlling factor may be the surface fouling layer or a combination of surface and internal fouling. With membrane fouling being the major hindrance of the wide spread implementation of microfiltration systems; an investigation into the mechanism of membrane fouling may be of interest. Once the actual mechanism is known, perhaps the impact of the fouling layer on the flux rates can be minimized.

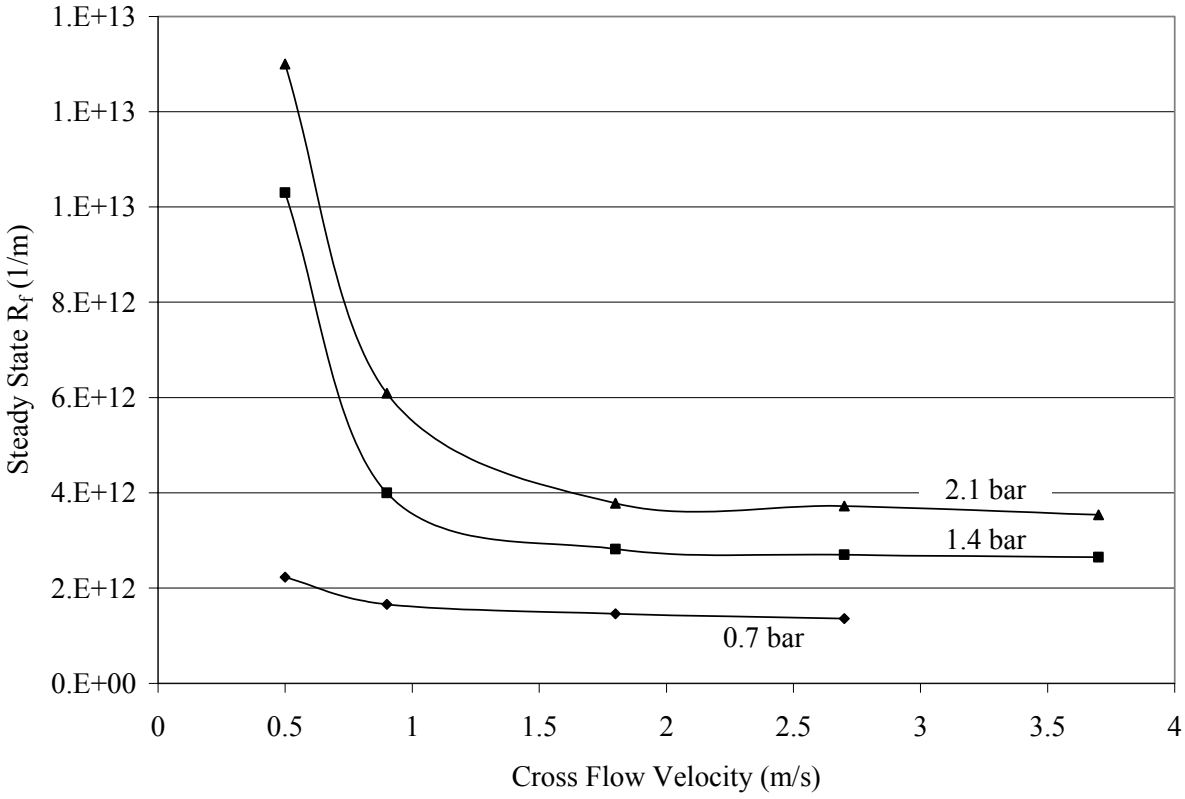

Figure 33: Steady State Fouling Layer Resistance – 0.2 μm

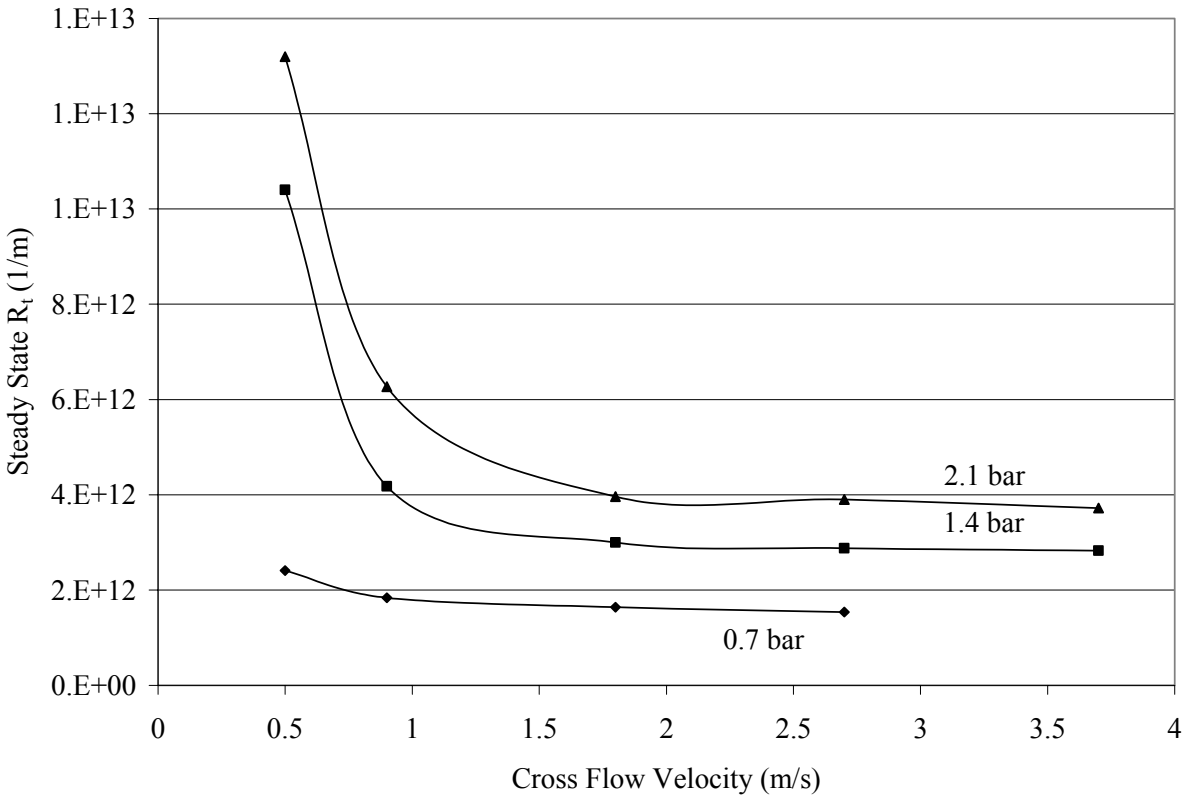

Figure 34: Steady State Total Resistance – 0.2 μm

4.2.10 Membrane Maintenance and Cleaning

The alkaline sodium hypochlorite cleaning solution (1,500 mg/L NaOCl) was effective in recovering much of the initial permeate flux rate under the experimental conditions of this study. The NaOCl solution was prepared by adding commercial bleach (~6% NaOCl) to city water in the process tank. The NaOCl solution was recirculated overnight (~12 to 16 hours) with a 1.4 bar inlet pressure and a 2.7 m/s cross flow velocity. The permeate valves were closed and the temperature was allowed to increase to greater than 40^{o}C. The more aggressive nitric acid solution was used in the same manner as the NaOCl solution. The HNO_3 solution was prepared with laboratory grade HNO_3. The nitric acid solution was only used after first cleaning with the NaOCl solution.

The 0.2 μm membrane was operate and cleaned 25 times. The initial flux rate after cleaning was measured using fresh city water and the permeability was calculated using equation 4. That permeability was compared to the permeability of a new membrane. The percent of permeability that was restored is shown in Figure 35. Throughout the initial fifteen experiments, the alkaline NaOCl solution returned the permeability to within 20% of the original permeability. For experiments 15 to 21, the feed suspended solids were increased and the alkaline sodium hypochlorite solution was not as effective as the permeability after cleaning was only 50-75% of the original permeability. At that time, the membrane was removed from the system and inspected. An orange color on both the feed and permeate side of the membrane was detected. This was the only observation of the orange color. The membrane was then cleaned more aggressively with alkaline sodium hypochlorite followed by nitric acid cleaning. This cleaning combination restored the permeability to the original rate. Additional cleanings with the alkaline NaOCl solution at low feed suspended solids levels were effective. Therefore, the suggested

cleaning procedure would be to first use the alkaline sodium hypochlorite. If the permeability is not restored by this procedure, the nitric acid solution should be used as a second step in the cleaning protocol.

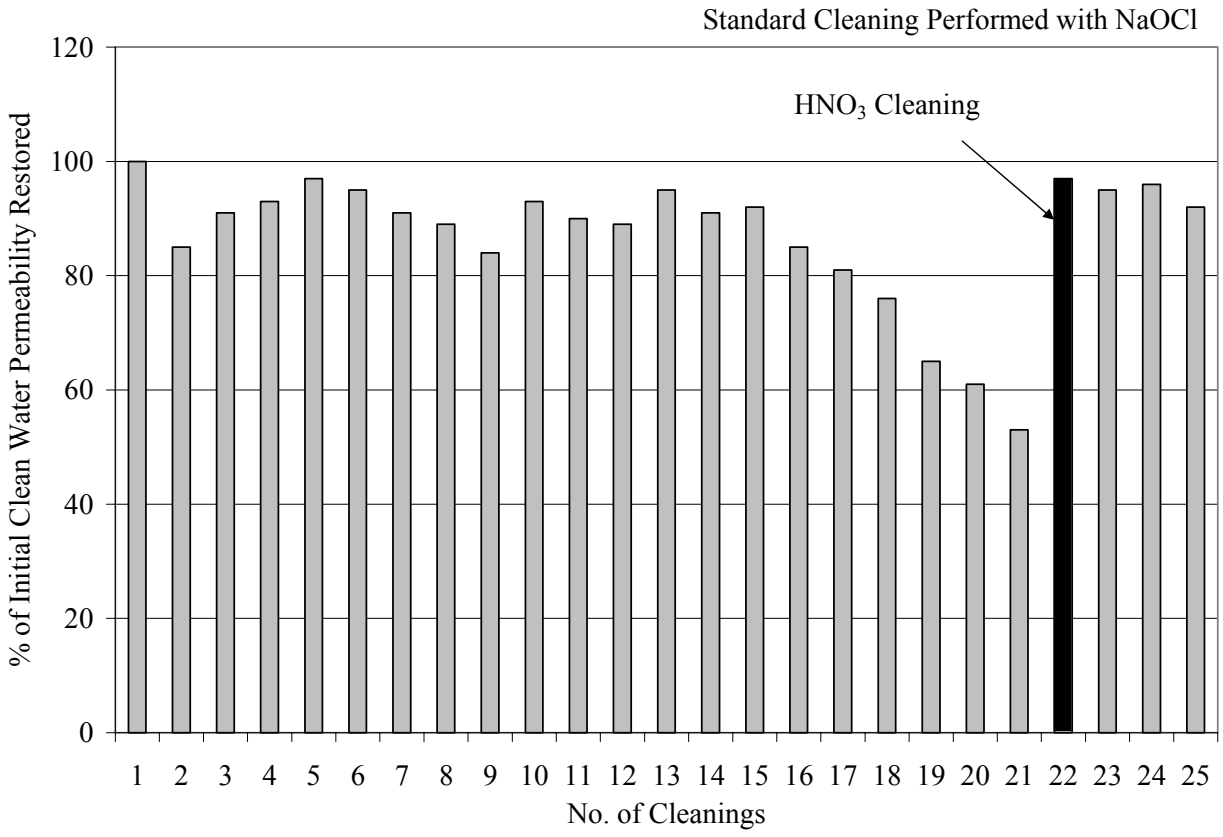

Figure 35: Cleaning Effectiveness – 0.2 μm

5.0 SUMMARY AND CONCLUSIONS

Cross flow microfiltration was evaluated for the treatment of a dilute primary sewage effluent (PSE) simulating combined sewer overflow (CSO) wastewater. Experiments were conducted to determine the preferred membrane pore size, cross flow velocity, transmembrane pressure and operating mode. In addition, experiments were performed to determine the impact of the backpulse, suspended solids and temperature on the steady state flux rates. These experiments were performed at both a bench scale and a pilot scale using PSE from the Allegheny County Sanitary Authority (ALCOSAN). A comparison between the ALCOSAN PSE and typical CSO wastewater quality demonstrates that the PSE simulates both the strength and the bacterial levels of CSO wastewater.

The bench scale investigation was used to assist in the planning and design of pilot scale experimental protocols. Specific emphasis was placed on evaluating the membrane pore sizes capable of meeting the selected water quality objectives for bacteria and on evaluating the effect of backpulse on the permeate flux rate. Results show that the use of the backpulse improved the steady state flux rate and was considered to a substantial advantage with a preferred backpulse frequency of 60 seconds.

Additional bench scale results demonstrated that membranes with a mean pore size less than 2.0 μm are capable of meeting the selected bacterial water quality objectives. Therefore, five membranes with a mean pore size below 2.0 μm (0.05, 0.2, 0.5, 0.8 and 1.4 μm) were evaluated at the pilot scale. Results indicate that all membranes were capable of meeting the water quality objectives for bacteria, BOD_5 and suspended solids and that all membranes greater than 0.05 μm produced a similar 6-hour steady state flux rate of 165 L/hr-m^2 at 20^{o}C. These results indicate that by using a membrane with a pore size greater than 0.2 μm no benefit in the

steady state flux will be achieved. In addition, an increase in pore size from 0.2 μm would increase the risk of bacteria passage through the membrane. Therefore, the 0.2 μm membrane was selected as the preferred membrane pore size and was used for further testing.

Throughout additional experiments using the 0.2 μm membrane, a total of 50 feed and 50 permeate samples were analyzed for fecal coliforms, *E Coli*, *enterococci*, BOD_5, COD, SS and NH_3-N. The data clearly demonstrate that the 0.2 μm membrane continually met the water quality objectives for bacteria, BOD_5 and SS. The permeate bacteria quality was excellent, with only two of the 150 bacteria samples having detectable bacteria. Those two results were well below the water quality objective. All SS concentrations were below the objective of 30 mg/L, with an average permeate concentration of 1.0 mg/L. The average BOD_5 (18 mg/L) was well below the objective (30 mg/L), with only 8 out of the 50 BOD_5 samples being greater than 30 mg/L. In addition, the technology demonstrates consistent results independent of the feed concentration. The 0.2 μm membrane was able to meet all water quality objectives at the maximum influent levels for each parameter.

A 15 experiment testing matrix using the 0.2 μm membrane was utilized to evaluate the influence of cross flow velocity and transmembrane pressure on the 6-hour steady state flux rate. The matrix consisted of three transmembrane pressure settings (0.7, 1.4 and 2.1 bar) operated at four or five cross flow velocity settings (0.5, 0.9, 1.8, 2.7 and 3.7 m/s). These results clearly point to an improvement in the steady state flux with an increase in cross flow velocity until the cross flow velocity reaches 1.8 m/s, with a flux of 165 L/hr-m^2 at 20^{o}C. For an increase in cross flow velocity greater than 1.8 m/s, the improvement in the steady state flux rate is negligible. Additionally, measured system specific power requirements indicate a decrease in cost until the cross flow velocity reaches 1.8 m/s. For all velocities greater than 1.8 m/s the cost increases.

Combing the steady state flux rates with the power costs indicates a preferred cross flow velocity of 1.8 m/s. The same data was used to evaluate the influence of transmembrane pressure on the steady state flux rate. A marginal improvement in permeate flux was observed for an increase in transmembrane pressure at low cross flow velocities (0.5 and 0.9 m/s). At higher cross flow velocities (1.8 and 2.7 m/s), the steady state flux rate increased as the transmembrane pressure increased. An increase in transmembrane pressure from 0.7 to 2.1 bar at the preferred cross flow velocity of 1.8 m/s results in a 44% increase in power costs. However, there are other costs associated with membrane systems, such as the high capital costs of the membranes. Additionally, the data collected at 1.4 and 2.1 bar indicate that the scouring effect at low cross flow velocities (< 1.0 m/s) may not be sufficient enough to overcome the adhesion and compaction of the solids on the membrane surface. Thus, for low cross flow velocities (< 1.0 m/s) the particles that accumulate at the membrane surface may form a hydraulic barrier that controls the steady state flux rate.

The feed suspended solids concentrations and temperature were evaluated to determine their impact on the steady state flux rate. An increase in the feed suspended solids concentration or a decrease in temperature is anticipated to make filtration more difficult. Separate experiments were performed to evaluate these relationships. It was observed that the steady state flux rate decreased until the feed suspended solids concentration reaches between 300 to 500 mg/L. The steady state permeate flux appears to remain constant at approximately 105 L/hr-m^2 for all feed concentration greater than 500 mg/L. The temperature data indicate that as the temperature increases, the steady sate flux rate increases. An increase in temperature from 12 to 26^oC increased the flux by nearly 30% from 82 to 116 L/hr-m^2. In order to compare flux rates independent of temperature the standard viscosity correction factor was used. These data

demonstrate that the standard viscosity correction factor was accurate with a coefficient of determination (R^2) of 0.9904 with the largest variation being only 4% at 23^{o}C.

Two common modes of operation for cross flow microfiltration systems are constant pressure and varying pressure. During constant pressure operation, it is believed that the initial rapid flow of water through the membrane forces particles into the membrane pores creating more severe internal fouling. By keeping the initial flux rate constant and varying the pressure, it is believed that fewer particles are pushed into the pores creating less severe fouling. To simulate a CSO event and to evaluate the different modes of operation, a three day (72-hour) experiment was conducted for each operating mode using the 0.2 μm membrane. The mode of varying pressure produced a higher flux rate after 24 hours, but not after 48 hours. Additionally, the varying pressure operation produced a greater flux rate until the suspended solids concentration reached approximately 300 mg/L. Beyond 300 mg/L, each mode of operation produced similar flux rates.

Bench scale and pilot scale results demonstrated that the fouling layer benefits the permeate water quality. Bench scale observations showed that during the period of rapid flux decline, permeate bacteria levels decreased, which was attributed to the buildup of the fouling layer creating improved filtration. To greater support this observation, pilot scale samples were collected at strategic times. During pilot scale testing nearly all permeate samples were non-detectable. Thus, a similar observation could not be reached. However, other surprising results during pilot testing indicate that the fouling layer benefits the permeate water quality. Results, using the 0.2 μm membrane, suggest a possible active biofilm is responsible for an improved permeate quality. Over time, with an increasing feed BOD_5 and COD concentration, the permeate BOD_5 concentration decreases, while the permeate COD concentration remains the

same. Additional results (24 of 50) using the 0.2 μm membrane produced a permeate ammonia concentration at least 1.0 mg/L less than the feed concentration. A greater ammonia reduction was observed when the feed wastewater has a high ammonia concentration and a low BOD_5, COD and SS concentration. Ammonia is soluble and a reduction would only be expected if ammonia reducing organisms were present and active on the membrane surface.

Between experiments, the membranes were chemically cleaned to ensure appropriate initial conditions. The alkaline sodium hypochlorite cleaning solution (1,500 mg/L NaOCl) was effective in recovering much of the initial permeability. After experiments with low feed suspended solids concentration, the alkaline NaOCl solution returned the permeability to within 20% of the original permeability. For experiments with increased feed suspended solids concentrations, the alkaline sodium hypochlorite solution returned to permeability to only 50-75% of the original permeability. The membrane was then cleaned more aggressively with the alkaline sodium hypochlorite solution followed by the nitric acid (1%) solution. This cleaning combination restored the permeability to the original rate. Additional cleanings with the alkaline NaOCl solution at low feed suspended solids levels were effective. Therefore, the suggested cleaning procedure would be to first use the alkaline sodium hypochlorite solution. If the permeability is not restored, the nitric acid solution should be used as a second step in the cleaning protocol.

6.0 RECOMMENDATIONS FOR FUTURE WORK

Once the fouling mechanism is known, perhaps the impact of the fouling layer can be better reduced. These results suggest that the surface fouling layer affects the flux rate. However, they do not demonstrate that the surface fouling layer controls the flux rate. The controlling factor may be the surface fouling layer or a combination of surface and internal fouling. With membrane fouling being the major hindrance of the wide spread implementation of microfiltration systems, a study to determine the whether fouling mechanism is internal or external is suggested.

In addition, the fouling layer also impacts the permeate water quality. Surprising results within this research, suggest a possible active biofilm. An investigation into the verification of the biofilm development is suggested.

Also, the backpulse is beneficial to the permeate flux rate. By some means, the fouling layer is disturbed. It is not clear whether the pores are cleared, the particles on the surface are cleared or both. A study to understand what the backpulse is actually doing is suggested.

APPENDIX A

Field Unit Water Quality Results

Appendix A

Table A.1

Water Quality Results from Pore Size Optimization Experiments

ΔP - 0.7 bar, CFV - 2.7 m/s, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate To Drain

	Pore Size	Time into Experiment	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH3-N
	(μm)	(hour)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.05	0.5	6,000,000	143,000	110,600	89.2	88.0	201	14.98
Permeate	0.05	0.5	<2	<1	<1	25.8	1.0	93	4.06
Feed	0.05	5.5	6,200,000	721,500	125,900	78.1	80.0	157	6.86
Permeate	0.05	5.5	<2	<1	1	12.7	0.2	62	6.58
Feed	0.05	0.5	<1000	<1000	<1000	37.0	34.0	73	5.46
Permeate	0.05	0.5	<2	<1	<1	15.5	0.7	45	5.18
Feed	0.05	5.5	5,000	1,000	1,000	42.6	40.0	87	8.96
Permeate	0.05	5.5	<2	<1	<1	19.3	0.4	35	6.58
Average Permeate	0.05	-	< 2	< 1	< 1	18.3	0.6	58.8	5.6

Appendix A
Table A.2
Water Quality Results from Pore Size Optimization Experiments
ΔP - 0.7 bar, CFV - 2.7 m/s, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate To Drain

	Pore Size	Time into Experiment	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH3-N
	(μm)	(hour)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.2	0.5	TNC	>2419	<2419	50.3	64.0	123	5.60
Permeate	0.2	0.5	<4	<1	<1	10.2	0.8	55	2.94
Feed	0.2	5.5	TNC	>2419	>2419	71.1	100.0	156	4.48
Permeate	0.2	5.5	17	1	<1	8.1	0.6	34	4.90
Feed	0.2	0.5	4,600,000	>2419	>2419	86.5	144.0	175	7.98
Permeate	0.2	0.5	<2	<1	<1	11.0	0.8	84	5.25
Feed	0.2	5.5	4,600,000	>2419	>2419	89.8	168.0	216	9.94
Permeate	0.2	5.5	<2	<1	<1	9.5	0.9	113	4.97
Average Permeate	0.2	-	< 6	< 1	< 1	9.7	0.8	71.5	4.5

Appendix A
Table A.3
Water Quality Results from Pore Size Optimization Experiments
ΔP - 0.7 bar, CFV - 2.7 m/s, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate To Drain

	Pore Size	Time into Experiment	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH3-N
	(μm)	(hour)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	0.5	4,000,000	>2419	>2419	54.7	66.0	132	8.19
Permeate	0.5	0.5	<2	<1	<1	18.3	0.4	54	5.11
Feed	0.5	5.5	17,000,000	>2419	>2419	77.5	98.0	70	6.44
Permeate	0.5	5.5	<2	<1	<1	11.4	0.3	10	5.25
Feed	0.5	0.5	1,600,000	>2419	>2419	42.0	30.7	74	6.09
Permeate	0.5	0.5	<2	<1	<1	17.2	0.2	30	4.90
Feed	0.5	5.5	4,600,000	>2419	>2419	44.5	68.0	130	6.65
Permeate	0.5	5.5	<2	<1	<1	10.1	0.2	45	4.83
Average Permeate	0.5	-	< 2	< 1	< 1	14.3	0.3	34.8	5.0

Appendix A
Table A.4
Water Quality Results from Pore Size Optimization Experiments
ΔP - 0.7 bar, CFV - 2.7 m/s, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate To Drain

	Pore Size	Time into Experiment	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH3-N
	(μm)	(hour)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.8	0.5	5,400,000	328,000	51,200	65.3	70.0	165	11.62
Permeate	0.8	0.5	1	2	2	11.2	0.5	70	5.81
Feed	0.8	5.5	27,000,000	75,400	689,300	157.0	90.0	440	7.00
Permeate	0.8	5.5	27	17	3	21.4	0.4	44	5.88
Feed	0.8	0.5	630,000	313,000	17,000	50.0	49.3	110	7.70
Permeate	0.8	0.5	2	2	<1	17.4	0.5	70	5.74
Feed	0.8	5.5	4,306,000	574,800	107,100	84.5	74.0	139	6.44
Permeate	0.8	5.5	2	9	2	16.7	0.3	63	3.78
Average Permeate	0.8	-	8	8	< 4	16.7	0.4	61.8	5.3

Appendix A
Table A.5
Water Quality Results from Pore Size Optimization Experiments
ΔP - 0.7 bar, CFV - 2.7 m/s, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate To Drain

	Pore Size	Time into Experiment	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH3-N
	(μm)	(hour)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	1.4	0.5	5,900,000	330,000	101,400	80.8	117.5	161	7.00
Permeate	1.4	0.5	<2	<1	<1	17.6	0.3	55	6.65
Feed	1.4	5.5	9,400,000	640,500	143,900	103.0	152.0	198	7.70
Permeate	1.4	5.5	<2	<1	<1	14.9	0.4	41	6.93
Feed	1.4	0.5	840,000	387,700	135,400	91.1	60.0	153	8.12
Permeate	1.4	0.5	<2	<1	<1	24.3	0.6	67	6.79
Feed	1.4	5.5	5,600,000	913,900	228,200	90.8	88.0	179	10.36
Permeate	1.4	5.5	<2	1	<1	16.3	0.1	45	6.51
Average Permeate	1.4	-	< 2	< 1	< 1	18.3	0.4	52.0	6.7

Appendix A
Table A.6
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	0.7	0.5	<2000	<1000	<1000	40.1	20.0	102	6.72
Permeate	0.5	0.7	0.5	<2	<1	<1	22.1	0.1	71	6.44
Feed	5.5	0.7	0.5	380	2,400	300	45.1	25.0	105	7.28
Permeate	5.5	0.7	0.5	<2	<1	<1	26.8	0.1	71	7.00
Average Permeate	-	-	-	< 2	< 1	< 1	24.5	0.1	71.0	6.7

Appendix A
Table A.7
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment (hour)	ΔP (bar)	CFV (m/s)	Fecal Coliform (CFU/100 mL)	*E.Coli* (MPN/100 mL)	*Enterococci* (MPN/100 mL)	BOD (mg/L)	SS (mg/L)	COD (mg/L)	NH_3-N (mg/L)
Feed	0.5	0.7	0.5	31,000	29,000	1,000	40.8	17.6	121	6.16
Permeate	0.5	0.7	0.5	<2	<1	<1	26.1	0.1	86	5.74
Feed	5.5	0.7	0.5	<2000	<1000	<1000	43.0	18.7	77	13.44
Permeate	5.5	0.7	0.5	<2	<1	<1	26.7	0.1	76	7.42
Average Permeate	-	-	-	< 2	< 1	< 1	26.4	0.1	81.0	6.6

Appendix A
Table A.8
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	0.7	1.8	4,500,000	1,046,000	96,000	61.9	62.0	134	7.56
Permeate	0.5	0.7	1.8	<2	<1	<1	18.6	0.1	49	6.58
Feed	5.5	0.7	1.8	4,200,000	1,553,000	107,000	48.2	50.0	133	7.56
Permeate	5.5	0.7	1.8	<2	<1	<1	13.3	0.1	78	7.00
Average Permeate	-	-	-	< 2	< 1	< 1	16.0	0.1	63.5	6.8

Appendix A
Table A.9
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	0.7	2.7	See Appendix A Table A.2						
Permeate	0.5	0.7	2.7							
Feed	5.5	0.7	2.7							
Permeate	5.5	0.7	2.7							
Average Permeate	-	-	-	-	-	-	-	-	-	-

Appendix A
Table A.10
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	1.4	0.5	390,000	146,150	14,050	80.8	86.0	204	13.30
Permeate	0.5	1.4	0.5	<1	<1	<1	30.2	0.3	116	8.96
Feed	5.5	1.4	0.5	670,000	365,000	44,250	76.4	111.4	226	12.88
Permeate	5.5	1.4	0.5	<1	<1	<1	21.4	0.4	107	8.26
Average Permeate	-	-	-	< 1	< 1	< 1	25.8	0.4	111.5	8.6

Appendix A
Table A.11
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	1.4	0.9	<5	200	<100	41.3	49.3	128	17.78
Permeate	0.5	1.4	0.9	<1	<1	<1	18.8	0.2	96	5.60
Feed	5.5	1.4	0.9	<5	<100	<100	46.8	45.3	146	13.58
Permeate	5.5	1.4	0.9	<1	<1	<1	22.9	0.4	71	6.58
Average Permeate	-	-	-	< 1	< 1	< 1	20.9	0.3	83.5	6.1

Appendix A
Table A.12
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	1.4	1.8	31	7,600	1,400	47.5	58.6	151	13.72
Permeate	0.5	1.4	1.8	<2	<1	<1	20.4	0.2	93	7.84
Feed	5.5	1.4	1.8	2,000	5,630	1,450	56.8	52.0	151	9.80
Permeate	5.5	1.4	1.8	<2	<1	<1	20.5	0.6	91	7.56
Average Permeate	-	-	-	< 2	< 1	< 1	20.5	0.4	92.0	7.7

Appendix A
Table A.13
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	1.4	2.7	130,000	43,500	9,100	58.7	24.0	137	13.30
Permeate	0.5	1.4	2.7	<2	<1	<1	39.6	0.1	101	7.98
Feed	5.5	1.4	2.7	>60000	>241900	54,800	49.3	36.0	146	9.24
Permeate	5.5	1.4	2.7	<2	<1	<1	33.4	0.4	100	8.12
Average Permeate	-	-	-	< 2	< 1	< 1	36.5	0.3	100.5	8.1

Appendix A
Table A.14
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	1.4	3.7	3,800,000	866,000	61,000	90.1	70.0	140	4.62
Permeate	0.5	1.4	3.7	<1	<1	<1	37.3	1.7	68	4.48
Feed	5.5	1.4	3.7	1,000,000	687,000	49,000	85.6	77.5	154	7.98
Permeate	5.5	1.4	3.7	<1	<1	<1	20.3	0.2	84	5.04
Average Permeate	-	-	-	< 1	< 1	< 1	28.8	1.0	76.0	4.8

Appendix A
Table A.15
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	2.1	0.5	2,600,000	816,000	46,000	94.3	136.0	200	5.18
Permeate	0.5	2.1	0.5	<1	1	1	21.1	1.1	75	4.90
Feed	5.5	2.1	0.5	2,700,000	488,000	41,000	117.5	100.0	198	3.64
Permeate	5.5	2.1	0.5	<1	<1	<1	15.3	0.7	60	3.22
Average Permeate	-	-	-	< 1	< 1	< 1	18.2	0.9	67.5	4.1

Appendix A
Table A.16
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	2.1	0.9	2,700,000	548,000	74,850	82.3	78.0	185	9.52
Permeate	0.5	2.1	0.9	<1	<1	<1	34.2	1.3	84	8.54
Feed	5.5	2.1	0.9	27,000,000	921,000	104,550	84.2	95.0	176	7.84
Permeate	5.5	2.1	0.9	<1	<1	<1	17.3	1.1	83	7.28
Average Permeate	-	-	-	< 1	< 1	< 1	25.8	1.2	83.5	7.9

Appendix A
Table A.17
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	2.1	1.8	1,560,000	579,000	68,450	37.0	48.0	129	12.88
Permeate	0.5	2.1	1.8	<1	<1	<1	7.3	0.5	88	7.98
Feed	5.5	2.1	1.8	2,000,000	77,000	76,300	44.3	44.0	136	12.74
Permeate	5.5	2.1	1.8	<1	<1	<1	8.4	0.1	89	6.58
Average Permeate	-	-	-	< 1	< 1	< 1	7.9	0.3	88.5	7.3

Appendix A
Table A.18
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	2.1	2.7	400,000	1,046,000	76,400	49.8	42.0	118	9.10
Permeate	0.5	2.1	2.7	<1	<1	<1	15.8	0.5	85	7.98
Feed	5.5	2.1	2.7	>600000	921,000	68,550	56.0	68.0	150	13.72
Permeate	5.5	2.1	2.7	<1	<1	<1	11.9	0.3	66	8.82
Average Permeate	-	-	-	< 1	< 1	< 1	13.9	0.4	75.5	8.4

Appendix A
Table A.19
Water Quality Results from Pressure and Velocity Optimization Experiments
Pore Size 0.2 μm, Backpulse Frequency - 60 sec, Feed - Primary Sewage Effluent, Permeate Recycle to Feed Tank

	Time into Experiment	ΔP	CFV	Fecal Coliform	*E.Coli*	*Enterococci*	BOD	SS	COD	NH_3-N
	(hour)	(bar)	(m/s)	(CFU/100 mL)	(MPN/100 mL)	(MPN/100 mL)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Feed	0.5	2.1	3.7	6,800,000	727,000	77,000	80.9	71.1	165	6.02
Permeate	0.5	2.1	3.7	<1	<1	<1	31.0	1.0	93	4.90
Feed	5.5	2.1	3.7	2,000,000	416,000	64,000	73.7	77.1	163	5.46
Permeate	5.5	2.1	3.7	<1	<1	<1	13.8	0.3	72	5.04
Average Permeate	-	-	-	< 1	< 1	< 1	22.4	0.7	82.5	5.0

Appendix A
Table A.20
Water Quality Results from Impact of Suspended Solids Experiments
ΔP - 1.0 bar, CFV - 1.8 m/s, Backpulse Frequency - 60 sec, Pore Size - 0.2 μm, Feed - Primary Sewage Effluent

Day	Feed/Permeate	Fecal Coliform (CFU/100 mL)	*E.Coli* (MPN/100 mL)	*Enterococci* (MPN/100 mL)	BOD (mg/L)	SS (mg/L)	COD (mg/L)	NH3-N (mg/L)
1	Feed	2,100,000	2,419,000	225,000	177.3	246.7	No Result	13.02
	Permeate	<1	<1	<1	34.5	1.9	No Result	9.52
2	Feed	3,400,000	1,553,000	172,000	178.6	5.6	313	12.88
	Permeate	<1	<1	<1	13.8	5.6	68	8.96
3	Feed	15,000,000	2,419,000	345,000	296.1	450.0	502	11.90
	Permeate	<1	<1	<1	4.1	4.2	58	10.22
4	Feed	12,500,000	>2,419,000	248,000	215.6	640.0	682	7.28
	Permeate	<1	<1	<1	14.0	0.7	62	6.16
5	Feed	11,500,000	7,270,000	300,000	277.8	490.0	385	5.04
	Permeate	<1	<1	<1	8.5	0.1	51	4.90

Appendix A
Table A.21
Water Quality Results from Impact of Temperature Experiments

ΔP - 1.4 bar, CFV - 1.8 m/s, Backpulse Frequency - 60 sec, Pore Size - 0.2 μm, Feed - Primary Sewage Effluent

Feed/Permeate	Fecal Coliform (CFU/100 mL)	*E.Coli* (MPN/100 mL)	*Enterococci* (MPN/100 mL)	BOD (mg/L)	SS (mg/L)	COD (mg/L)	NH3-N (mg/L)
Feed	30,000	47,000	4,000	32.0	50.0	124	5.04
Permeate	<1	<1	<1	<2	2.4	99	4.76

Appendix A
Table A.22
Water Quality Results from 3-Day Constant Pressure Experiment

ΔP - 1.0 bar, CFV - 1.8 m/s, Backpulse Frequency - 60 sec, Pore Size - 0.2 μm, Feed - Primary Sewage Effluent

Day	Feed/Permeate	Fecal Coliform (CFU/100 mL)	*E.Coli* (MPN/100 mL)	*Enterococci* (MPN/100 mL)	BOD (mg/L)	SS (mg/L)	COD (mg/L)	NH3-N (mg/L)
1	Feed	5,200,000	2,419,000	167,000	111.5	76.0	179	10.78
	Permeate	<1	<1	<1	28.5	<10	79	10.22
2	Feed	12,000,000	7,700,000	270,000	209.3	204.0	376	7.98
	Permeate	<1	<1	<1	11.2	0.9	57	7.98
3	Feed	35,000,000	9,210,000	710,000	326.2	290.0	494	8.40
	Permeate	<1	<1	<1	9.6	1.0	64	6.72
4	Feed	19,000,000	9,210,000	880,000	291.6	840.0	626	7.42
	Permeate	<1	<1	<1	3.4	1.5	80	7.00

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Table A.23

Water Quality Results from 3-Day Varying Pressure Experiment

ΔP - Increase to 1.4 bar, CFV - 1.8 m/s, Backpulse Frequency - 60 sec, Pore Size - 0.2 μm, Feed - Primary Sewage

Day	Feed/Permeate	Fecal Coliform (CFU/100 mL)	*E.Coli* (MPN/100 mL)	*Enterococci* (MPN/100 mL)	BOD (mg/L)	SS (mg/L)	COD (mg/L)	NH3-N (mg/L)
1	Feed	270,000	816,000	51,000	90.2	160.0	224	4.76
	Permeate	<1	<1	<1	27.6	2.4	92	4.76
2	Feed	4,800,000	4,610,000	210,000	117.5	220.0	267	6.58
	Permeate	<1	<1	<1	11.3	2.0	52	5.74
3	Feed	33,000,000	6,490,000	1,530,000	203.0	270.0	428	6.02
	Permeate	<1	<1	<1	10.5	1.8	118	5.88
4	Feed	23,000,000	6,870,000	430,000	237.2	380.0	589	6.72
	Permeate	<1	<1	<1	6.0	2.0	48	6.44

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